Electronic Supplementary Material (ESI) for Physical Chemistry Chemical Physics.

Electronic Supporting Information for:

Connecting chloride solvation with hydration in deep eutectic systems

Maria Enrica Di Pietro[a,†], Oliver Hammond[b,†], Adriaan van den Bruinhorst[b], Alberto Mannu[a], Agilio Padua[b,*], Andrea Mele[a,c*], Margarida Costa Gomes[b]

[a.] Department of Chemistry, Materials and Chemical Engineering 'G. Natta', Politecnico di Milano, Piazza L. da Vinci 32, 20133 Milano, Italy.

[b.] École Normale Supérieure de Lyon and CNRS, Laboratoire de Chimie, 46 allée d'Italie, 69364 Lyon Cedex 07, France.

[c.] CNR-SCITEC Istituto di Scienze e Tecnologie Chimiche, Via a. Corti 12, 20133 Milano, Italy.

† These authors contributed equally as joint first author.

Table of Contents

Nomenclature

We note potentially problematic discrepancies in the literature between the notations commonly used to describe these systems, due to there being no agreed standard. The most common DESs of choline chloride and urea where x_{ChCl} = 0.33 is either listed eponymously, or as ChCl:U, ChCl-U, ChCl/U, ChCl+U, or ‘reline’. Moreover, such systems have been given many general names such as deep eutectic solvents/systems (DESs), eutectic mixtures, low transition temperature mixtures (LTTMs), low melting mixtures (LMMs) and more. This variety in terminology presents indexing issues and derives from the persistent yet deprecated idea that DESs are defined complex ionic liquids, even though they are mixtures, where the mole fraction of each component is variable, and the structure is diffuse. For consistency and brevity, we elect to use the colon notation i.e. ‘ChCl:U’ to describe our DES of choline chloride-urea where x_{ChCl} = 0.33, and ChCl:G to describe our DES of choline chloride-glycolic acid where x_{ChCl} = 0.5.

Experimental

Sample preparation

All chemicals are listed in Table S1 and were used without further purification. The DESs ChCl:U and ChCl:G were prepared by the heating method, by mixing in the desired mole fractions at 60 °C under constant stirring until a homogeneous liquid was formed (typically 20 min–2 h for amounts of 5–25 g).

Table S1. Chemicals used in this work

Chemical	**Affiliation**	**Supplier**	**Purity**[a,b]
Choline chloride (ChCl)	Milano	Sigma-Aldrich	≥98%
	Lyon	Sigma-Aldrich	≥98%
Urea (U)	Milano	Sigma-Aldrich	98 %
	Lyon	Merck	>99%
Glycolic acid (G)	Milano	Sigma-Aldrich	99%
	Lyon	Merck	99%

[a] mass-based; [b] as stated by the supplier.

The mixtures were subsequently diluted with up to 98 wt% of water (Table S2). Note that DESs without added water contain an initial amount of water (up to 1.3 wt%), as the freshly prepared DESs nor their starting components were dried. The NMR spectra are not significantly affected since it can tolerate vestigial amounts of moisture that may be present. The effect of the initial water content on viscosity and, to a lesser extent, density is significant. Hence, the water content of the neat DESs was determined prior to these measurements.

Table S2. Mixtures prepared for NMR and viscosity experiments and modelled using MD for both ChCl:U and ChCl:G DES. Note the difference in eutectic ratio between the two DESs. We acknowledge the differing methodologies in the literature for calculating this quantity, thus note that the mole fraction of H_2O is in this case calculated as $x_{H_2O} = \frac{n_{H_2O}}{n_{H_2O} + n_{ChCl} + n_{HBD}}$; ie. The DES is herein considered as a mixture of a salt and a HBD.

	ChCl:U x_{ChCl} = 0.33		**ChCl:G x_{ChCl} = 0.5**	
wt% H_2O	x_{H_2O}	n_{H_2O}/n_{Ch}	x_{H_2O}	n_{H_2O}/n_{Ch}
0.0	0.00000	0.00	0.00000	0.00
2.9	0.12552	0.43	0.15166	0.36
5.7	0.22510	0.87	0.26568	0.72
8.3	0.30313	1.30	0.35140	1.08
10.7	0.36542	1.73	0.41766	1.43
13.0	0.41797	2.15	0.47213	1.79
15.3	0.46471	2.60	0.51952	2.16
17.4	0.50308	3.04	0.55770	2.52
23.1	0.59078	4.33	0.64261	3.60
33.3	0.70583	7.20	0.74927	5.98
41.2	0.77103	10.10	0.80747	8.39
47.4	0.81241	12.99	0.84360	10.79
58.3	0.87045	20.16	0.89326	16.74
66.7	0.90589	28.88	0.92301	23.98
75.0	0.93514	43.25	0.94725	35.91
83.3	0.95996	71.92	0.96759	59.71
90.9	0.97959	144.02	0.98355	119.58
95.2*	0.98962	285.95	0.99165	237.44
96.8*	0.99317	436.14	0.99451	362.14
98.0*	0.99577	706.47	0.99660	586.60

*These sample compositions were measured using NMR spectroscopy, but not simulated using MD, because the boxes would have an excessively low concentration of DES species, giving poor statistics and large simulation boxes.

NMR measurements and analysis

All samples of Table S2 were transferred to 5 mm NMR tubes, and these were subsequently fitted with a coaxial inserts containing a solution of 0.5 M NaCl, used as ^{35}Cl reference, in D_2O, which was required for field-frequency lock. NMR spectra were acquired on the freshly prepared tubes (0.5h-6h after preparation) to reduce degradation issues especially in ChCl:G samples. Chlorine has two NMR-active isotopes, ^{35}Cl and ^{37}Cl, both with relatively low gyromagnetic ratios and moderate quadrupole moments, making them technically demanding (see Table S3 for a summary of nuclear properties). On the other hand, chlorine NMR is extremely sensitive to the local electronic and structural micro-surrounding.[1–4]. Even though the broadening of NMR signals is smaller for the ^{37}Cl nucleus due to its smaller quadrupole moment, ^{35}Cl is usually preferred, and was used in this work, due to its higher natural abundance, giving spectra with higher signal-to-noise ratios.[4]

Table S3. Nuclear properties of chlorine.[5]

	Natural abundance (%)	Nuclear spin quantum number	Gyromagnetic ratio γ (10^7 rad s^{-1} T^{-1})	Nuclear electric quadrupole moment Q (fm^2)	NMR Larmor frequency (MHz) at 11.74 T	Molar Receptivity R_M(H) [a]	Receptivity at natural abundance R_{NA}(C) [b]
^{35}Cl	75.76	3/2	2.6241991	-8.165	49.002	$4.72\cdot10^{-3}$	$2.10\cdot10^{+1}$
^{37}Cl	24.24	3/2	2.1843688	-6.435	40.789	$2.72\cdot10^{-3}$	$3.88\cdot10^{0}$

[a] sensitivity of equal number of nuclei at constant field relative to ^{1}H=1.00
[b] sensitivity at natural abundance relative to ^{13}C=1.00

All spectra were recorded at 298 K on a Bruker Avance 500 NMR spectrometer equipped with a 5 mm BBFO i-Probe, operating at ^{35}Cl frequency of 49.00 MHz.

^{35}Cl spectra were collected with standard 1D acquisition sequences, using a ARING pulse train to reduce acoustic ringing artefacts in ^{35}Cl measurements. Automatic and manual peak-picking and linewidth measurements yielded statistically identical ^{35}Cl chemical shift and FWHM estimations. The former method was thus employed for all samples, but for the lower dilutions, where the peaks were too broad to be analysed automatically.

Since the natural linewidth of the ^{35}Cl resonances ranged from tens to thousands Hz, i.e. orders of magnitude larger than the line broadening due to magnetic field inhomogeneities, ^{35}Cl T_2 relaxation times were estimated directly from the $FWHM$ values of the chloride ion signal ($T_2 \approx T_2^* = \left(1/R_2\right)^{-1} = (\pi FWHM)^{-1}$).[1,6,7] Validation of the method was performed by comparing the T_2 relaxation times calculated from the FWHM with those obtained with the CPMG pulse sequence for samples at high dilution having relatively narrow linewidths (20-25 Hz). Table S4 shows that an acceptable agreement is achieved.

Table S4. Comparison of ^{35}Cl T_2 relaxation times obtained from the linewidths and measured *via* CPMG experiments for selected ChCl:U and ChCl:G samples.

	^{35}Cl T_2 ChCl:U x_{ChCl} = 0.33 (Hz)		**^{35}Cl T_2 ChCl:G x_{ChCl} = 0.5 (Hz)**	
wt% H_2O	**from FWHM**	**from CPMG**	**from FWHM**	**from CPMG**
95.2	14.81	15.78	12.89	14.18
96.8	17.39	17.83	16.67	18.13

Density and viscosity measurements

Prior to the density and viscosity measurements, the water content of the neat DES was determined by Karl-Fischer titration. A C40 Mettler-Toledo coulometric titrator equipped with a generator electrode without diaphragm and Hydranal Coulomat E as reagent were used. Aiming for at least 800 µg water per injection, 0.06–0.20 g of sample was dissolved and the average value of 5 injections was taken as the water content. The density and viscosity were measured at 298.15 K (ChCl:G) and 293.15–323.15 K (ChCl:U) using a U-shaped vibration-tube density meter (model DMA 5000 from Anton Paar) and a rolling ball viscosity meter (Anton PaarLovis 2000 ME). The temperature was controlled to 0.001 K and 0.005 K and measured with an accuracy better than 0.01 K and 0.02 K for the density and viscosity measurement, respectively. The densimeter was calibrated with air and a certified water sample, the overall uncertainty of the density measurements was estimated to be $5 \cdot 10^{-6}$ g·cm^{-3}. Three capillaries with different inner diameters, previously calibrated using appropriate standard oils, were used for the viscosity measurements: $\emptyset_{inn}$ = 1.59 mm for $\eta < 5$ mPa·s, $\emptyset_{inn}$ = 1.8 mm for $5 < \eta < 300$ mPa·s, and $\emptyset_{inn}$ = 2.5 mm for $\eta > 300$ mPa·s. The measurement angle was determined automatically by the equipment between 30° and 70°. The samples were not degassed prior to analysis.

Molecular dynamics simulations

Molecular dynamics simulations of the systems matching the experimental (NMR) hydration values were performed using LAMMPS. Models were constructed up to a concentration of 90.9 wt% H_2O for both DES, because above this point simulation boxes became too large or had too few ChCl to obtain good statistics. Simulations were performed at 1 bar and at a constant temperature of 353 K, which was chosen to improve the fluidity of the very viscous samples with low water contents, and is not expected to significantly affect structure. Force field parameters were derived from a combination of OPLS-AA parameters,[8] and the generalised IL force field/OPLS-AA parameters of Canongia Lopes and Padua.[9–14] The ubiquitous SPC/E parameters were used for water. Ionic species were scaled to charges of 0.8*e*. Simulations were allowed to equilibrate under the NPT ensemble (Nosé-Hoover thermostat) for 1 ns before productions runs, also under NPT, of 10 ns. Simulation box compositions are shown in Table S5, and correspond with the sample compositions shown in Table S2. From the production runs, the average densities were calculated, as well as the effect of water on the diffusion coefficient, and radial distribution functions (RDFs) for all species around chloride.

Table S5. Number of molecules, by type, used to build each of the MD simulation boxes for this study.

	ChCl:U x_{ChCl} = 0.33				ChCl:G x_{ChCl} = 0.5			
wt% H_2O	**Ch**	**Cl**	**Urea**	**Water**	**Ch**	**Cl**	**Glyc Acid**	**Water**
0.0	526	526	1052	0	645	645	645	0
2.9	509	509	1018	219	624	624	624	223
5.7	491	491	982	428	603	603	603	436
8.3	477	477	954	622	584	584	584	633
10.7	463	463	926	800	567	567	567	813
13.0	450	450	900	969	550	550	550	984
15.3	437	437	874	1138	534	534	534	1155
17.4	425	425	850	1291	521	521	521	1314
23.1	392	392	784	1698	480	480	480	1726
33.3	336	336	672	2419	410	410	410	2450
41.2	293	293	586	2960	356	356	356	2986
47.4	260	260	520	3378	316	316	316	3409
58.3	203	203	406	4092	246	246	246	4117
66.7	160	160	320	4621	194	194	194	4652
75.0	119	119	238	5147	144	144	144	5172
83.3	79	79	158	5681	95	95	95	5673
90.9	50	50	100	7201	51	51	51	6099

Results

^{35}Cl NMR measurements

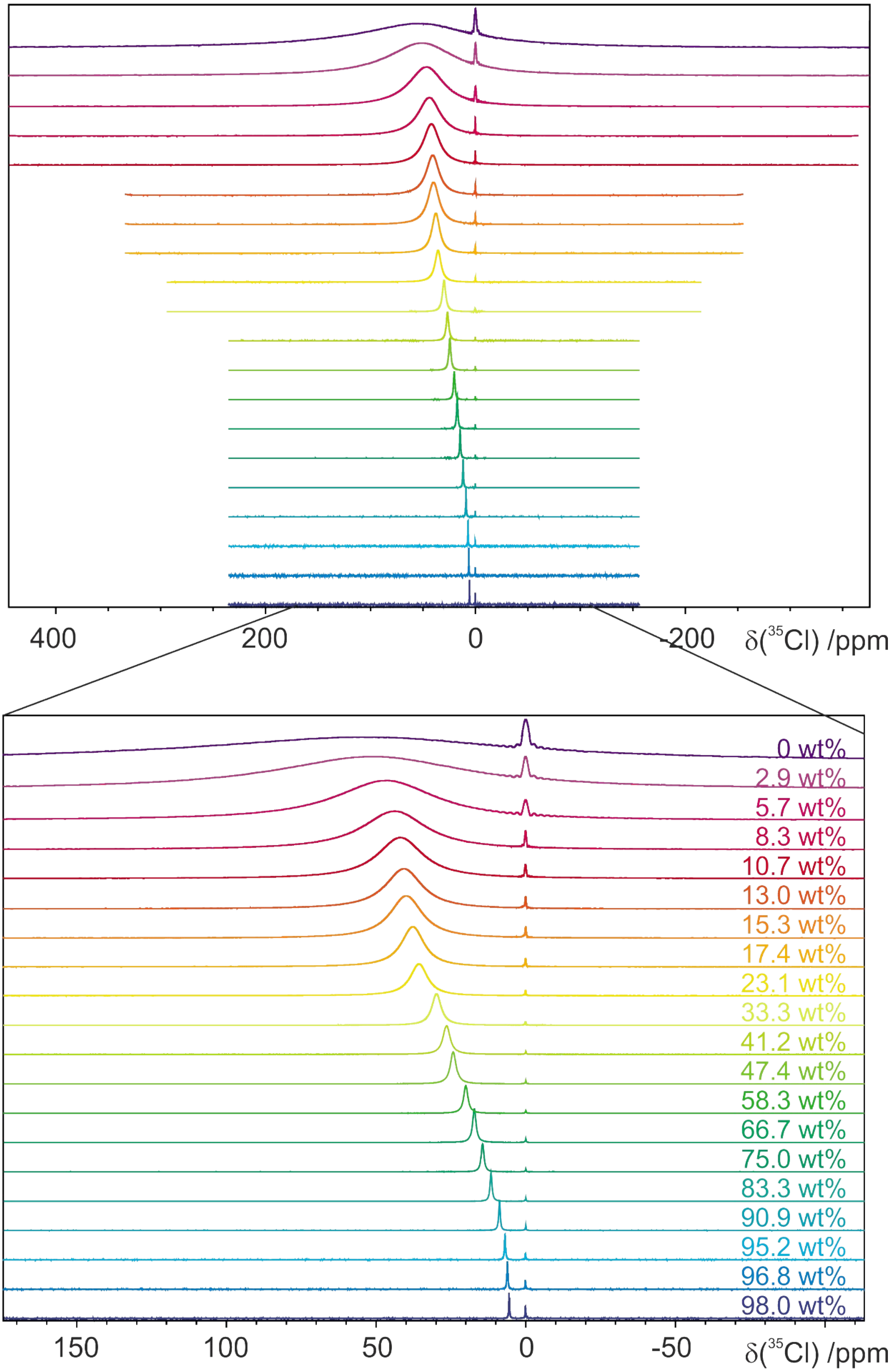

Figure S1. ^{35}Cl NMR spectra of ChCl:U samples upon dilution. The reference peak at 0 ppm corresponds to Cl$^-$ of a 0.5M NaCl solution in the coaxial insert.

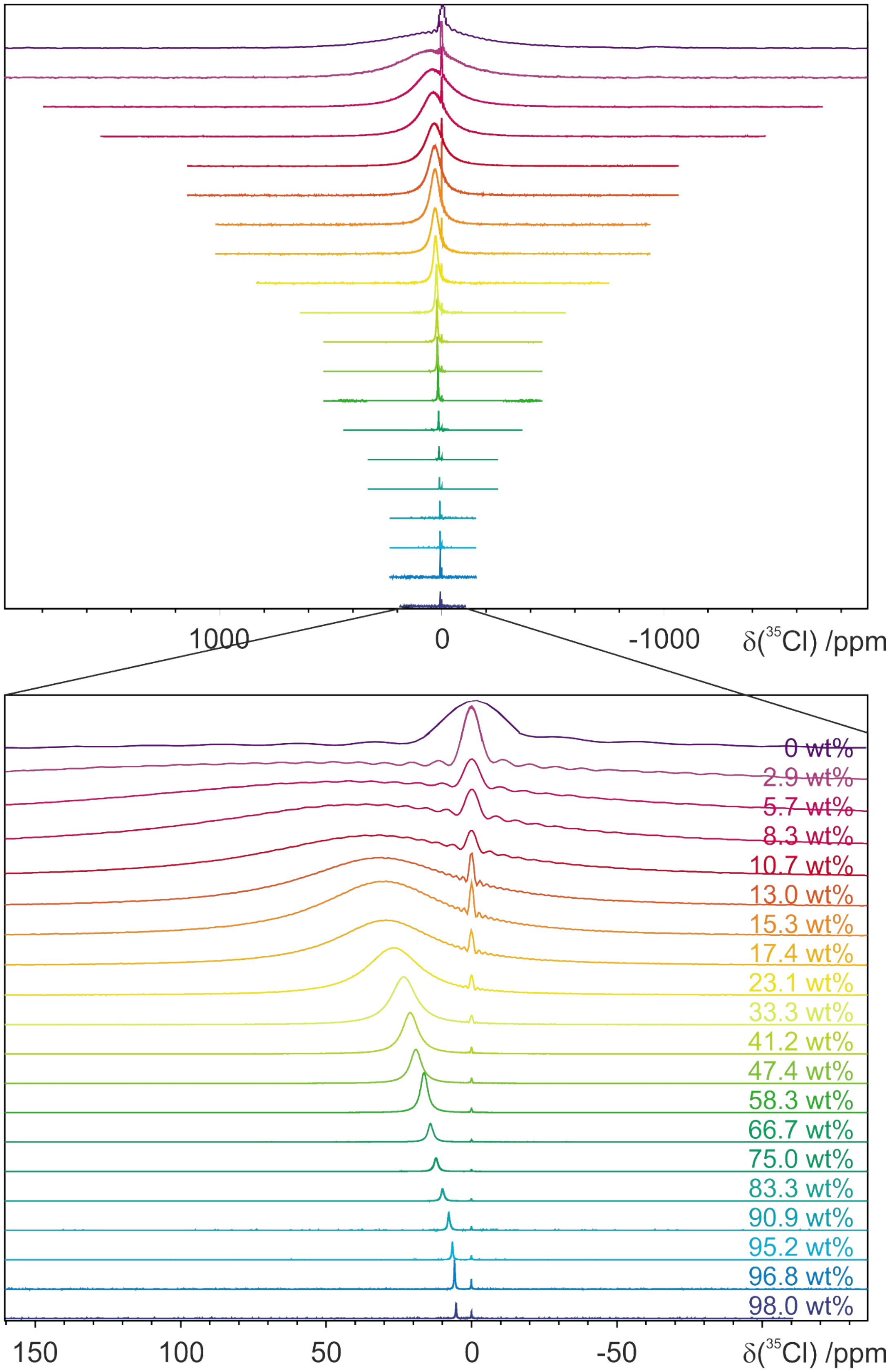

Figure S2. ^{35}Cl NMR spectra of ChCl:G samples upon dilution. The reference peak at 0 ppm corresponds to Cl^{-} of a 0.5M NaCl solution in the coaxial insert.

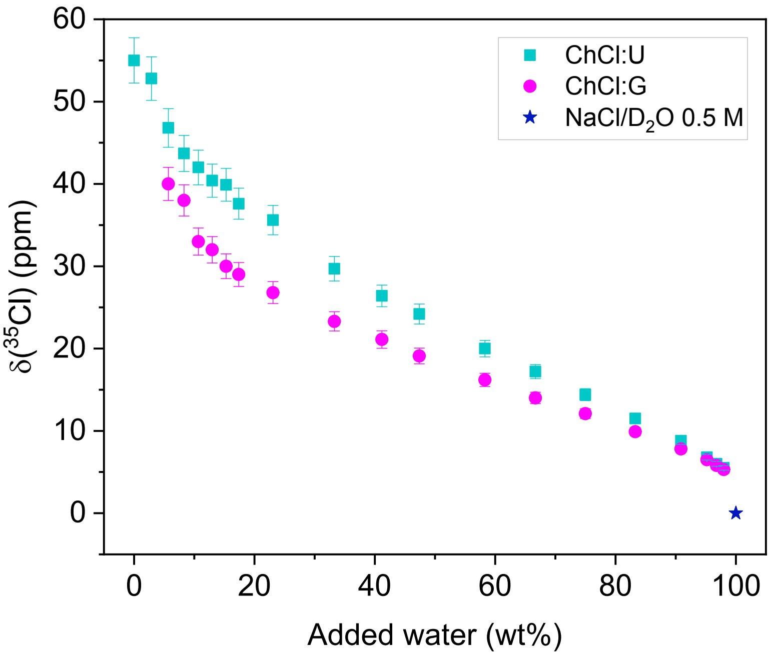

Figure S3. ^{35}Cl chemical shift as a function of the added water content.

Table S6. ^{35}Cl chemical shift of ChCl:U and ChCl:G samples relative to a 0.5M NaCl solution. Note that the considerable line broadening observed reduces the accuracy of the chemical shifts at the lowest water contents.

wt% H_2O	**δ(^{35}Cl) ChCl:U x_{ChCl} = 0.33 (ppm)**	**δ(^{35}Cl) ChCl:G x_{ChCl} = 0.5 (ppm)**
0	55	n.a.
2.9	53	n.a.
5.7	47	40
8.3	44	38
10.7	42	33
13.0	40.4	32
15.3	39.9	30
17.4	37.6	29
23.1	35.6	26.8
33.3	29.7	23.3
41.2	26.4	21.1
47.4	24.2	19.1
58.3	20.0	16.2
66.7	17.2	14.0
75.0	14.4	12.1
83.3	11.5	9.9
90.9	8.8	7.8
95.2	6.8	6.5
96.8	6.0	5.8
98.0	5.5	5.3

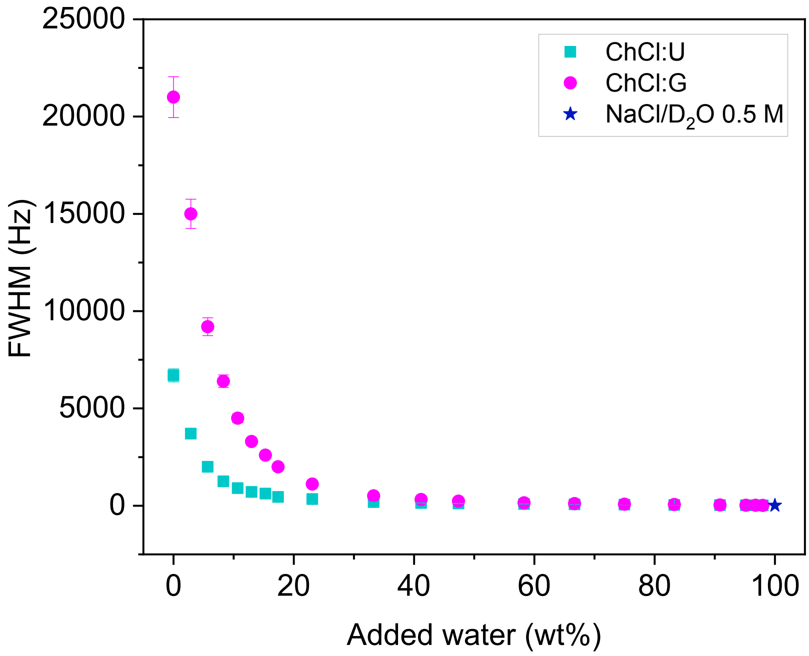

Figure S4. Linewidth (FWHM = full width at half maximum) for the ^{35}Cl signal of ChCl:U and ChCl:G samples as a function of the water content.

Table S7. Linewidth ($FWHM$ = full width at half maximum), viscosity-corrected linewidth ($FWHM^0$) and T_2 relaxation times for the ^{35}Cl signal of ChCl:U and ChCl:G hydrated samples. Maximum errors are estimated to be 5% of the value.

wt% H_2O	**^{35}Cl ChCl:U x_{ChCl} = 0.33**			**^{35}Cl ChCl:G x_{ChCl} = 0.5**		
	$FWHM$ **(Hz)**	$FWHM^0$ **(Hz)** [a]	**T_2 (ms)**	$FWHM$ **(Hz)**	$FWHM^0$ **(Hz)**	**T_2 (ms)**
0	6700	4.7	0.048	21000	30.5	0.015
2.9	3700	11.4	0.086	15000	50.4	0.021
5.7	2000	16.0	0.159	9200	56.8	0.035
8.3	1250	19.0	0.255	6400	63.5	0.05
10.7	900	21.9	0.354	4500	65.8	0.071
13.0	706	25.0	0.451	3300	67.5	0.096
15.3	625	30.4	0.509	2600	72.2	0.122
17.4	450	28.1	0.707	2000	71.7	0.159
23.1	342	37.3	0.931	1110	72.5	0.287
33.3	183	40.2	1.74	504	73.8	0.632
41.2	139	44.9	2.29	318	74.0	1
47.4	114.8	47.1	2.77	230	71.7	1.38
58.3	85.7	48.8	3.71	146.7	68.7	2.17
66.7	68.3	47.2	4.66	104.3	62.3	3.05
75.0	52.2	42.2	6.1	76.2	55.6	4.18
83.3	39.7	36.5	8.02	57.1	49.2	5.57
90.9	30.2	30.7	10.54	37.7	37.1	8.44
95.2	21.5	23.0	14.81	24.7	25.9	12.89
96.8	18.3	19.9	17.39	19.1	20.5	16.67
98.0	15.2	16.7	20.94	16.4	17.9	19.41

[a] Data from Agieienko and Buchner used for the correction.[15]

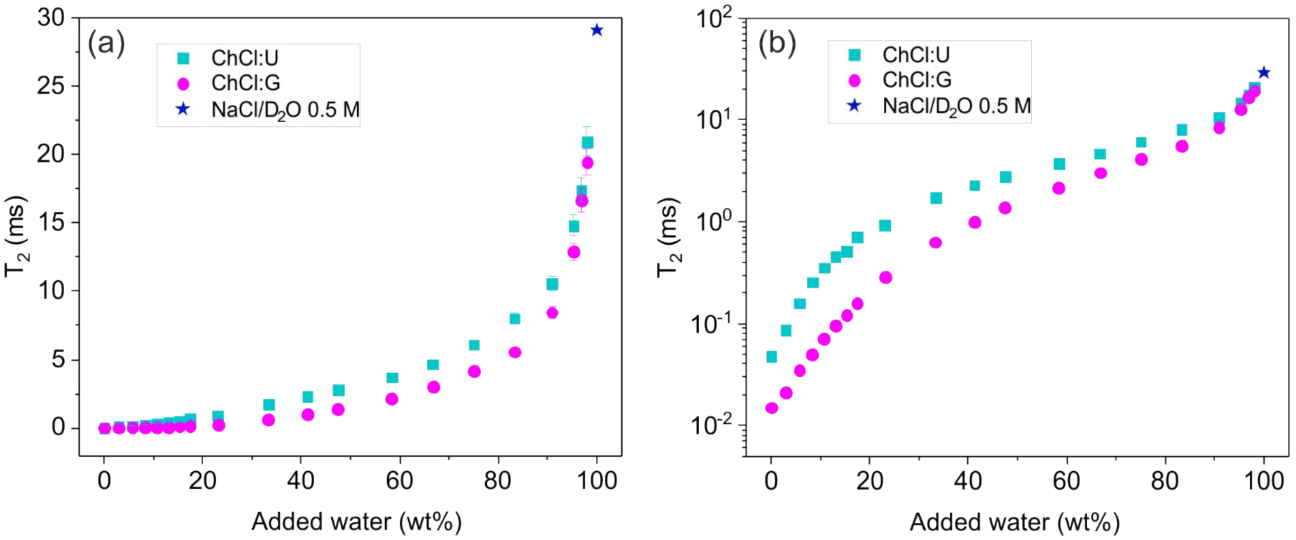

Figure S5. Linear (a) and logarithmic (b) plot of ^{35}Cl T_2 relaxation times of ChCl:U and ChCl:G samples as a function of the water content.

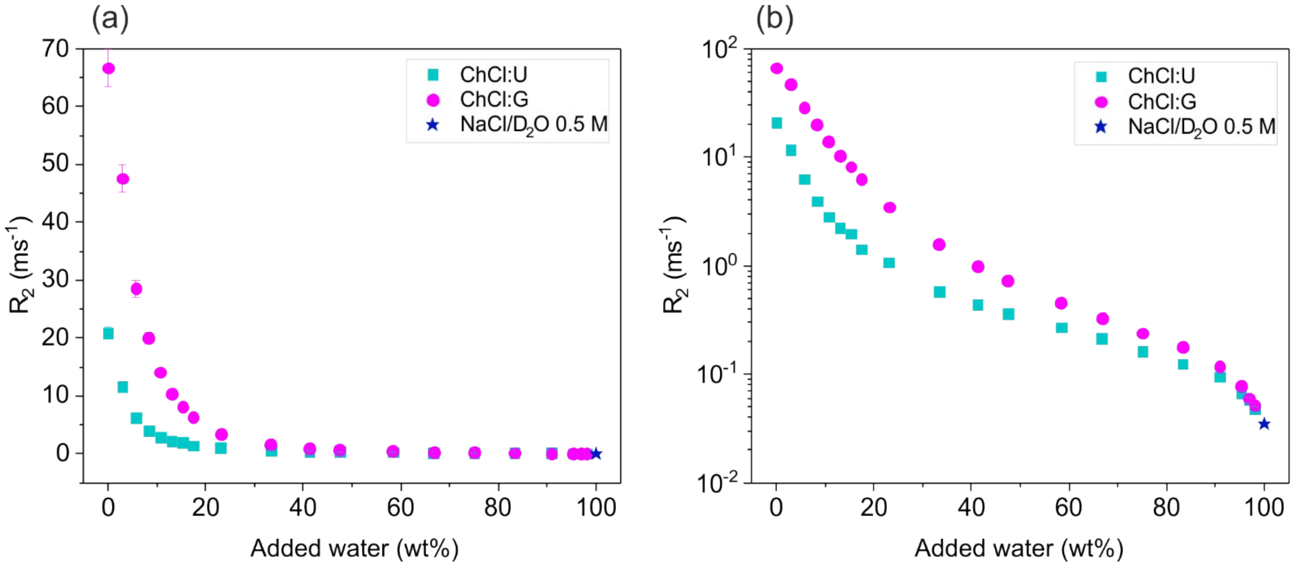

Figure S6. Linear (a) and logarithmic (b) R_2 relaxation rates for the ^{35}Cl signal of ChCl:U and ChCl:G samples as a function of the water content.

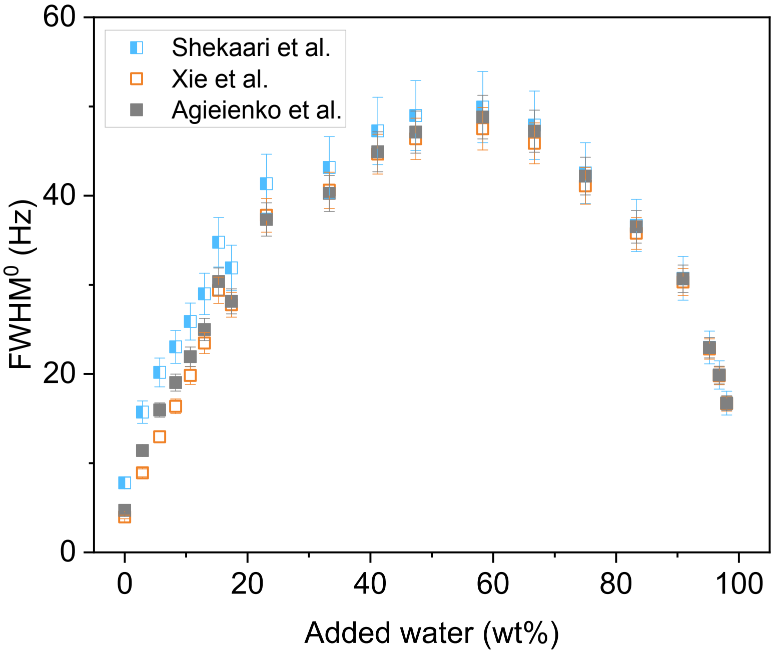

Figure S7. Comparison of viscosity-corrected linewidth ($FWHM^0$) for the ^{35}Cl signal of ChCl:U samples as a function of the water content, using data from Shekaari et al.,[16] Xie et al.,[17] and Agieienko et al..[15]

Molecular dynamics

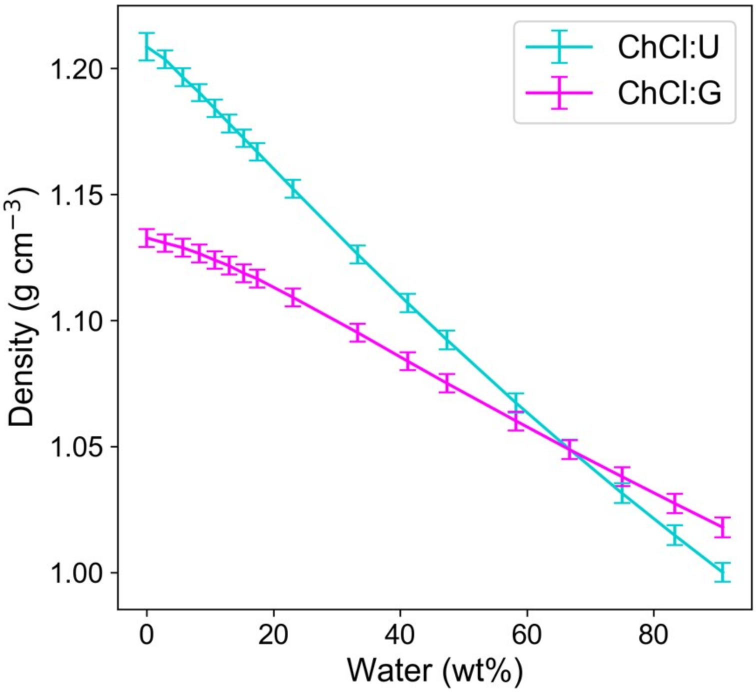

Figure S8. Densities and errors for the ChCl:U (x_{ChCl} = 0.33) and ChCl:G (x_{ChCl} = 0.5) DES, calculated as an average of 10 ns trajectories of stable equilibrated MD models in the NPT ensemble.

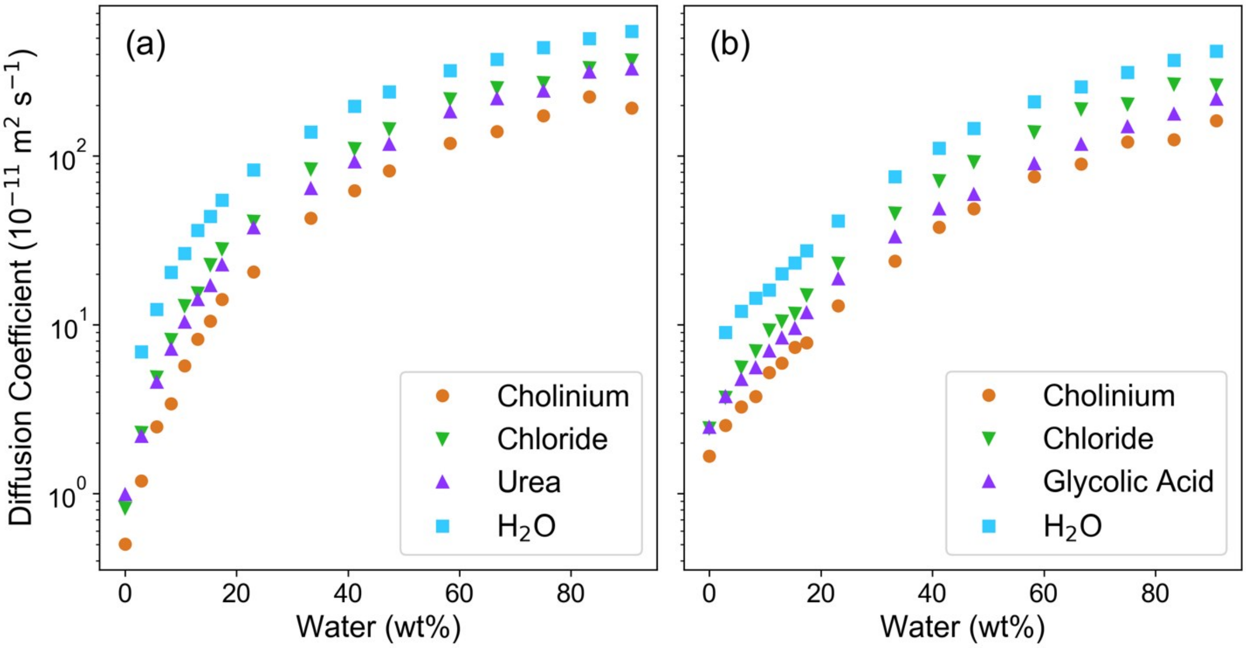

Figure S9. Diffusion coefficients, *D* (10^{-11} m^2 s^{-1}) as a function of DES water content, calculated from MD simulations of the ChCl:U (x_{ChCl} = 0.33) and ChCl:G (x_{ChCl} = 0.5) DES. Diffusion coefficients were calculated for each group of molecules from the 10 ns NPT production runs, which were in a Fickian diffusion regime, and applying the Einstein relationship to the gradients of the molecular mean-squared displacements as a function of time.

Viscosity and density measurements

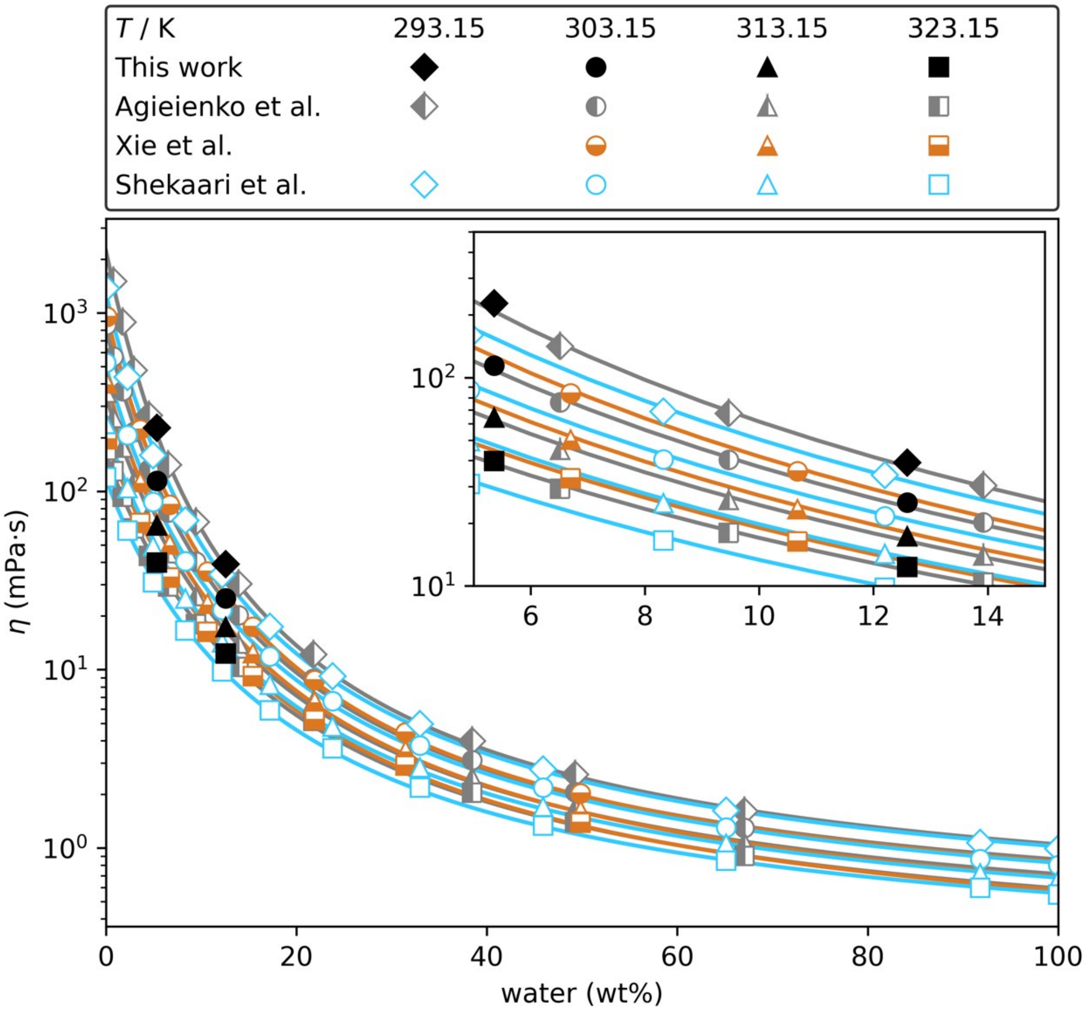

Figure S10.Viscosity (η) of ChCl:U at temperatures *T* as a function of water content (w_{H2O}) taking the initial water into account. The lines are interpolations of the literature data from Agieienko et al., [15] Xie et al.,[17] and Shekaari et al.[16].

Table S8. Experimental viscosity (η) and density (ρ) of ChCl:U at water contents w_{H2O} and temperatures T.

w_{H2O} wt%	x_{H2O}	T K	η mPa·s	ρ g·cm^{-3}
5.36	0.214	293.15	226.8	1.189840
		303.15	114.3	1.184378
		313.15	64.29	1.178969
		323.15	39.77	1.173609
12.59	0.409	293.15	39.065	1.174373
		303.15	25.11	1.169007
		313.15	17.32	1.163644
		323.15	12.31	1.158269

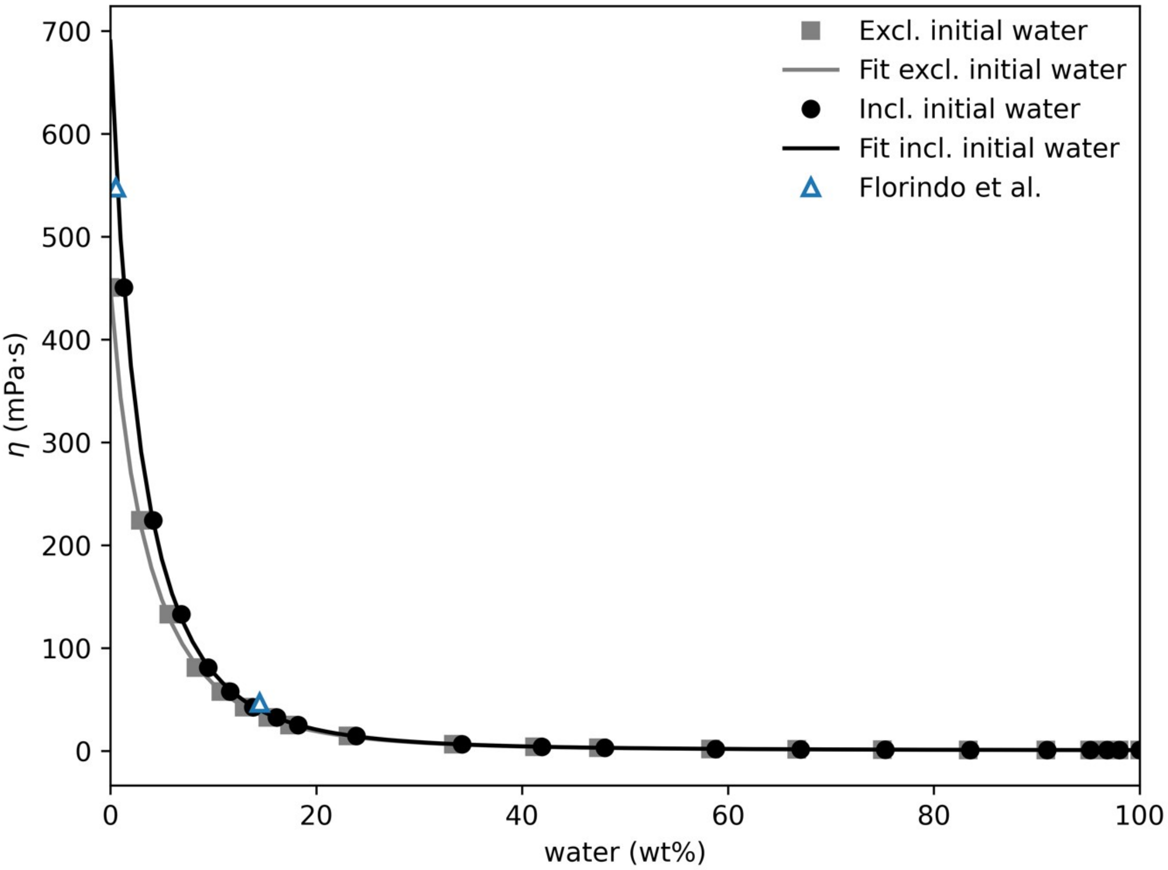

Figure S11. Viscosity (η) of ChCl:G at 298.15 K as a function of water content (w_{H2O}) taking the initial water into account (Incl. initial water) or not (Excl. initial water). The data of Florindo et al. [18] has been added as a reference.

Table S9 Experimental viscosity (η) and density (ρ) of ChCl:G at various water contents w_{H2O} and 298.15 K.

w_{H2O} wt%	x_{H2O}	ρ g·cm^{-3}	η mPa·s
1.314	0.074	1.194580	450.5
4.158	0.206	1.189407	224.4
6.895	0.307	1.184194	133.0
9.490	0.386	1.179339	81.13
11.64	0.441	1.174906	57.84
13.89	0.491	1.170489	42.60
16.16	0.536	1.165952	32.64
18.24	0.572	1.161704	25.38
23.89	0.653	1.150302	14.54
34.17	0.757	1.129356	6.593
41.91	0.812	1.113132	4.191
48.03	0.847	1.100484	3.112
58.80	0.895	1.078303	1.954
67.05	0.924	1.061574	1.694
75.29	0.948	1.045093	1.382
83.54	0.968	1.028837	1.155
91.01	0.984	1.014337	1.014
95.21	0.992	1.006249	0.949
96.83	0.995	1.003111	0.928
98.01	0.997	1.000852	0.912

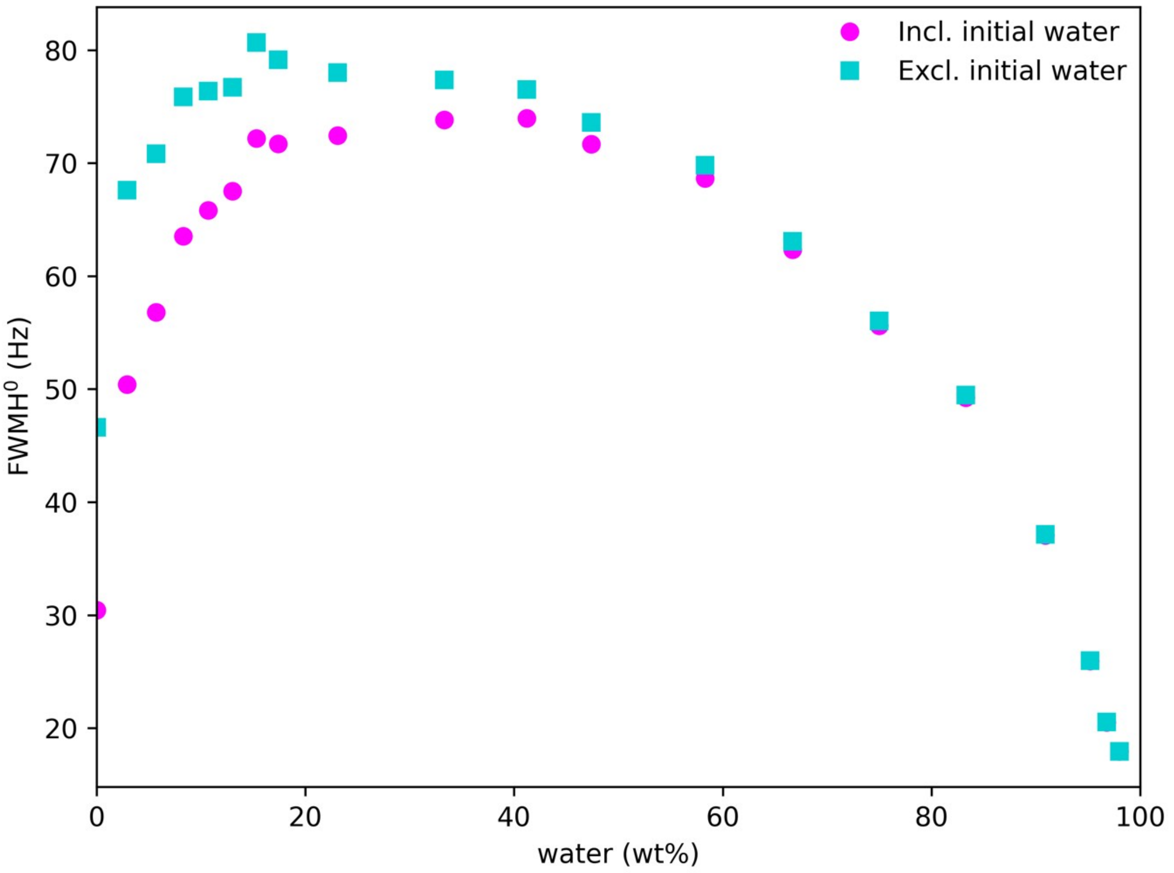

Figure S12 FWHM^0 of ChCl:G corrected for viscosity as a function of the water content, with (incl.) and without (excl.) taking into account the initial water content.

References

1 B. Lindman and S. Forsén, *Chlorine, Bromine and Iodine NMR Physico-Chemical and Biological Applications*, Springer-Verlag, Berlin, 1976.

2 J. W. Akitt, in *Multinuclear NMR*, ed. J. Mason, Plenum Press, New York, 1987, pp. 447–461.

3 H. Wennerström, B. Lindman and S. Forsén, The interaction of halide ions with organic cations containing charged nitrogen, phosphorus, or sulfur in aqueous solutions studied by nuclear quadrupole relaxation, *J. Phys. Chem.*, 1971, **75**, 2936–2942.

4 R. P. Chapman, C. M. Widdifield and D. L. Bryce, Solid-state NMR of quadrupolar halogen nuclei, *Prog. Nucl. Magn. Reson. Spectrosc.*, 2009, **55**, 215–237.

5 *Bruker Almanac*, 2012.

6 R. C. Remsing, R. P. Swatloski, R. D. Rogers and G. Moyna, Mechanism of cellulose dissolution in the ionic liquid 1-n-butyl-3- methylimidazolium chloride: A 13C and 35/37Cl NMR relaxation study on model systems, *Chem. Commun.*, 2006, 1271–1273.

7 R. C. Remsing, G. Hernandez, R. P. Swatloski, W. W. Massefski, R. D. Rogers and G. Moyna, Solvation of carbohydrates in N,N'-dialkylimidazolium ionic liquids: A multinuclear NMR spectroscopy study, *J. Phys. Chem. B*, 2008, **112**, 11071–11078.

8 W. L. Jorgensen, D. S. Maxwell and J. Tirado-rives, Development and Testing of the OPLS All-Atom Force Field on Conformational Energetics and Properties of Organic Liquids, 1996, **7863**, 11225–11236.

9 J. N. Canongia Lopes, J. Deschamps and A. A. H. Padua, Modeling Ionic Liquids Using a Systematic All-Atom Force Field, *J. Phys. Chem. B*, 2004, **108**, 2038–2047.

10 J. N. Canongia Lopes, J. Deschamps and A. A. H. Padua, Additions and corrections Modeling Ionic Liquids Using a Systematic All-Atom Force Field, *J. Phys. Chem. B*, 2004, **108**, 11250.

11 J. N. Canongia Lopes and A. A. H. Padua, Molecular Force Field for Ionic Liquids Composed of Triflate or Bistriflylimide Anions, *J. Phys. Chem. B*, 2004, **108**, 16893–16898.

12 J. N. Canongia Lopes and A. A. H. Padua, Molecular Force Field for Ionic Liquids III: Imidazolium, Pyridinium, and Phosphonium Cations; Chloride, Bromide, and Dicyanamide Anions, *J. Phys. Chem. B*, 2006, **110**, 19586–19592.

13 J. N. Canongia Lopes, A. A. H. Padua and K. Shimizu, Molecular Force Field for Ionic Liquids IV: Trialkylimidazolium and Alkoxycarbonyl-Imidazolium Cations; Alkylsulfonate and Alkylsulfate Anions, *J. Phys. Chem.*, 2008, **112**, 5039–5046.

14 K. Shimizu, D. Almantariotis, M. F. Costa Gomes, A. A. H. Padua and J. N. Canongia Lopes, Molecular Force Field for Ionic Liquids V : Hydroxyethylimidazolium , Dimethoxy-2-Methylimidazolium, and Fluoroalkylimidazolium Cations and Bis(Fluorosulfonyl)Amide, Perfluoroalkanesulfonylamide, and Fluoroalkylfluorophosphate Anions, *J. Phys. Chem. B*, 2010, **114**, 3592–3600.

15 V. Agieienko and R. Buchner, Densities, Viscosities, and Electrical Conductivities of Pure Anhydrous Reline and Its Mixtures with Water in the Temperature Range (293.15 to 338.15) K, *J. Chem. Eng. Data*, 2019, **64**, 4763–4774.

16 H. Shekaari, M. T. Zafarani-moattar and B. Mohammadi, Thermophysical characterization of aqueous deep eutectic solvent (choline chloride / urea) solutions in full ranges of concentration at, *J. Mol. Liq.*, 2017, **243**, 451–461.

17 Y. Xie, H. Dong, S. Zhang, X. Lu and X. Ji, Effect of Water on the Density , Viscosity, and CO2 Solubility in Choline Chloride / Urea, 2014, **2014**, 3344–3352.

18 C. Florindo, F. S. Oliveira, L. P. N. Rebelo, A. M. Fernandes and I. M. Marrucho, Insights into the synthesis and properties of deep eutectic solvents based on cholinium chloride and carboxylic acids, *ACS Sustain. Chem. Eng.*, 2014, **2**, 2416–2425.