EDITORS NOTE

The following article from Prof. Rafael Mujeriego is intended to promote discussion on the important issue of the SI units that we use (with different interpretations in different parts of the industry and different regions) and the need to develop a common approach where practical. This article is also posted on the Water Wiki site and you are encouraged to contribute to the discussion.

We would like to publish other possible discussions that we should have within the Specialist Group on topics that are of importance to us all and so invite contributions on other topics that you feel are of importance and deserve further discussion within the SG.

Effective and reliable communication: the International System (SI) of units

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Diversity of measurement units, particularly related to volume and volume-related quantities, has become common in papers and presentations from the Water Reuse Specialists Group activities. Metric system units, like cubic meter (m^3), traditionally used by authors from numerous European countries, share written space in technical documents with new measurement units (megaliters, gigaliters), adopted by authors from non-metric system in their attempt to assure global communication, aside their traditional English-derived units of measurements.

However, that positive transition to a global system of measurements units seems to have ignored the existence of an international system of units, the Meter Convention, that has been providing guidance in those same matters since it was first established in 1875 in Paris by representatives of seventeen nations, including the United States of America (http://www.bipm.org/en/worldwide-metrology/). Currently, the Meter Convention treaty includes 51 Member States, representing all the major industrialized nations. The original Meter Convention was modified slightly in 1921 and remains the basis of all international agreements on units of measurement.

The Meter Convention created the International Bureau of Weights and Measures (BIPM), an intergovernmental organization under the authority of the General Conference on Weights and Measures (CGPM) and the supervision of the International Committee for Weights and Measures (CIPM). The BIPM acts in matters of world metrology, particularly concerning the demand for measurement standards of ever increasing accuracy, range and diversity, and the need to demonstrate equivalence between national measurement standards.

Practical Benefits of Common Units

Adequate expression of measurements is of vital importance to all. Measurement science (metrology) is not the exclusive domain of scientists, but also of engineers and the public at large when they quantify and communicate the results of their activities. Scientific and engineering studies and projects, as well as services, supplies and communications that we use in our common daily life rely ultimately on metrology for their efficient and reliable operation. The economic success of nations depends upon the ability to manufacture and trade precisely made and tested products and components (http://www.bipm.org/en/worldwide-metrology/). Engineering proposals, designs, drawings and specifications rely on clearly quantified measurements to assure they achieve their expected costs, construction and ultimate objectives.

The practical difficulties encountered by authors of non-metric systems when converting to the SI system has resulted in inadequate notations and controversial units of measurement, like those raised by Prof. Peter J. le B. Williams in Volume 13 of the Bulletin of the American Society of Limnology and Oceanography (2004), where he called for the correct use of SI of units. Those comments, made about 10 years ago, are readily applicable to volume units that have become common in journals and reports published by the International Water Association. The reluctance by authors to use some high volume SI units in papers refereed within the IWA editorial system has even seen how corrections introduced during the review process were subsequently reversed by authors, without deserving any remarks from editors.

The non-SI units have also entered international institutions like the European Commission, as it appears in the recent evaluation of the Public Consultation on water reuse, where the following expressions are used: " 946 Mm3/year wastewater treated and reused in Europe (2.4 % of all treated wastewater)" and also "Total water abstraction in EU 247 billion m^3/year". The appearance of "billion" introduces an additional source of potential error, considering the quite different meaning it has in English (thousand million) as compared to other languages like French and Spanish (an English trillion). It is not uncommon to see inadequate use or translation of those units in articles and books in technical and economic publications.

The Water Environment Federation (WEF), the American Water Works Association (AWWA) and the International Water Association (IWA) jointly published the updated 4th edition of WEF Manual of Practice no. 6 (2011) with the objective of establishing units of expression that are universally understandable and readily comparable for design, operation and performance factors in the water sector. However, the Manual of Practice no. 6 considers the "liter" as an accepted unit for volume (Table 1.3, page 4), while recognizing that "incorporation of this unit makes the whole system incoherent", and explicitly indicates (bottom of Table 2.1, page 9) that "use of (hecto SI prefix) should be avoided", extending the same proposal to other three prefixes, without indication for such recommendation, and in contrast to the official updated publications of the SI (http://www.bipm.org/en/publications/si-brochure/).

To further illustrate the diversity of issues that an inconsistent use of measurement units can raise, Figure 1 shows the use of abbreviated "megaliter" units, indicated with the "ml" symbol, a measurement unit that most readers associate to a milliliter. It is not hard to imagine the friendly smile that some readers may have shown after realizing that such notation refers to the size of an underground water storage. It is evident that a widely known and clear set of guidelines on the use of the SI units should have aided reviewers, editors and printers to produce a correct figure.


9.5ml

The size of the underground storage tank that will hold the desalinated water.

16km

The length of pipeline the water is sent through San Marcos for use by San Diego residents and businesses.

1,960

The number of reverse osmosis vessels in the facility.

not accounted for could cause the pump station to dislodge from its location. The design team mitigated this issue by designing the pump station to have thick concrete walls and a 1.2-meter thick foundation slab. The added mass resists the tidally-influenced soil and groundwater pressure and ensures that the pump station will stay in place.

From the pump station, another pipeline transfers water to the desalination plant itself, located 152.4 meters inland on a sandstone bluff. This is where the design team encountered a second challenge – managing and mitigating corrosion.

Plant challenges caused by corrosion were somewhat expected, considering the close proximity of the Pacific Ocean and two major roadways. The first step in combating the problem was to recommend using cast-in-place reinforced concrete for the plant's structures. For steel, the rate of corrosion is dependent on the availability of water, oxygen, and chloride ions, the electrical resistivity of the concrete, and temperature. The availability of oxygen is a function of its rate of diffusion through the concrete, which is affected by how saturated the concrete is with water. When totally submerged, the diffusion rate is slowed because oxygen must diffuse through the pore water. When the concrete is dry, the oxygen can freely move through the pores. Alternating wet and dry cycles, like incoming and

Figure 1. Volume and surface of an underground water storage, as reported in "World Water: Water Reuse and Desalination/Spring 2014", page 12.

Aside from the surprise that such units may produce to readers, it is reasonable to anticipate that a continued use of inadequate measurement units may result in significant scientific and technical errors, interpretation uncertainties, contractual controversies, economic disputes and serious legal responsibilities. Just the same variety of critical issues that the founders of the Metric Convention wanted to resolve when they established the early treaty in 1875.

OBJECTIVE

The main objective of this contribution is to present a brief summary of the contents and use of the SI units, particularly in the water sector, describing the base units, their prefixes, the derived units and the accepted units, as described in official documents published by the BIPM and NIST. This call for adoption of SI units should also be extended to editors and manuscript preparation personnel, so we are all fully involved in producing the highest quality of scientific and technical documents, regardless of the geographical area in which we work.

THE "SI" OF UNITS

The updated (2014) 8th edition of the SI Brochure defines and presents the International System of Units (http://www.bipm.org/en/publications/si-brochure/), as published by the BIPM. The SI consists of a set of base units, their prefixes, the derived units and the accepted units, as described in following sections, adapted from the electronic version of the updated (2014) 8th edition of the SI Brochure.

The SI base units are a choice of seven well-defined units which by convention are regarded as dimensionally independent. The base units of the SI are listed in Table 1, which relates the base quantity to the unit name and unit symbol for each of the seven base units, using US English.

Table 1. SI base units, adapted from the updated (2014) 8th edition of the SI Brochure.

Base quantity		**SI base unit**	
Name	**Symbol**	**Name**	**Symbol**
length	l, x, r, etc.	meter	m
mass	m	kilogram	kg
time, duration	t	second	s
electric current	I, i	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

Derived Units

Derived units are formed by combining the base units according to the algebraic relations linking the corresponding quantities. The names and symbols of some of the units thus formed can be replaced by special names and symbols which can themselves be used to form expressions and symbols of other derived units. The number of quantities in science is without limit, and it is not possible to provide a complete list of derived quantities and derived units. However, Table 2 lists some examples of derived quantities, and the corresponding coherent derived units expressed directly in terms of base units, using US English.

Table 2. Examples of coherent derived units in the SI expressed in terms of base units, adapted from the updated (2014) 8th edition of the SI Brochure.

Derived quantity		**SI coherent derived unit**	
Name	**Symbol**	**Name**	**Symbol**
area	A	square meter	m^2
volume	V	cubic meter	m^3
speed, velocity	v	meter per second	m/s
acceleration	a	meter per second squared	m/s^2
wavenumber	σ, $\tilde{\nu}$	reciprocal meter	m^{-1}
density, mass density	ρ	kilogram per cubic meter	kg/m^3
surface density	ρ_A	kilogram per square meter	kg/m^2
specific volume	v	cubic meter per kilogram	m^3/kg
current density	j	ampere per square meter	A/m^2
magnetic field strength	H	ampere per meter	A/m
amount concentration (a), concentration	c	mole per cubic meter	mol/m^3
mass concentration	ρ, γ	kilogram per cubic meter	kg/m^3
luminance	L_v	candela per square meter	cd/m^2
refractive index (b)	n	one	1
relative permeability (b)	μ_r	one	1

(a) In the field of clinical chemistry this quantity is also called substance concentration.

(b) These are dimensionless quantities, or quantities of dimension one, and the symbol "1" for the unit (the nu

Prefix Names and Symbols

Table 3 lists all approved prefix names and prefix symbols to form the names and symbols of the decimal multiples and submultiples of SI units as adopted over the years by the CGPM.

Table 3. SI prefixes, adapted from the updated (2014) 8th edition of the SI Brochure.

Factor	**Name**	**Symbol**	**Factor**	**Name**	**Symbol**
10^1	deca	da	10^{-1}	deci	d
10^2	hecto	h	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	m
10^6	mega	M	10^{-6}	micro	µ
10^9	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
10^{15}	peta	P	10^{-15}	femto	f
10^{18}	exa	E	10^{-18}	atto	a
10^{21}	zetta	Z	10^{-21}	zepto	z
10^{24}	yotta	Y	10^{-24}	yocto	y

Prefix symbols are printed in roman (upright) type, as are unit symbols, regardless of the type used in the surrounding text, and are attached to unit symbols without a space between the prefix symbol and the unit symbol. With the exception of da (deca), h (hecto), and k (kilo), all multiple prefix symbols are capital (upper case) letters, and all submultiple prefix symbols are lower case letters. All prefix names are printed in lower case letters, except at the beginning of a sentence.

The grouping formed by a prefix symbol attached to a unit symbol constitutes a new inseparable unit symbol (forming a multiple or submultiple of the unit concerned) that can be raised to a positive or negative power and that can be combined with other unit symbols to form compound unit symbols. The following examples illustrate those rules:

$1\ \mathrm{cm}^{-1} = 1\ (\mathrm{cm})^{-1} = 1\ (10^{-2}\ \mathrm{m})^{-1} = 10^{2}\ \mathrm{m}^{-1} = 100\ \mathrm{m}^{-1}$

$2.3\ \mathrm{cm}^{3} = 2.3\ (\mathrm{cm})^{3} = 2.3\ (10^{-2}\ \mathrm{m})^{3} = 2.3 \text{ x } 10^{-6}\ \mathrm{m}^{3}$

$1\ \mathrm{hm}^{3} = 1\ (\mathrm{hm})^{3} = 1\ (100\ \mathrm{m})^{3} = 1\ (10^{2}\ \mathrm{m})^{3} = 10^{6}\ \mathrm{m}^{3} = 1\ 000\ 000\ \mathrm{m}^{3}$

Accepted Non-SI Units

As the updated (2014) 8th edition of the SI Brochure clearly indicates, the SI is a system of units that provides the internationally agreed reference framework in terms of which all other units are defined. It is recommended for use throughout science, technology, engineering and commerce. The SI base units and the SI coherent derived units, including those with special names, have the important advantage of forming a coherent set, with the effect that unit conversions are not required when inserting particular values for quantities into quantity equations. Because the SI is the only system of units that is globally recognized, it also has a clear advantage for establishing a worldwide dialogue. Finally, it simplifies the teaching of science and technology to the next generation, if everyone uses this system.

Nonetheless the CGPM recognizes that some non-SI units still appear in the scientific, technical and commercial literature, and will continue to be used for many years. Some non-SI units are of historical importance in the established literature. Other non-SI units, such as the units of time and angle, are so deeply embedded in the history and culture of the human race that they will continue to be used for the foreseeable future. Individual scientists should also have the freedom to sometimes use non-SI units for which they see a particular scientific advantage in their work. For these reasons it is helpful to list some of the more important non-SI units, as is done below. However, if these units are used it should be understood that the advantages of the SI are lost.

The updated (2014) 8th edition of the SI Brochure highlights that the inclusion of non-SI units in the Brochure does not imply that the use of non-SI units is to be encouraged. For the reasons stated in the Brochure, SI units are generally to be preferred. It is also desirable to avoid combining non-SI units with units of the SI; in particular, the combination of non-SI units with the SI to form compound units should be restricted to special cases in order not to compromise the advantages of the SI. Finally, when any of the non-SI in Table 6 are used, it is good practice to define the non-SI unit in terms of the corresponding SI unit.

Table 4 includes the traditional units of time and angle. It also contains the hectare, the liter (in US English) and the tonne, which are all in common everyday use throughout the world, and which differ from the corresponding coherent SI unit by an integer power of ten. The SI prefixes are used with several of these units, but not with the units of time.

Table 4. Non-SI units accepted for use with the International System of Units, as adapted from the updated (2014) 8th edition of the SI Brochure.

Quantity	Name of unit	Symbol for unit	Value in SI units
time	minute	min	1 min = 60 s
	hour (a)	h	1 h = 60 min = 3600 s
	day	d	1 d = 24 h = 86 400 s
plane angle	degree (b,c)	°	1° = (π/180) rad
	minute	'	1' = (1/60)° = (π/10 800) rad
	second (d)	"	1" = (1/60)' = (π/648 000) rad
area	hectare (e)	ha	1 ha = 1 hm^2 = 10^4 m^2
volume	liter (f)	L, l	1 L = 1 l = 1 dm^3 = 10^3 cm^3 = 10^{-3} m^3
mass	tonne (g)	t	1 t = 10^3 kg
length	astronomical unit (h)	au	1 au = 149 597 870 700 m

(a) The symbol of this unit is included in Resolution 7 of the 9th CGPM (1948).

(b) ISO 80000-3:2006 recommends that the degree be divided decimally rather than using the minute and the second. For navigation and surveying, however, the minute has the advantage that one minute of latitude on the surface of the Earth corresponds (approximately) to one nautical mile (defined in Table 8).

(c) The gon (or grad, where grad is an alternative name for the gon) is an alternative unit of plane angle to the degree, defined as (π/200) rad. Thus there are 100 gon in a right angle. The potential value of the gon in navigation is that because the distance from the pole to the equator of the Earth is approximately 10 000 km, 1 km on the surface of the Earth subtends an angle of one centigon at the centre of the Earth. However the gon is rarely used.

(d) For applications in astronomy, small angles are measured in arcseconds (i.e. seconds of plane angle), denoted by the symbol as or "; also used are milliarcseconds, microarcseconds, and picoarcseconds, denoted by the symbols mas, µas, and pas, respectively, where arcsecond is an alternative name for second of plane angle.

(e) The unit hectare, and its symbol ha, were adopted by the CIPM in 1879 (PV, 1879, 41). The hectare is used to express land area.

(f) The liter, and the symbol lower-case l, were adopted by the CIPM in 1879 (PV, 1879, 41). The alternative symbol, capital L, was adopted by the 16th CGPM (1979, Resolution 6) in order to avoid the risk of confusion between the letter l (el) and the numeral 1 (one).

(g) The tonne, and its symbol t, were adopted by the CIPM in 1879 (PV, 1879, 41). In English speaking countries this unit is usually called "metric ton".

(h) The astronomical unit of length was redefined by the XXVIII General Assembly of the International Astronomical Union (Resolution B2, 2012).

SUMMARY

The SI of units provides an internationally agreed reference framework that is recommended for use throughout science, technology, engineering and commerce. The SI base units and the SI coherent derived units form a coherent set that prevents unit conversions when inserting particular values for quantities into quantity equations. The SI is the only system of units globally recognized, has a clear advantage for establishing a worldwide dialogue and simplifies the teaching of science and technology to next generations.
Although national organizations can legitimately set measurement units in which non-SI units are accepted, international organizations like IWA and particularly expert groups like the Water Reuse Specialist Group should strongly promote the use of SI units among authors, reviewers and editors as

to assure that scientific and technical documents reach the highest level of effective and reliable communication, when they are edited, presented and published.

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