Applied Chemistry

Water Distribution and Hardness of Water

1. Graphical Presentation of Water Distribution on Earth

Water is the most abundant compound on the surface of the Earth, covering roughly seventy percent of its surface. However, the vast majority of this water is not directly usable for drinking, agriculture, or most industrial purposes, since it exists as saline water in oceans and seas. Only a small fraction of the Earth's total water exists as fresh water, and of this fraction, most is not easily accessible, being locked away in glaciers and ice caps or held underground as groundwater.

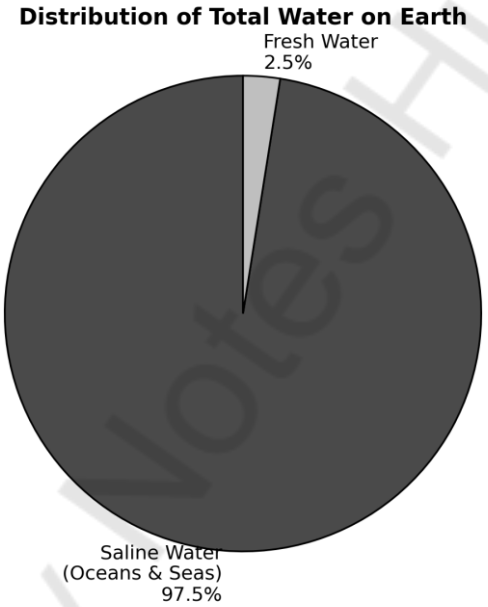

Figure 1: Distribution of total water on Earth — saline water (oceans and seas) versus fresh water

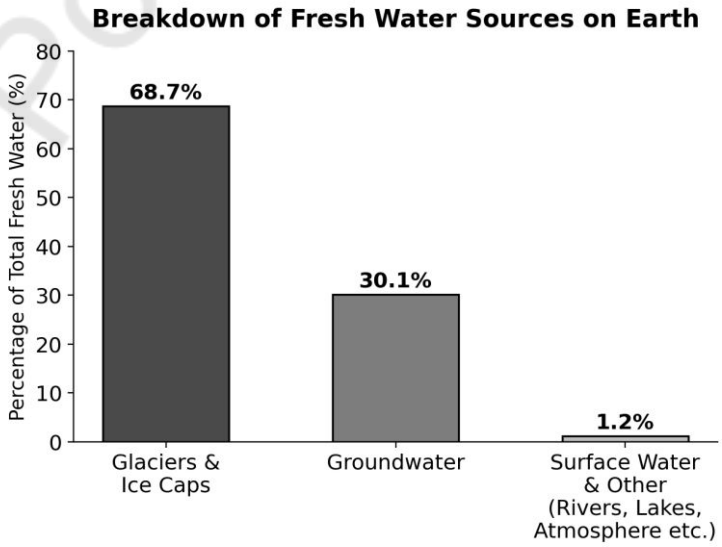

Figure 2: Breakdown of fresh water sources on Earth — glaciers and ice caps, groundwater, and surface water

As shown in Figure 1, approximately 97.5% of the total water on Earth is saline water, present in oceans and seas, while only about 2.5% exists as fresh water. Of this small fraction of fresh water, as shown in Figure 2, the largest share (approximately 68.7%) is locked up as ice in glaciers and polar ice caps, a further significant share (approximately 30.1%) exists as groundwater, and only a very small fraction (approximately 1.2%) is readily available as surface water in rivers, lakes, and the atmosphere — the very sources from which most of the fresh water used by humans is actually drawn.

This distribution highlights why fresh, easily accessible water is considered a precious and limited resource, despite water itself being abundant on the planet as a whole, and underscores the importance of water conservation and the sustainable use of available fresh water resources.

2. Classification of Soft and Hard Water Based on Soap Test

Natural water is broadly classified as soft water or hard water, based on its behaviour when mixed with soap, a test commonly known as the soap test.

2.1 Soap Test

Soap is a sodium (or potassium) salt of long-chain fatty acids. When soap is added to water and shaken:

- If the water produces an abundant, stable lather (foam) readily, without forming any noticeable scum, it is classified as soft water.
- If the water fails to produce lather readily, and instead forms an insoluble, curdy, white precipitate known as scum, it is classified as hard water; lather is produced only after a considerable amount of soap has first been used up in reacting with the dissolved salts responsible for hardness.

The scum formed in hard water is due to a chemical reaction between the soap and the calcium and magnesium ions dissolved in the water, which produces insoluble calcium and magnesium salts of the fatty acids present in the soap. This reaction consumes the soap without producing any useful lather, which is why hard water is considered less suitable for washing purposes, as it wastes soap and leaves a scum residue on fabrics and utensils.

Soft water, in contrast, contains little or no dissolved calcium or magnesium salts, allowing the soap to dissolve and produce lather freely, without being consumed in unwanted side reactions.

3. Salts Causing Hardness of Water

The hardness of water is caused specifically by the presence of dissolved salts of calcium and magnesium in the water, and is broadly classified into two types, depending on the particular salts responsible:

Type of Hardness	Cause	Salts Responsible
Temporary Hardness	Presence of dissolved bicarbonate salts of calcium and magnesium; can be removed simply by boiling the water	Calcium bicarbonate [$Ca(HCO_3)_2$], Magnesium bicarbonate [$Mg(HCO_3)_2$]
Permanent Hardness	Presence of dissolved chloride and sulphate salts of calcium and magnesium; cannot be removed by boiling, and requires chemical treatment	Calcium chloride ($CaCl_2$), Calcium sulphate ($CaSO_4$), Magnesium chloride ($MgCl_2$), Magnesium sulphate ($MgSO_4$)

In most natural hard water sources, both temporary and permanent hardness are present together, and the total hardness of the water is considered as the sum of these two components.

4. Unit of Hardness

Since the hardness of water arises from several different dissolved salts (bicarbonates, chlorides, and sulphates of calcium and magnesium), it is conventionally expressed not as the actual concentration of each individual salt, but as an equivalent amount of calcium carbonate ($CaCO_3$) that would produce the same degree of hardness. This convention is adopted because calcium carbonate has a simple, convenient molar mass (100 g/mol) and allows the hardness contributions of different salts to be compared and added together on a common basis.

The commonly used units for expressing water hardness are given below:

Unit of Hardness	Definition
Parts per million (ppm)	1 part of $CaCO_3$ equivalent hardness present per million parts of water (by mass); numerically the same as mg/L
Milligrams per litre (mg/L)	1 milligram of $CaCO_3$ equivalent hardness present per litre of water; the most commonly used unit in modern water analysis

Degree Clark (°Cl)	Number of grains (1 grain = 1/70 of a gram approximately) of CaCO3 equivalent hardness present per gallon (imperial) of water
Degree French (°Fh)	Number of parts of CaCO3 equivalent hardness present per 100,000 parts of water

Of these, parts per million (ppm) and milligrams per litre (mg/L) are numerically identical and are the units most widely used in modern water quality analysis and reporting.

5. Simple Numerical Problems on Water Hardness

Worked Example 1:

A sample of water contains 146 mg of calcium bicarbonate [Ca(HCO3)2, molar mass 162 g/mol] dissolved per litre. Calculate the hardness of the water in terms of ppm of CaCO3 equivalent (molar mass of CaCO3 = 100 g/mol).

Solution: Hardness (as CaCO3 equivalent) = [Mass of salt × Molar mass of CaCO3] / Molar mass of salt = (146 × 100) / 162 = 14600 / 162 ≈ 90.1 mg/L. Therefore, the hardness of the water sample is approximately 90.1 ppm (as CaCO3 equivalent).

Worked Example 2:

A water sample contains 20 mg/L of hardness-causing salts, expressed as CaCO3 equivalent. Express this hardness in degree French (°Fh).

Solution: Since 1°Fh corresponds to 1 part of CaCO3 equivalent hardness per 100,000 parts of water, and 1 ppm corresponds to 1 part per million (10^6) parts of water, the conversion factor between ppm and °Fh is: 1°Fh = 10 ppm. Therefore, hardness in °Fh = 20 / 10 = 2°Fh. Since this value is quite low, the water sample would generally be classified as soft to moderately soft water.

6. Multiple Choice Questions (MCQs)

Answer the following questions by selecting the most appropriate option.

1. The percentage of total water on Earth that exists as saline (ocean) water is approximately:

A) 50%
B) 75%
C) 97.5%
D) 25%

2. The largest share of fresh water on Earth is locked up in:

A) Rivers and lakes

B) Groundwater

C) Glaciers and ice caps

D) The atmosphere

3. Hard water is water that:

A) Produces lather easily with soap

B) Does not produce lather easily with soap due to dissolved calcium and magnesium salts

C) Contains no dissolved salts at all

D) Is always unsafe to drink

4. Soft water is water that:

A) Produces lather easily with soap

B) Forms a scum with soap

C) Always contains dissolved calcium bicarbonate

D) Cannot be used for washing

5. In the soap test, the scum (curdy precipitate) formed with hard water is due to the reaction of soap with:

A) Dissolved oxygen in water

B) Calcium and magnesium ions present in the water

C) Sodium and potassium ions present in the water

D) Dissolved carbon dioxide

6. Temporary hardness of water is caused mainly by the presence of:

A) Chlorides of calcium and magnesium

B) Sulphates of calcium and magnesium

C) Bicarbonates of calcium and magnesium

D) Sodium chloride

7. Temporary hardness of water can be removed simply by:

A) Filtration

B) Boiling

C) Adding more soap

D) Freezing

8. Permanent hardness of water is caused mainly by the presence of:

A) Bicarbonates of calcium and magnesium only

B) Chlorides and sulphates of calcium and magnesium

C) Dissolved oxygen and nitrogen

D) Sodium bicarbonate

9. Permanent hardness of water cannot be removed by:

A) Boiling alone

B) Chemical treatment
C) Ion exchange methods
D) The addition of washing soda

10. The hardness of water is conventionally expressed in terms of an equivalent amount of:

A) Sodium chloride (NaCl)
B) Calcium carbonate ($CaCO_3$)
C) Magnesium oxide (MgO)
D) Potassium sulphate

11. 1 ppm of hardness is numerically equivalent to:

A) 1 g/L
B) 1 mg/L
C) 1 mg per 100 mL
D) 1 g per 100 mL

12. Which unit of water hardness is defined as parts of $CaCO_3$ equivalent hardness per 100,000 parts of water?

A) Degree Clark
B) Degree French
C) ppm
D) mg/L

Answer Key

1. C) 97.5% | 2. C) Glaciers and ice caps | 3. B) Does not produce lather easily with soap due to dissolved calcium and magnesium salts | 4. A) Produces lather easily with soap | 5. B) Calcium and magnesium ions present in the water | 6. C) Bicarbonates of calcium and magnesium | 7. B) Boiling | 8. B) Chlorides and sulphates of calcium and magnesium | 9. A) Boiling alone | 10. B) Calcium carbonate ($CaCO_3$) | 11. B) 1 mg/L | 12. B) Degree French

7. Broad / Long Answer and Numerical Questions

1. Describe, with the help of a diagram, the distribution of total water on Earth between saline and fresh water sources.

2. Describe the breakdown of fresh water sources on Earth, mentioning the approximate share held by glaciers, groundwater, and surface water.

3. Explain the soap test used to classify water as soft or hard, describing what is observed in each case.

4. Distinguish between soft water and hard water, referring to their behaviour with soap.

5. Explain temporary hardness and permanent hardness of water, naming the salts responsible for each type.

6. Explain why temporary hardness can be removed by boiling, while permanent hardness cannot.

7. Explain the concept of expressing water hardness in terms of calcium carbonate ($CaCO_3$) equivalents.

8. Describe the different units used to express the hardness of water, namely ppm, mg/L, degree Clark, and degree French.

9. A sample of water contains 146 mg of calcium bicarbonate [$Ca(HCO_3)_2$, molar mass 162 g/mol] dissolved per litre. Calculate the hardness of the water in terms of ppm of $CaCO_3$ equivalent (molar mass of $CaCO_3$ = 100 g/mol).

10. A water sample contains 20 mg/L of hardness-causing salts, expressed as $CaCO_3$ equivalent. Express this hardness in degree French (°Fh) and comment on whether the water sample would be classified as hard or soft.