Sustainability and Chemistry
CH5106: L3

Instructors: Sayam Sengupta
Swaminathan Sivaram
Amitava Das

Ecosystems of early human evolution

What drove shifts in mammal communities over the past 7 million years? One of the most well-documented changes is the expansion of grasslands throughout the past 4 million years.

The fossil record of herbivores closely follows the shifting environments, with changes in the representation of these groups tracking long-term grassland expansion.

PNAS, 2019, 116 (43) 21478-21483; https://attheu.utah.edu/facultystaff/ecosystems-of-early-human-evolution/

Organisms could cope with environmental fluctuations through genetic adaptation, wherein multiple alleles—different versions of a gene—exist within a population at varying frequencies. As conditions shift, **natural selection** favours the genetic version(s) best suited to the new environment. Genes that enable phenotypic plasticity—the ability to express different traits under different conditions—can further aid adaptation.

Another strategy involves evolving structures and behaviours that allow organisms to function across diverse environments. The selection of such traits in response to environmental instability is known as **variability selection**. https://humanorigins.si.edu/

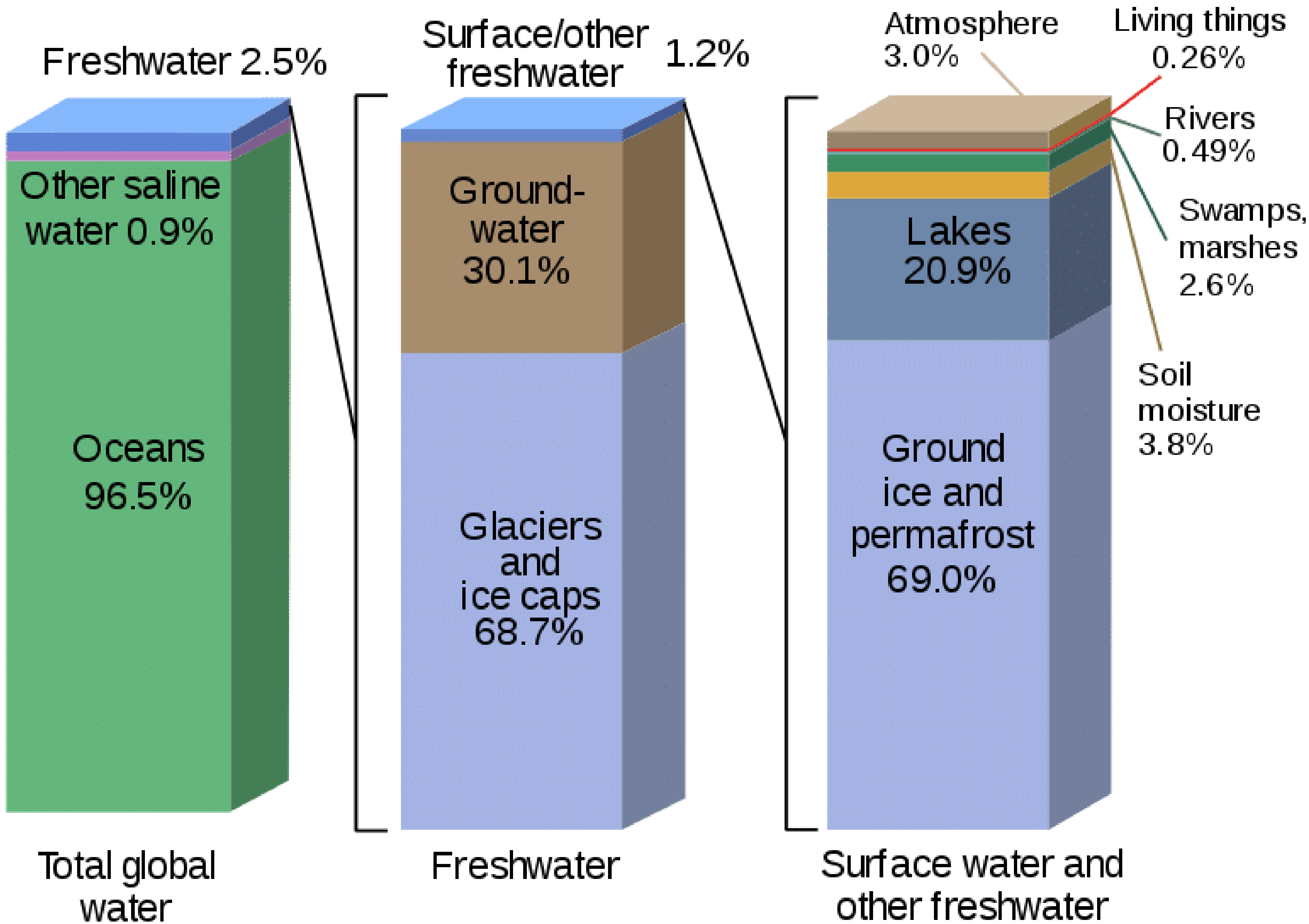
Ecosystem: An ecosystem is a community of living organisms (plants, animals, and microbes) that interact with one another and with their physical environment as a unified system. It comprises both biotic (living) and abiotic (non-living) components of a specific area, connected through nutrient cycles and energy flows.'

Neolithic Revolution: Traditional hunter-gatherer lifestyles, followed by humans since their evolution, were swept aside in favour of permanent settlements and a reliable food supply. Domestication, an accelerated evolutionary process driven by human intervention and natural selection, was a unique form of mutualism that developed between humans and the target plant or animal population and had strong selective advantages for both partners. During the domestication process, many traits in plants underwent dramatic modifications to meet human demands. After domestication, only favourable haplotypes were retained around selected genes, leading to the creation of a valley with extremely low genetic diversity.

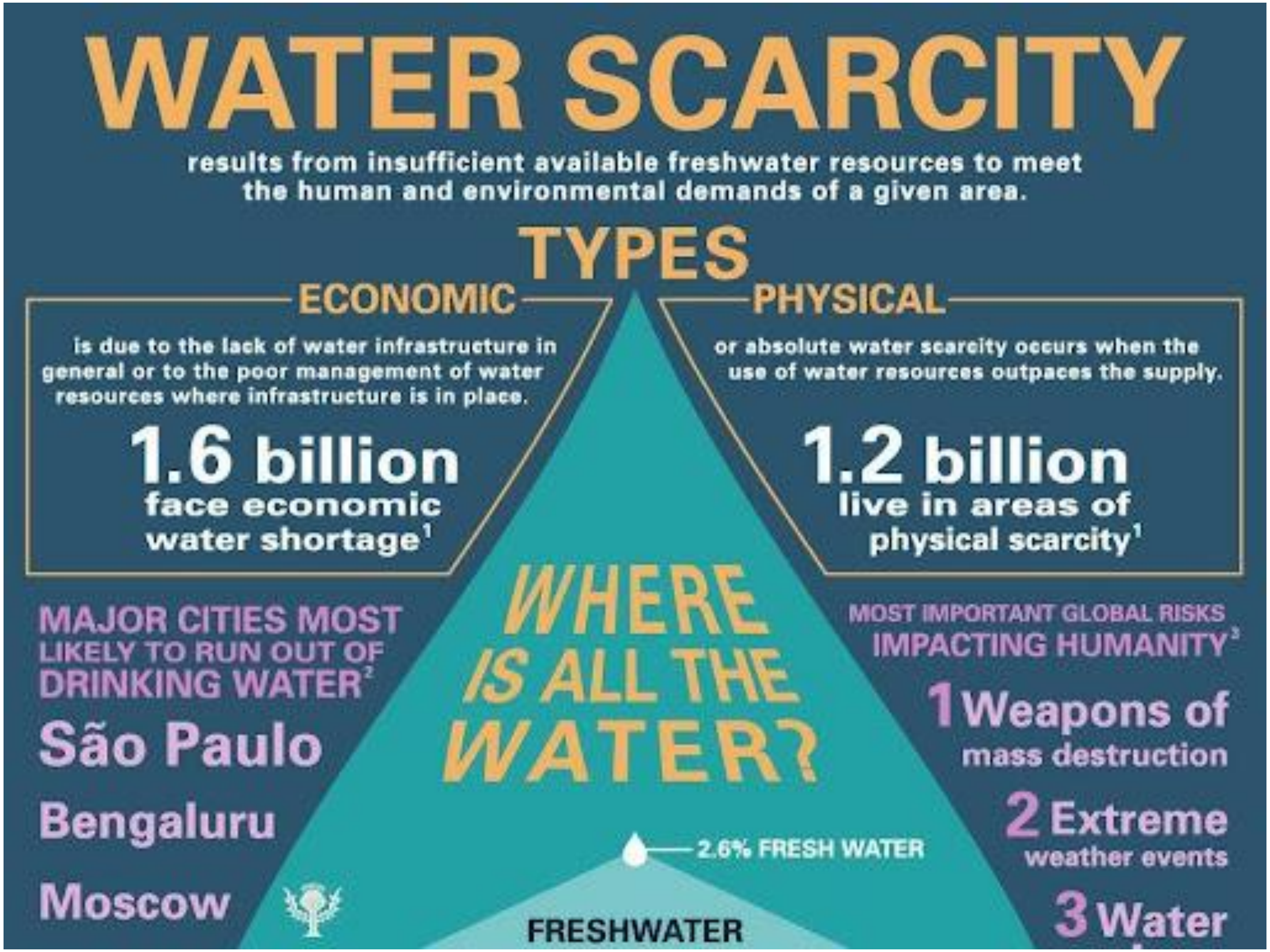
A population will generally expand until it reaches the **carrying capacity**, the maximum number of individuals an environment can support without detrimental effects, at which time it will level off. Continued expansion beyond the carrying capacity generally results in a crash.

If enough genetic diversity remains, the population may recover; it may also become extinct.

Where is Earth's Water?

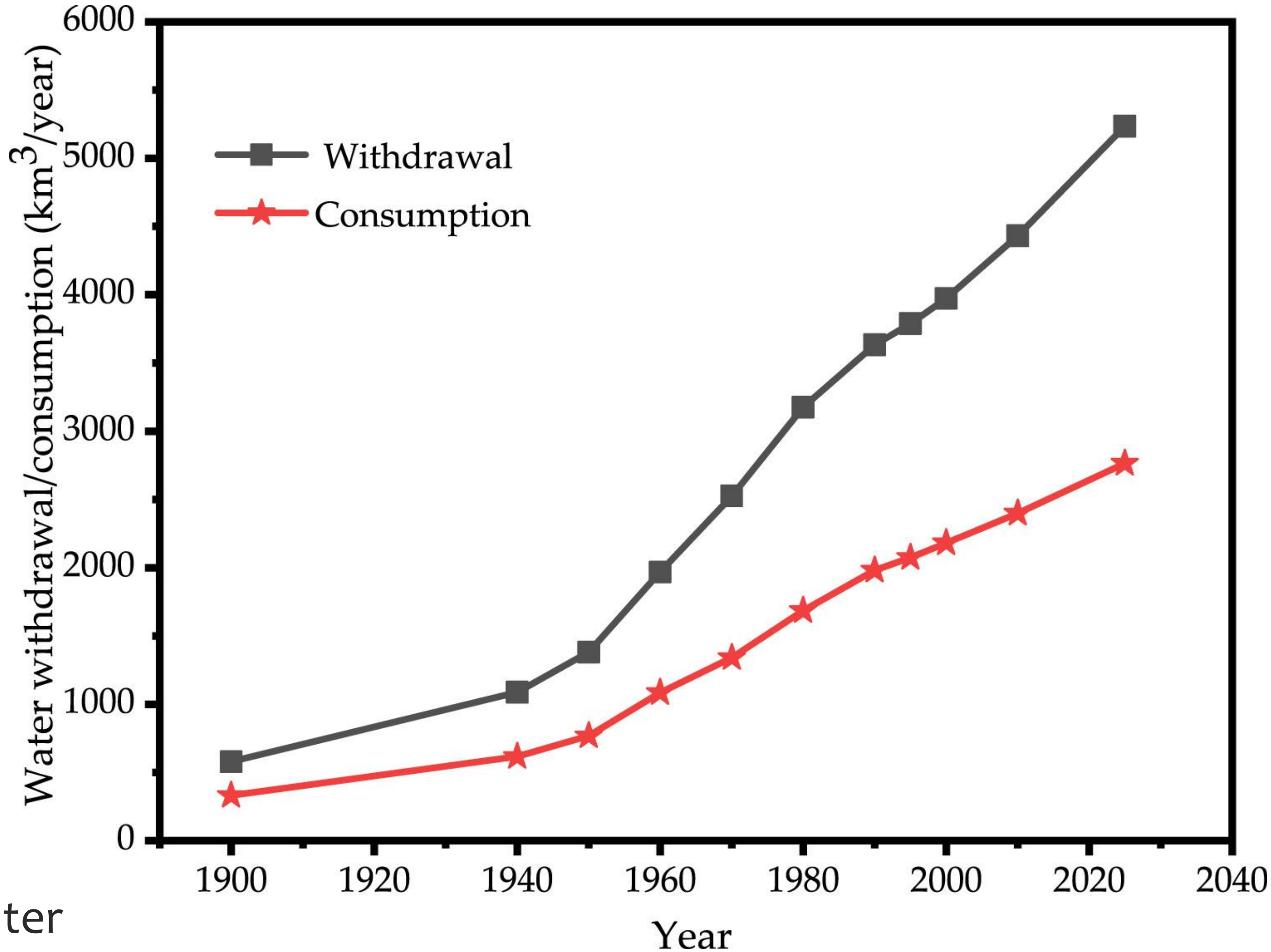


https://lotusarise.com/water-resources-upsc/



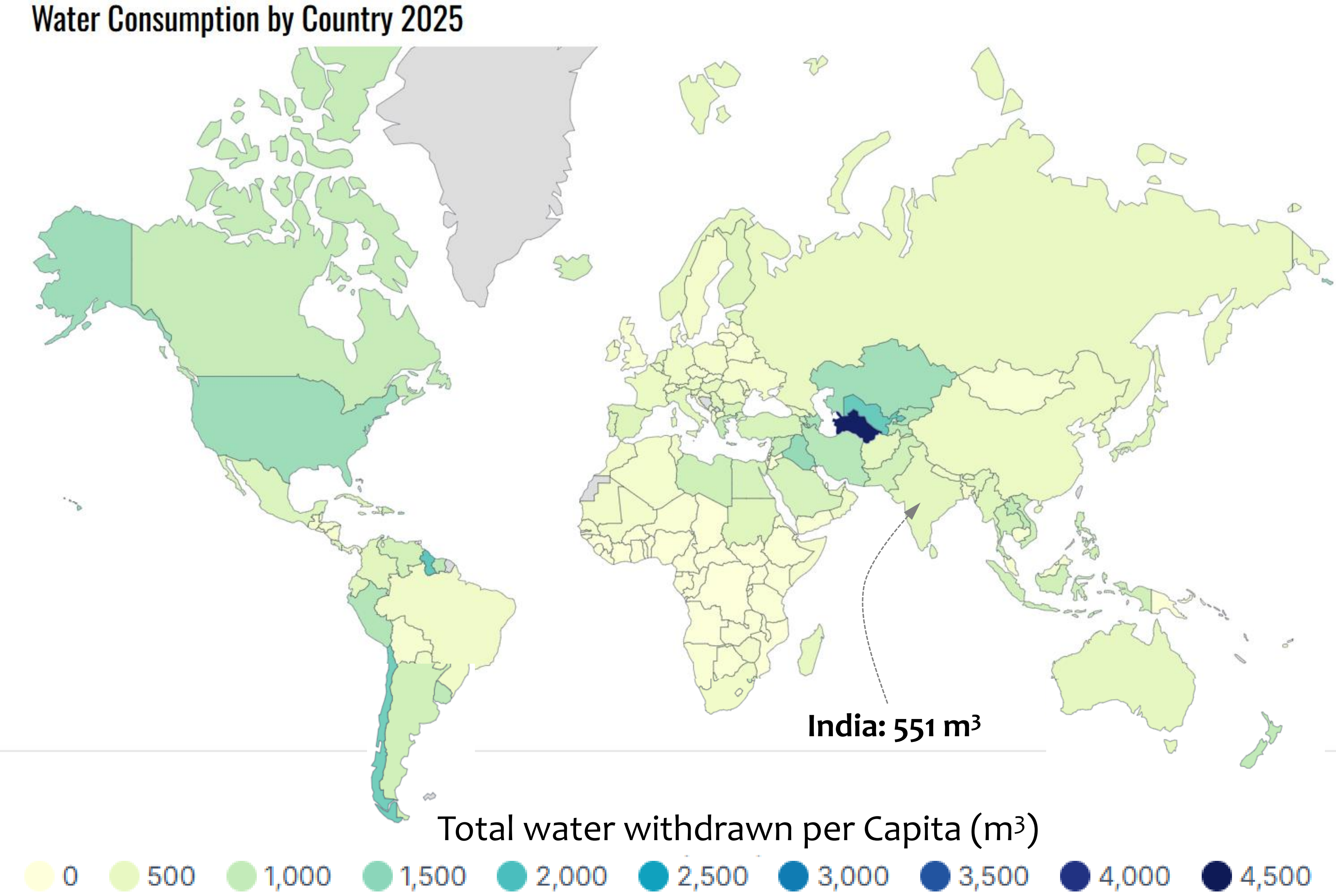
https://www.iasgyan.in/daily-current-affairs/global-water-crisis

Fresh water resource, scarcity, water salinity challenges and possible remedies: A review, Heliyon, 2023, 9, e18685.

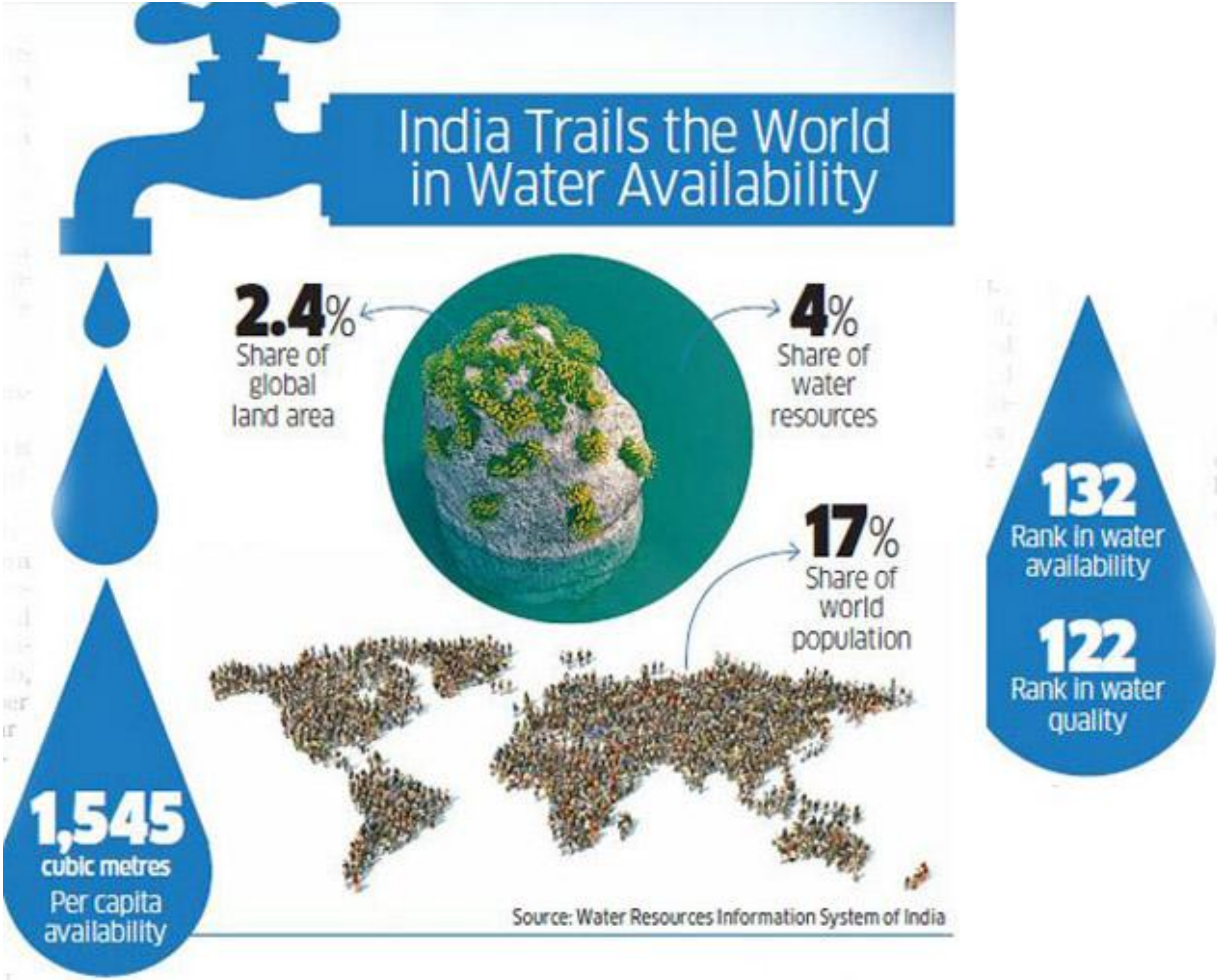


The costs of unsafe water

- 2.2 billion people do not have access to clean water at home.
- 2.3 billion people lack access to basic sanitation services, such as toilets or latrines.
- Every day, more than 800 children under five years of age die from diarrhea caused by dirty water.
- 700 million people worldwide could be displaced by intense water scarcity by 2030.



https://worldpopulationreview.com/country-rankings/water-consumption-by-country


India Trails the World in Water Availability
2.4%
Share of global land area
4%
Share of water resources
17%
Share of world population
132
Rank in water availability
122
Rank in water quality
1,545
cubic metres
Per capita availability
Source: Water Resources Information System of India

Facts on India's Drinking Water Challenge

163 Mn

people do not have access to safe drinking water

*Source: Aid report

>6 in 10

households report that they do no treat their water prior to drinking

*Source: NFHS-4 (2015-16)

21%

of the disease reported in the country are water related

*Source: World Bank Report

India loses **73 Mn** working days due to water-borne diseases

*Source: IndiaSpend report 2016

443 Mn

School days are lost each year from water related illness

*Source: Human Development Report 2006

~66 Mn people in **20** states are at risk because of the excessive fluoride in water

*Source: Ministry of Drinking Water and Sanitation (MDWS) Report

~6 Mn

children below age 14 suffer from dental, skeletal and non-skeletal fluorosis

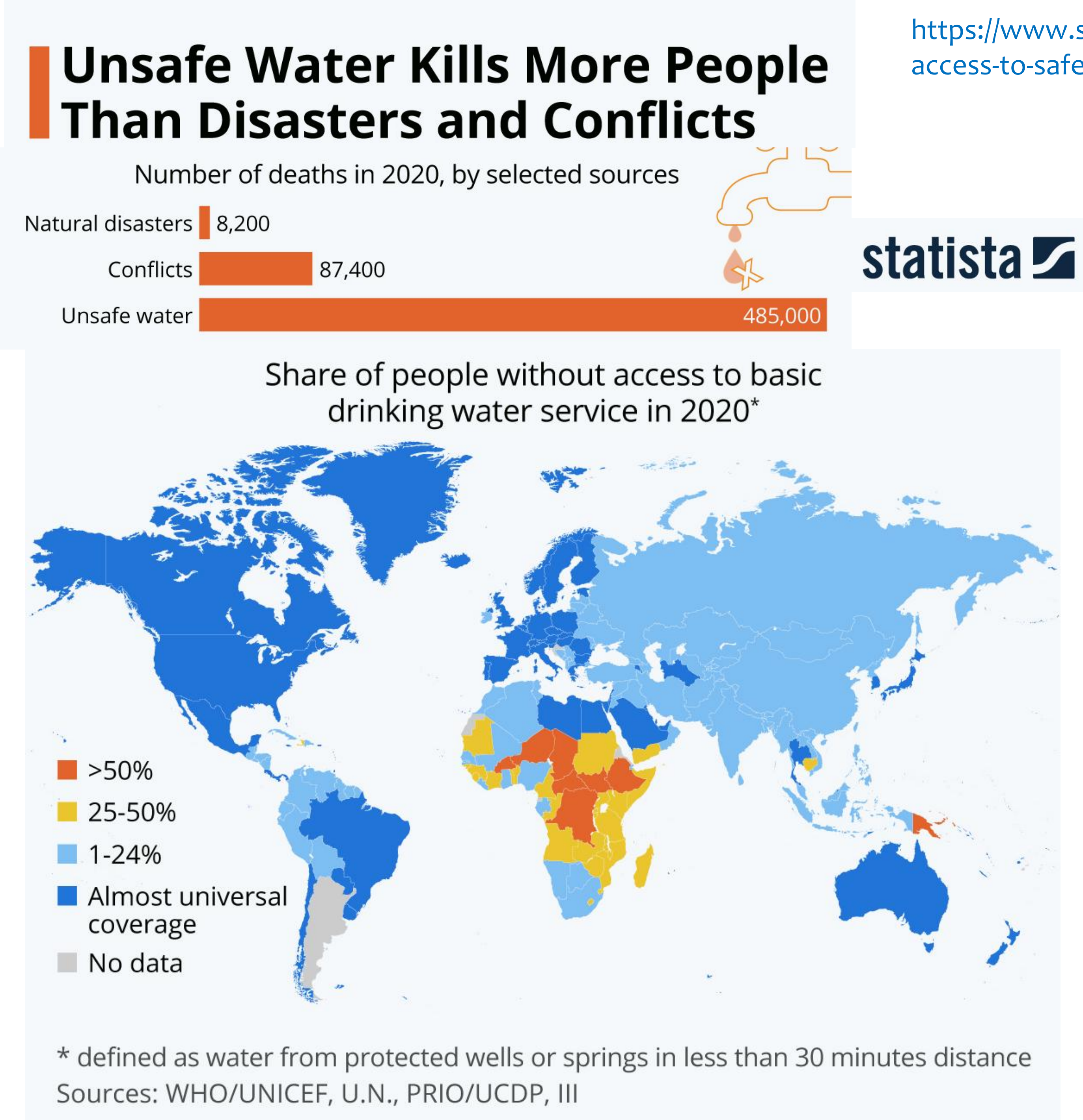
*Source: Fluorosis Research and Rural Development Foundation

Arsenic is the other big killer putting at risk nearly **~10 Mn** people

*Source: World bank report

- Approximately **92 % of rural Indians** have basic access, i.e., an improved source within 30 minutes.
- However, **'basic access' does not always equate to tap water directly in the home** (as of mid-2025).
- The **Jal Jeevan Mission,** India's flagship rural tap-water project, has provided tap connections to around **80.9 % of rural households** (15.67 crore households out of approx. 19.36 crore).
- About **50–60 %** of rural households have a **functional tap connection within the dwelling or premises**, according to government administrative data and surveys.
- Yet, household surveys (by National Sample Survey Office) suggest that only about **30 %** of rural households use **tap water at home or yard** as their primary source of drinking water.

https://www.statista.com/chart/17445/global-access-to-safe-drinking-water/



The **Stage of Ground Water Extraction** is a metric used in India to assess the pressure on groundwater resources in a specific area. It is defined as the **percentage of annual groundwater extraction compared to the annual extractable groundwater resources**. Based on this percentage, areas are categorized to indicate their groundwater status, which helps guide regulation, conservation, and planning efforts.

Annual Extractable Groundwater Resources (**AEGR**) is the portion of the total annually replenishable groundwater (**ARGW**) that can be safely extracted for use without causing long-term depletion or degradation of the aquifer.

Concept	Typical Calculation Basis
ARGR (Total recharge)	Rainfall, irrigation return flow, etc.
AEGR (Extractable)	ARGR × 0.7 (command) or 0.9 (non-command)
Stage of Extraction (%)	Annual Extraction ÷ AEGR × 100

This classification is maintained and updated periodically by the **Central Ground Water Board (CGWB)** under the **Ministry of Jal Shakti**, Government of India.

The latest nationwide assessment (2022) shows:

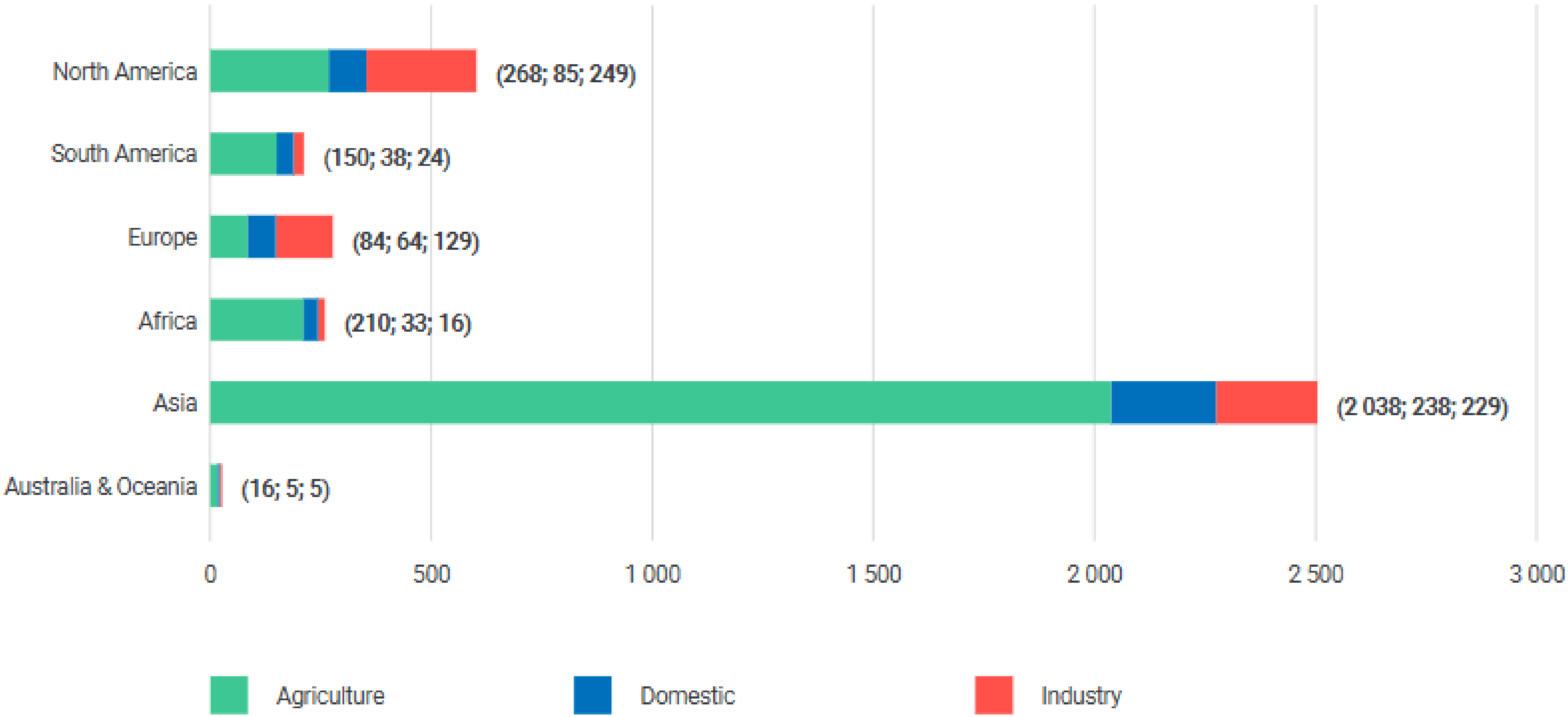
•**Out of 6,965 assessed units (blocks/mandals/wards):**

- **Over-exploited**: ~1,006 units (14.4%)
- **Critical**: ~260 units (3.7%)
- **Semi-critical**: ~885 units (12.7%)
- **Safe**: ~4,690 units (67.4%)
- **Saline**: ~124 units (1.8%)

(Source: CGWB, 2022 — *Dynamic Ground Water Resources of India*)

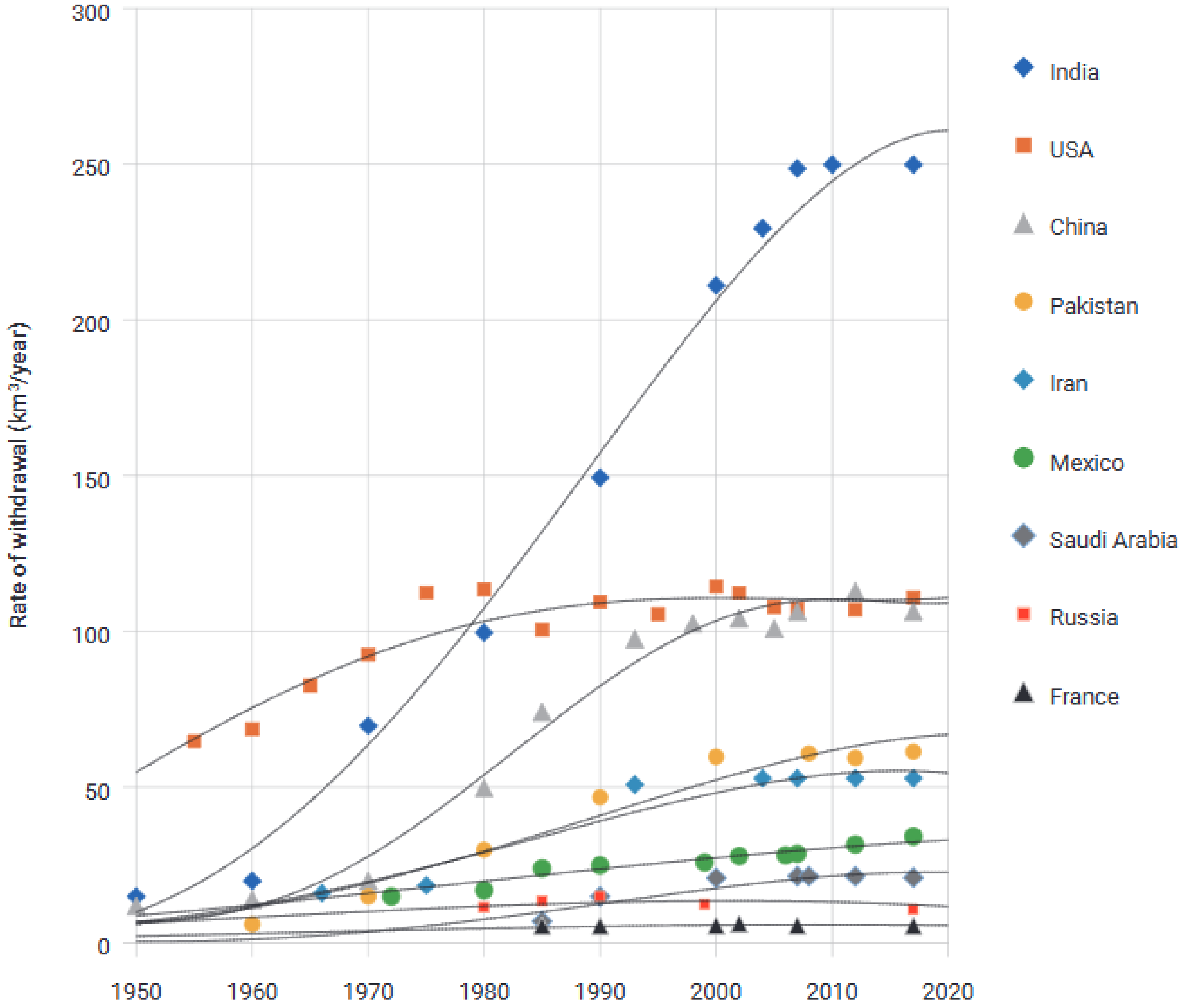
Category	Stage of Groundwater Extraction (%)	Description
Safe	≤ 70%	Groundwater extraction is within sustainable limits.
Semi-critical	> 70% and ≤ 90%	Extraction is nearing critical levels; needs monitoring and regulation.
Critical	> 90% and ≤ 100%	Very high stress; extraction almost equals recharge. Conservation is essential.
Over-exploited	> 100%	Extraction exceeds recharge; aquifers are being depleted. Urgent action needed.
Saline	Not defined by extraction %	Groundwater is saline and not suitable for most uses without treatment.

Freshwater withdrawal in 2017, aggregated by continent and by water sector use (km^3/year)



Margat, J. and Van der Gun, J. 2013. Groundwater around the World: A Geographical Synopsis. Boca Raton, Fla., CRC Press. and The United Nations World Water Development Report 2022, Published in 2022 by the United Nations Educational, Scientific and Cultural Organization

Evolution of total groundwater withdrawal in selected countries, 1950–2020



Margat, J. and Van der Gun, J. 2013. Groundwater around the World: A Geographical Synopsis. Boca Raton, Fla., CRC Press. and The United Nations World Water Development Report 2022, Published in 2022 by the United Nations Educational, Scientific and Cultural Organization

Fast Track Initiative – Final report; ADA Project No. 2725-00/2014

Groundwater Abstraction		[km^3/year]				Change rate
Ranking	Countries	2010	Share	2050	Share	(% of 2010)
1	India	201	25%	278	25%	139
2	USA	103	13%	118	11%	114
3	China	102	13%	152	14%	150
4	Iran	60	8%	73	7%	122
5	Pakistan	60	8%	70	6%	116
6	Mexico	25	3%	32	3%	127
7	Russian Federation	22	3%	37	3%	168
8	Saudi Arabia	22	3%	29	3%	135
9	Bangladesh	11	1%	13	1%	117
10	Japan	11	1%	12	1%	109

Alternate source of water

Traditionally, freshwater has come from rivers, lakes, streams, and groundwater aquifers. These traditional sources are becoming unavailable for various reasons. Need to switch to alternative sources of water, including rainwater, storm water, grey water, reclaimed water, and brackish & seawater desalination.

National policy for identifying appropriate technologies for securing the supply of fresh water as per the need.

Country	Total groundwater withdrawals (km^3)	Total renewable groundwater resources (km^3)	Percent of withdrawals to total renewable groundwater resources	Percent national share of global withdrawals
India	190	419	45.3	28.9
United States	110	1,300	8.5	16.7
Pakistan	60	55	109.1	9.1
China	53	828	6.4	8.1
Iran	53	49	108.2	8.1
Mexico	25	139	18.0	3.8
Saudi Arabia	21	2.2	954.5	3.2
Italy	14	43	32.6	2.1
Japan	14	27	51.9	2.1
Bangladesh	11	21	52.4	1.7
Brazil	8	1,874	0.4	1.2
Turkey	8	68	11.8	1.2
Uzbekistan	7	9	77.8	1.1
Germany	7	46	15.2	1.1
Egypt	7	2	350.0	1.1
France	6	100	6.0	0.9
Spain	5	30	16.7	0.8
Bulgaria	5	6	83.3	0.8
Argentina	5	128	3.9	0.8
Libya	4	0.5	800.0	0.6
Rest of the world	76	6,135	1.2	11.6
Total	658	11,282	5.8	100.0

[a] Sources: FAO, AQUASTAT (**http://www.fao.org/nr/water/aquastat/main/index.stm**; 40, 41).

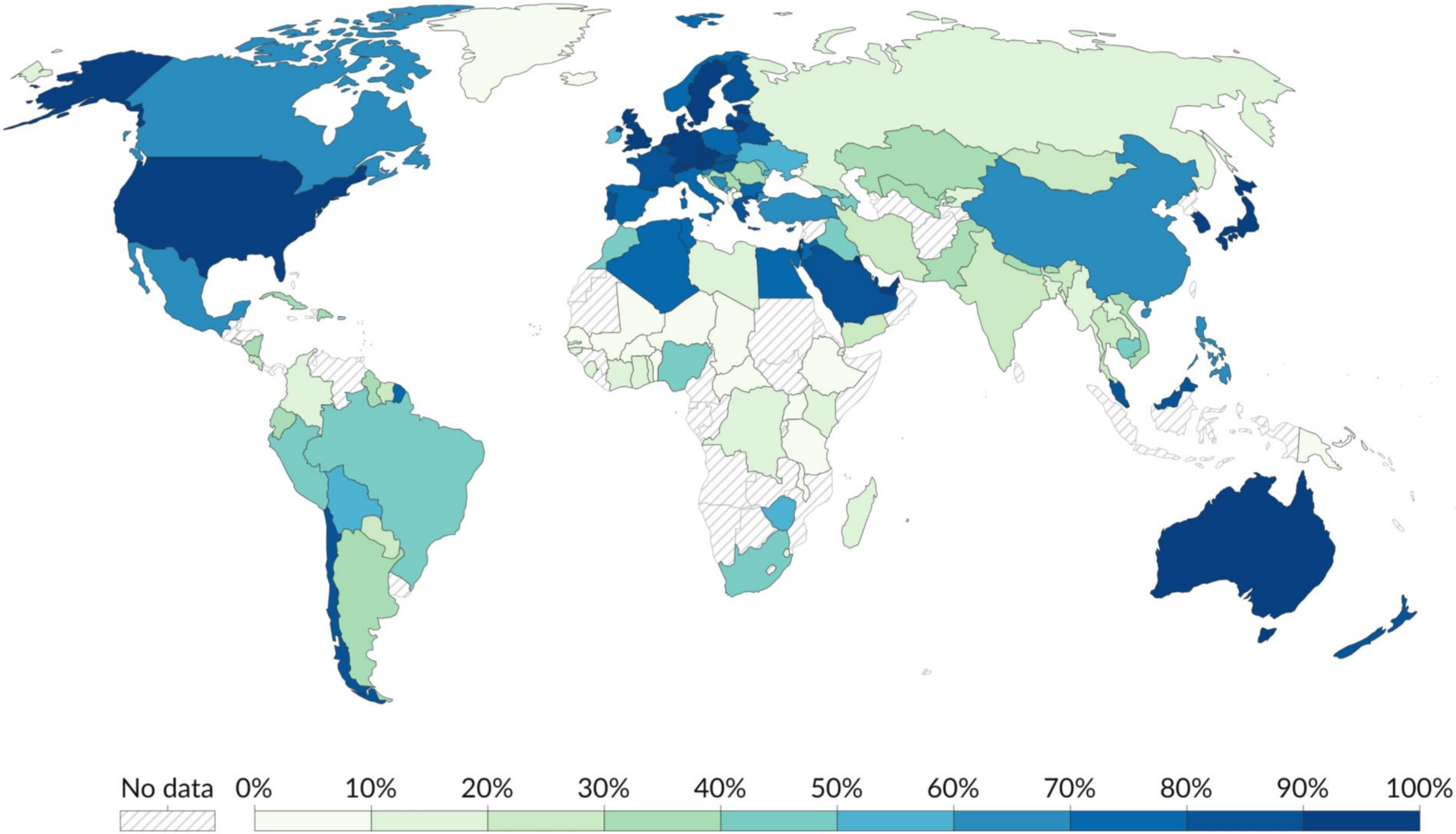
The 15 nations with the largest estimated annual groundwater extractions (2010):

Country	Population 2010 (in thousands)	Groundwater extraction			
		Estimated groundwater extraction 2010 (km^3/yr)	Breakdown by sector		
			Groundwater extraction for irrigation (%)	Groundwater extraction for domestic use (%)	Groundwater extraction for industry (%)
India	1224614	251.00	89	9	2
China	1341335	111.95	54	20	26
United States	310384	111.70	71	23	6
Pakistan	173593	64.82	94	6	0
Iran	73974	63.40	87	11	2
Bangladesh	148692	30.21	86	13	1
Mexico	113423	29.45	72	22	6
Saudi Arabia	27448	24.24	92	5	3
Indonesia	239871	14.93	2	93	5
Turkey	72752	13.22	60	32	8
Russia	142985	11.62	3	79	18
Syria	20411	11.29	90	5	5
Japan	126536	10.94	23	29	48
Thailand	69122	10.74	14	60	26
Italy	60551	10.40	67	23	10

https://www.ngwa.org/what-is-groundwater/About-groundwater/facts-about-global-groundwater-usage

Share of domestic wastewater that is safely treated, 2022

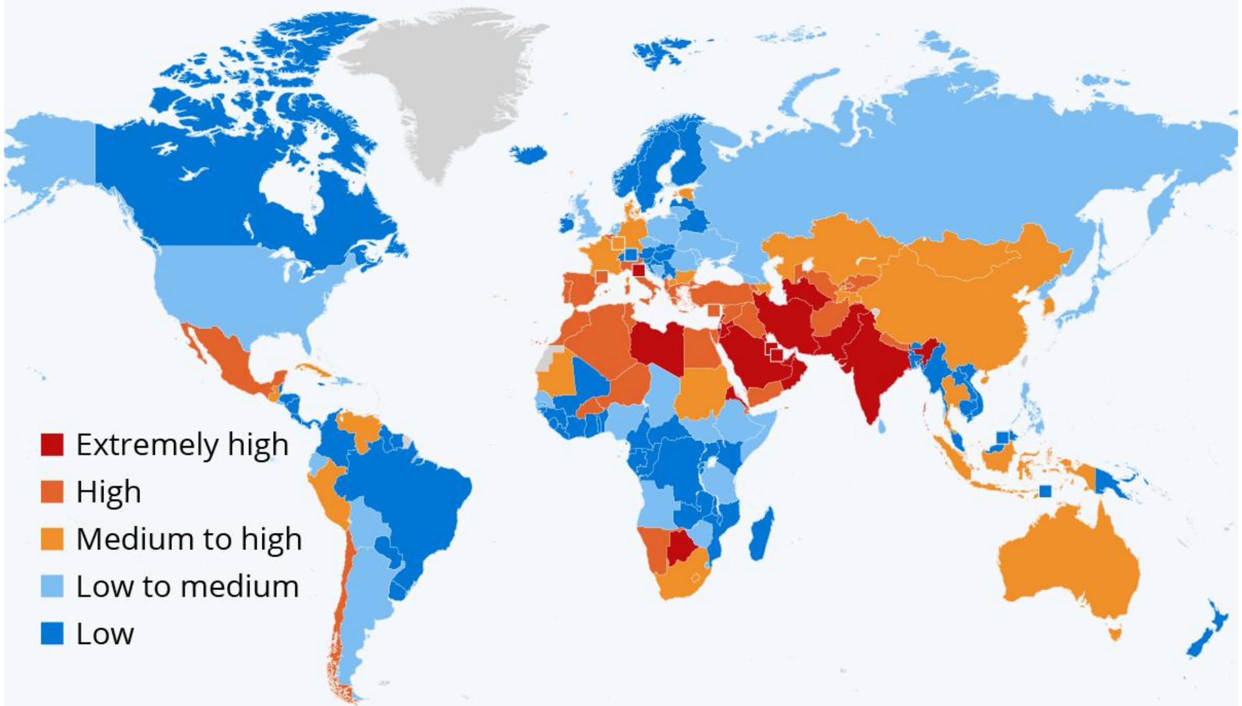
The proportion of wastewater from households and the service industry that is safely treated at the source or through centralized wastewater treatment plants before being discharged.



Nations Human Settlements Programme, World Health Organization and United Nations Statistics Division – Learn more about this data; OurWorldinData.org/water-use-stress

Where Groundwater Is (Not) Scarce

Index according to the risk of groundwater shortages in 2019, by country



* Index measures the ratio of total water withdrawals to available renewable surface and groundwater supplies. Withdrawals include domestic use as well as industrial, irrigation and livestock.

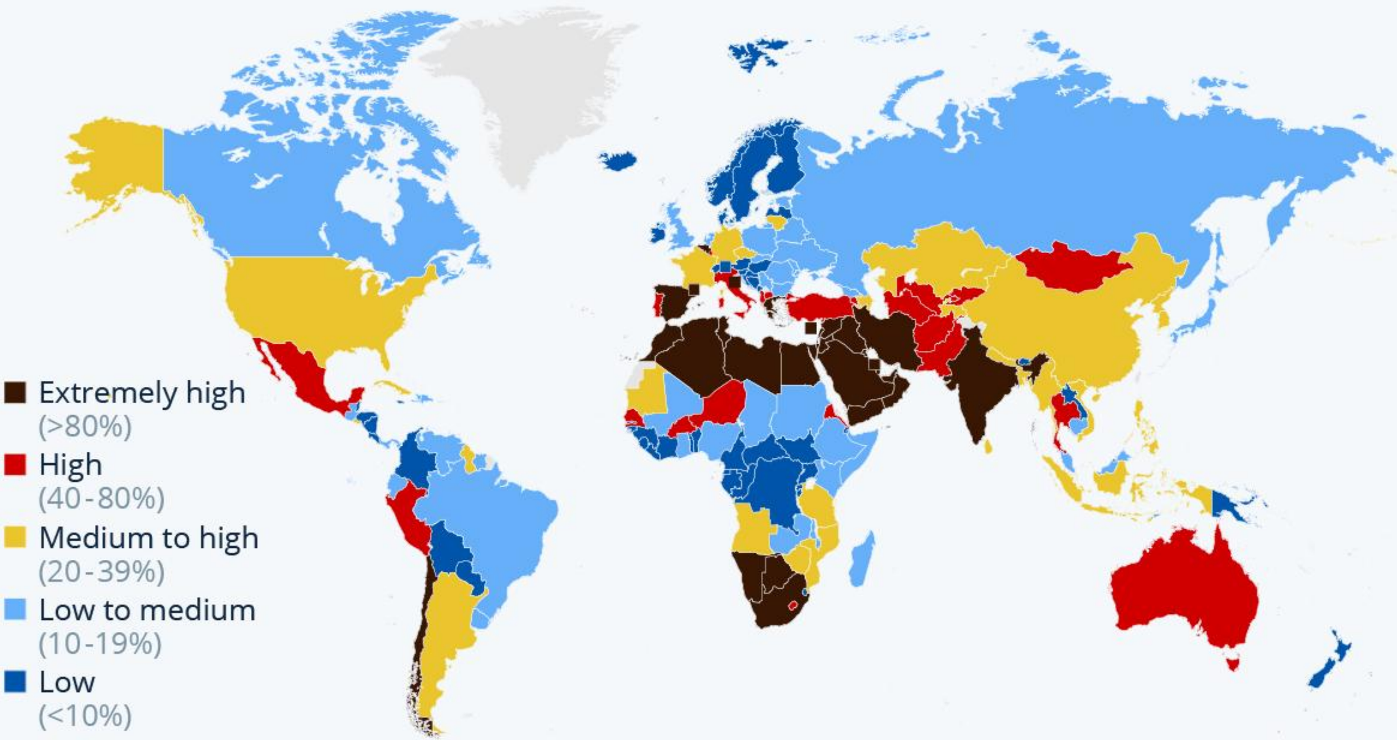
Source: World Resources Institute

statista

https://www.statista.com/chart/27274/water-stress-scarcity-current-situation/

Where Water Stress Will Be Highest by 2050

Projected ratio of human water demand to water availability (water stress level) in 2050*



* According to "business as usual" scenario = middle-of-the-road future where temperatures increase by 2.8°C to 4.6°C by 2100

Source: World Resources Institute

https://www.statista.com/chart/26140/water-stress-projections-global/

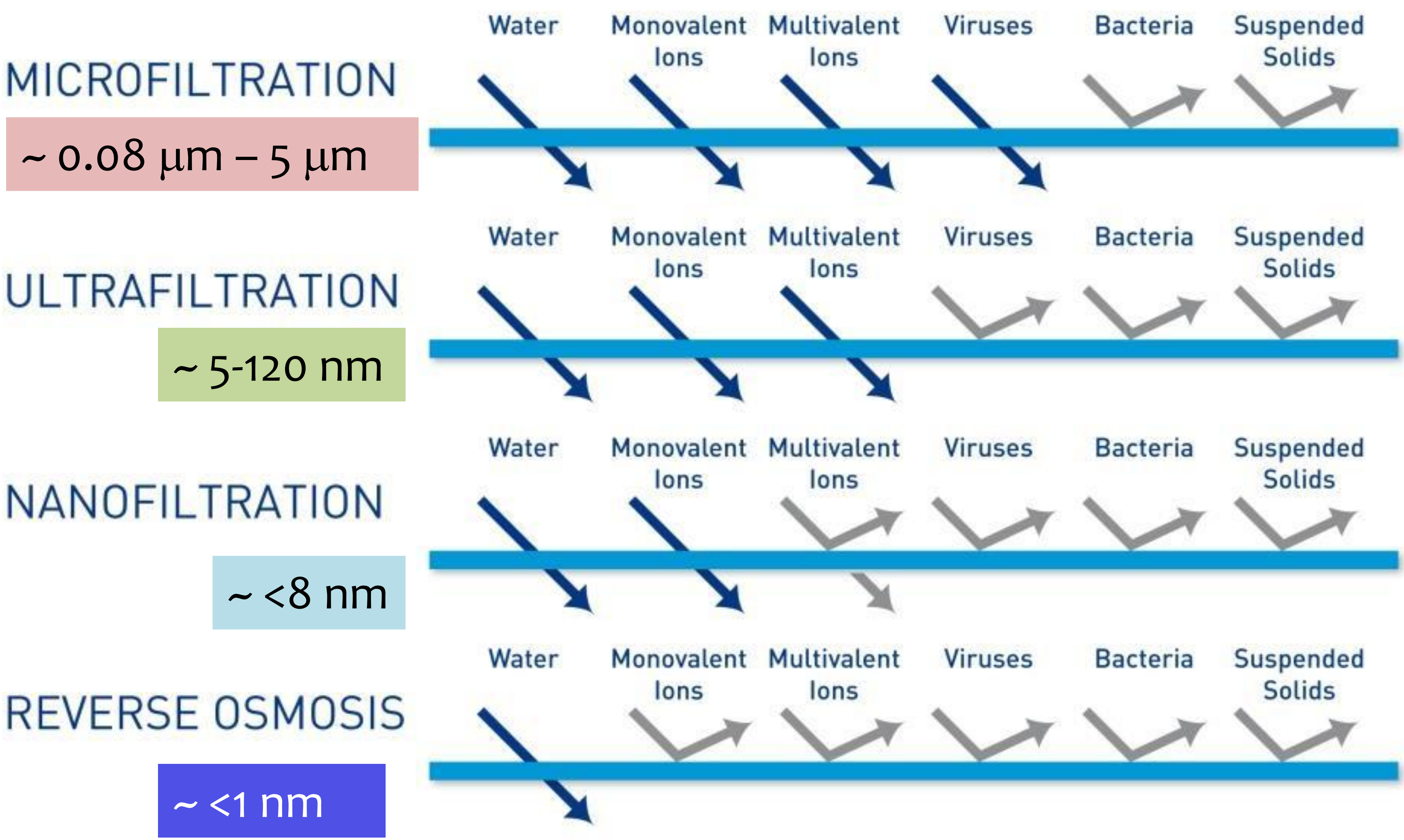
Traditionally, Chennai city of 9 million - which has some of the highest annual rainfall in India - has taken its water from four major lakes that are replenished by the annual monsoon rains. However, while Chennai needs around 1,200 MLD of water each year, these lakes, in their current condition, are only able to supply between 500 to 800 MLD a year, depending on the volume of rainfall that has occurred.

The Solution – Seawater desalination.

IVRCL along with Chennai Water Desalination Plant Limited, commissioned seawater desalination project by reverse osmosis process to get potable water as per IS10500:1991. Today 2.5 million residents of this city get potable drinking water from the 100 Million Litres per Day desalination plant.

The Minjur Desalination Plant is a reverse osmosis, water desalination plant at Katupalli village, a northern suburb of Chennai, India, on the coast of the Bay of Bengal that supplies water to the city of Chennai. Built on a 60-acre site, it is the largest desalination plant in India.

TYPE OF MEMBRANES AND CHARACTERISTICS



Major Research Focus: Potable Water through desalination of sea water/ brackish water/ pathogen removal/ removal of contaminants like Fluoride/ Arsenic/ iron/ etc

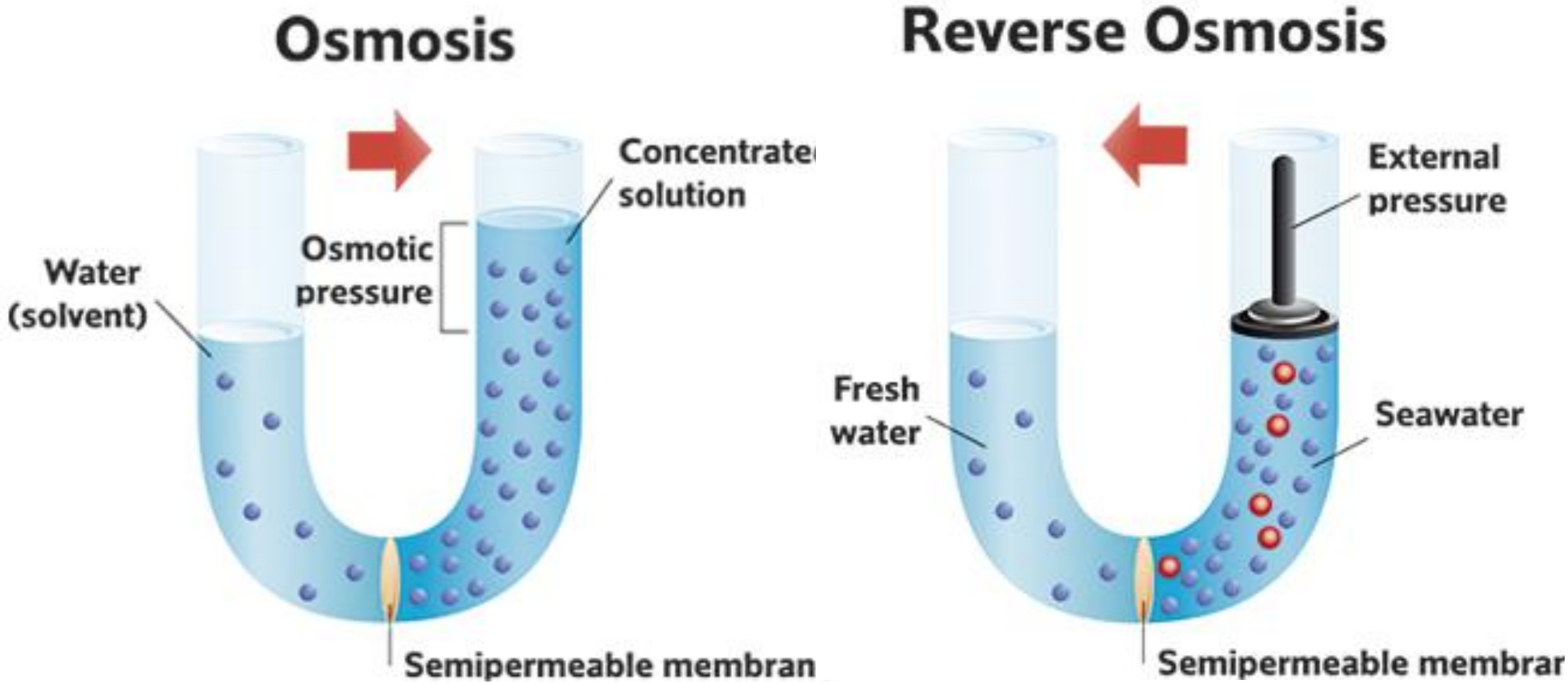
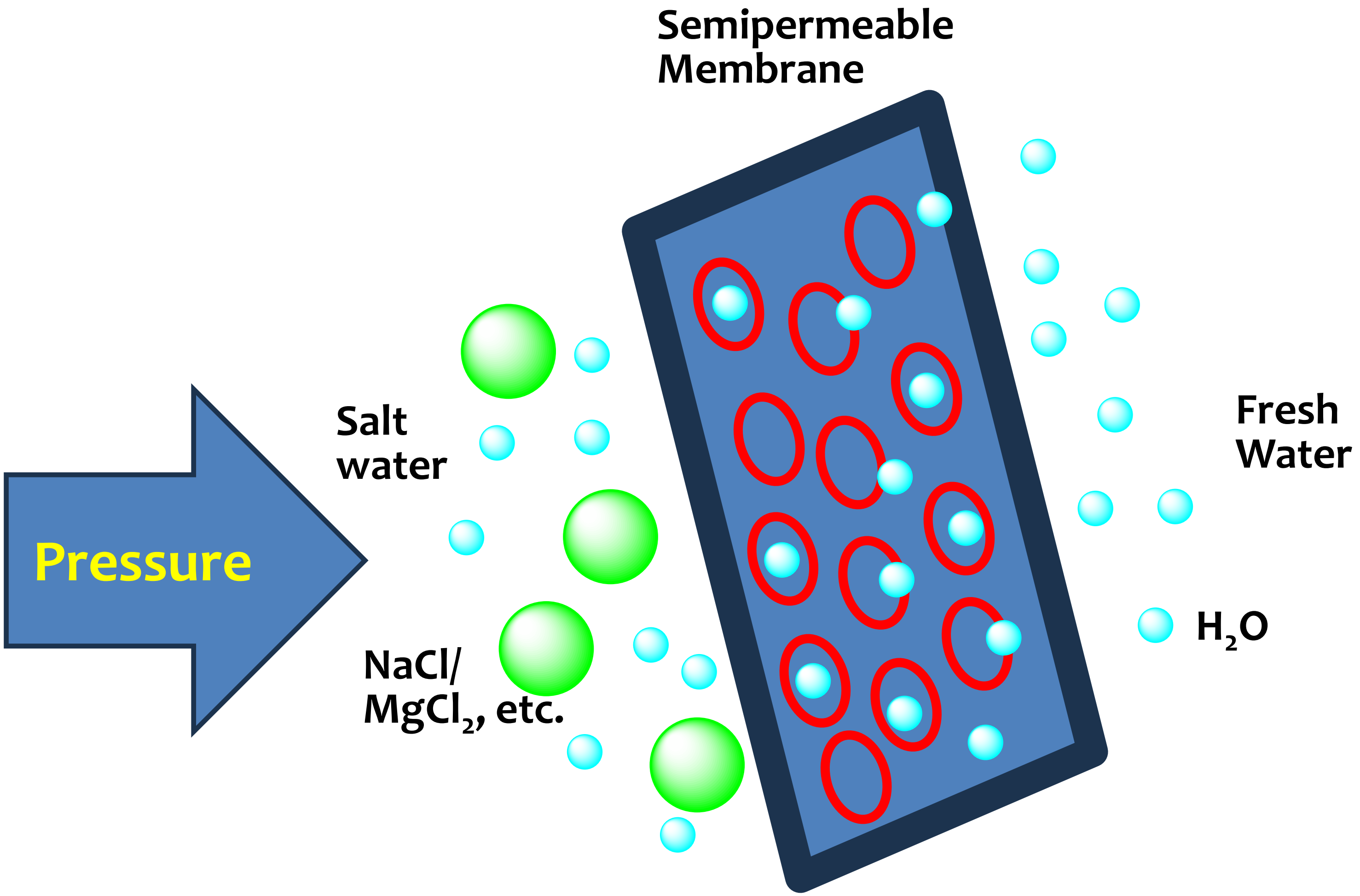
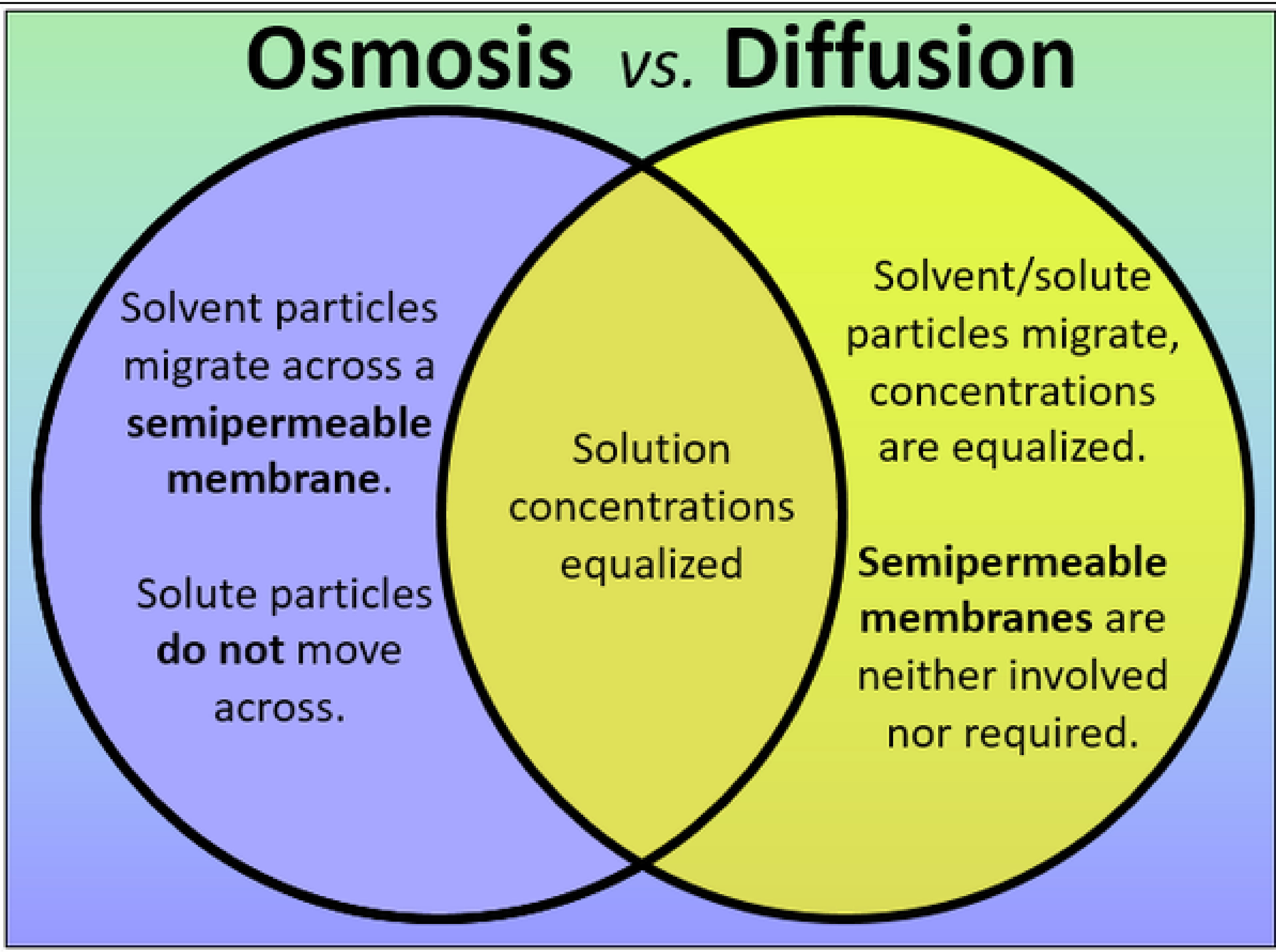


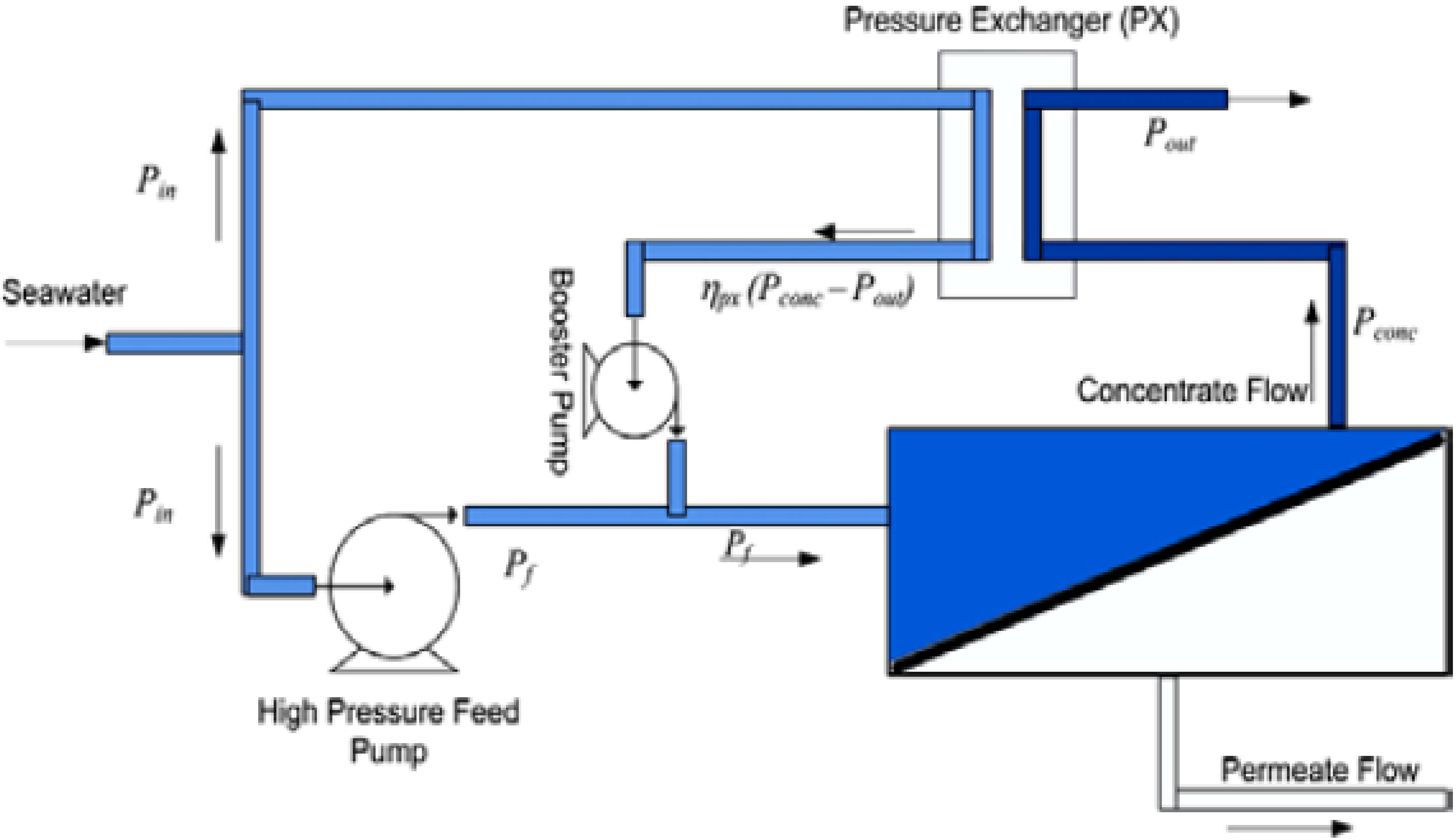
Diagram of osmosis in a U-shaped tube through a dialysis membrane that separates two solutions having different solute concentration.

Osmosis is a process that is fundamental to the physiology of all living things. It is the selective transport of water across a semipermeable membrane from high to low chemical potential caused by a difference in solute concentrations and/or hydrostatic pressures.



https://www.slideshare.net/9495094029/reverse-osmosis-based-desalination


Osmosis vs. Diffusion
Solvent particles migrate across a semipermeable membrane.
Solute particles do not move across.
Solution concentrations equalized
Solvent/solute particles migrate, concentrations are equalized.
Semipermeable membranes are neither involved nor required.

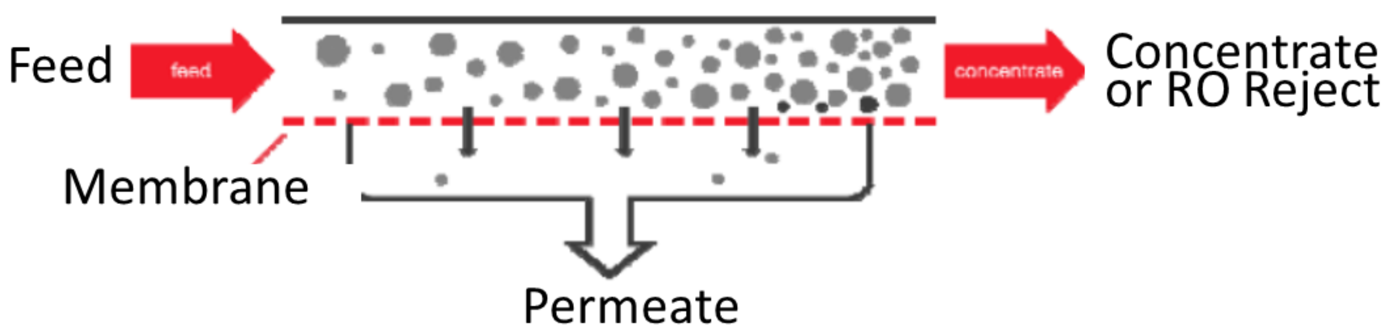


The RO desalination process

Desalination, 2010, 263, 76–88

The natural tendency of water with dissolved salts to flow through a membrane from lower to higher salt concentration. This process is found throughout nature. Plants use it to absorb water and nutrients from the soil. **RO** works by **reversing the principle** of **osmosis using a semipermeable membrane.**

RO can be used for seawater and brackish water desalination, to produce water for industrial/ agricultural application and drinking water. It can also be applied for the production of ultrapure water (for semiconductor, pharmaceutical industries) and boiler feed water. In addition, RO membrane systems are used for wastewater and water reuse treatments.



https://lpt.lanxess.com/uploads/tx_lxsmatrix/01_lewabrane_manual_ro_theory.pdf

This thermodynamic description is well established, but it says nothing about the kinetic mechanism responsible for osmosis. Despite its fundamental importance, the explanation for its physical basis has remained a controversial topic for well over a century, with many different mechanisms being proposed (Guell 1991; Weiss 1996). In current biophysics (Finkelstein 1987; Sperelakis 2012; Weiss 1996) and physics (Benedek and Villars 2000) textbooks, osmotic transport through a porous membrane is described as the *convective flow* of water through narrow pores that are selective for water over solutes. Within the convective flow model, a finite pressure gradient is always required within the pore for osmotic flow to occur. [Eur Biophys J. 2017 Jan; 46(1): 59–64]

In membrane filtration, convective flow refers to the transport of solutes (dissolved substances) across a semi-permeable membrane along with the flow of the solvent (usually water) due to a pressure difference (transmembrane pressure). It's a mechanism where solute molecules are "swept along" with the solvent as it moves through the membrane. This contrasts with diffusion, where solute movement is driven by concentration gradients.

Ultrafiltration and microfiltration membranes are both considered as porous membranes in which rejection is mainly determined by the size and shape of solute relative to the pore size of the membrane and where the transport of solvent is directly proportional to the applied pressure. For laminar convective flow through a porous membrane, both the Hagen-Poiseuille and the Carman-Kozeny equations can be applied (Mulder 1996). If the membrane consists of straight capillaries, the Hagen-Poiseuille relationship is applicable in which the mass velocity of fluid (N) through the membrane….

$$N = \frac{\varepsilon \rho D^2}{32 \mu L \tau} \Delta p$$

where ρ (density); μ (viscosity); ε (porosity), *D* (pore diameter), *L* (thickness); τ (tortuosity) of the membrane.

For a cylindrical perpendicular pore, τ = 1. If the pore is not straight, the product Lτ represents the actual length of the pore.

Eighteenth-century **French physicist Jean Antoine Nollet (1748)** gets the credit for the first conceptualisation of RO membrane. However, two centuries after Nollet's discovery, RO was still not much more than a laboratory phenomenon until a Thayer student project helped create a new multi-million dollar RO industry.

Researchers from both University of California at Los Angeles and the University of Florida successfully produced fresh water from seawater in the mid-1950s, but the flux was too low to be commercially viable. Two UCLA engineering graduate students, **Sidney Loeb** and **Srinivasa Sourirajan**, made that process possible. The pair created the first practical RO membrane using cellulose acetate. They filed for a patent on the new membrane in 1960.

Srinivasa Sourirajan is known as the "Father of Reverse Osmosis". Prof. Sourirajan has been nominated three times for the Nobel Prize. His research studies were not only novel, but also very creative and even visionary.

Semi-permeable membrane is the heart of RO process

Efficacy is evaluated based on the

- Flux across the membrane
- Salt rejection

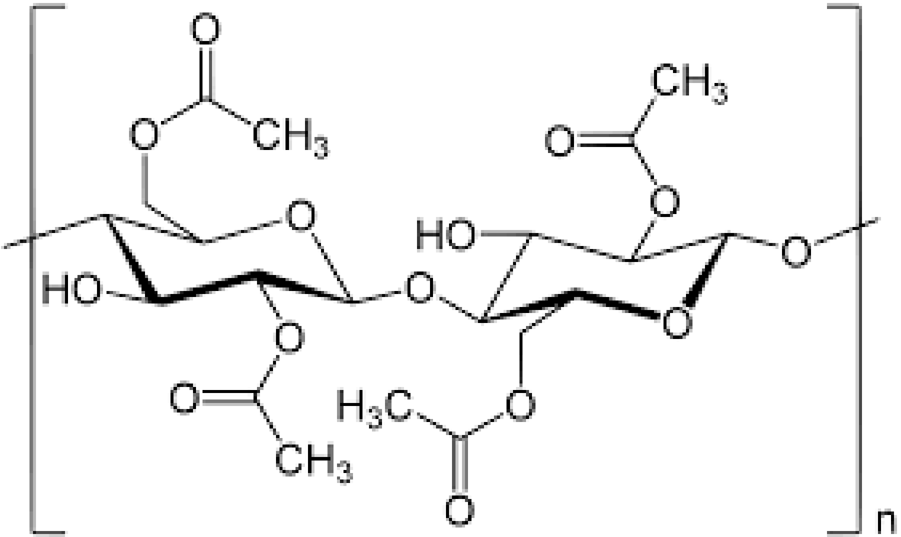
Asymmetric cellulose acetate membrane was developed first by Loeb and Sourirajan in 1963 for RO use

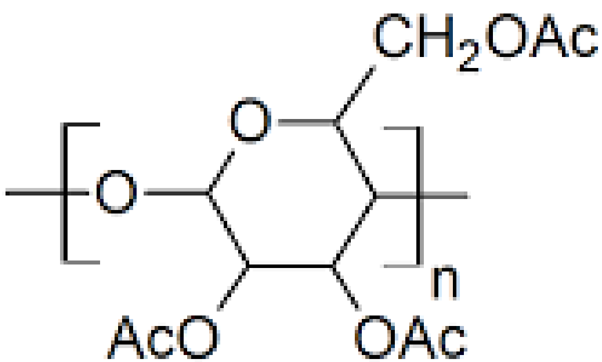
Cellulose Acetate (CA) is prepared by acetylation of cellulose and the degree of acetylation varies between 0 – 3.

Higher degree of acetylation leads to a membrane with high salt rejection and low permeate flux

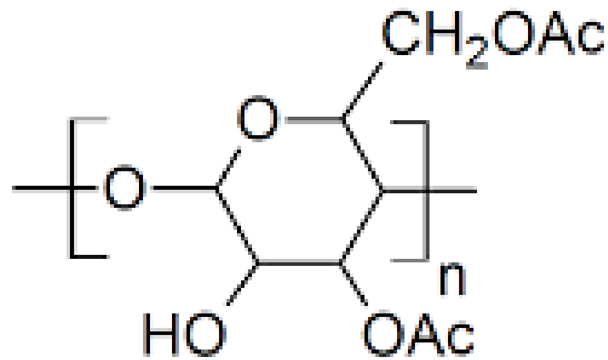
Lower acetylation leads to inferior salt rejection with higher permeate flux.

For commercial CA membrane, degree of acetylation is typically ~ 2.7





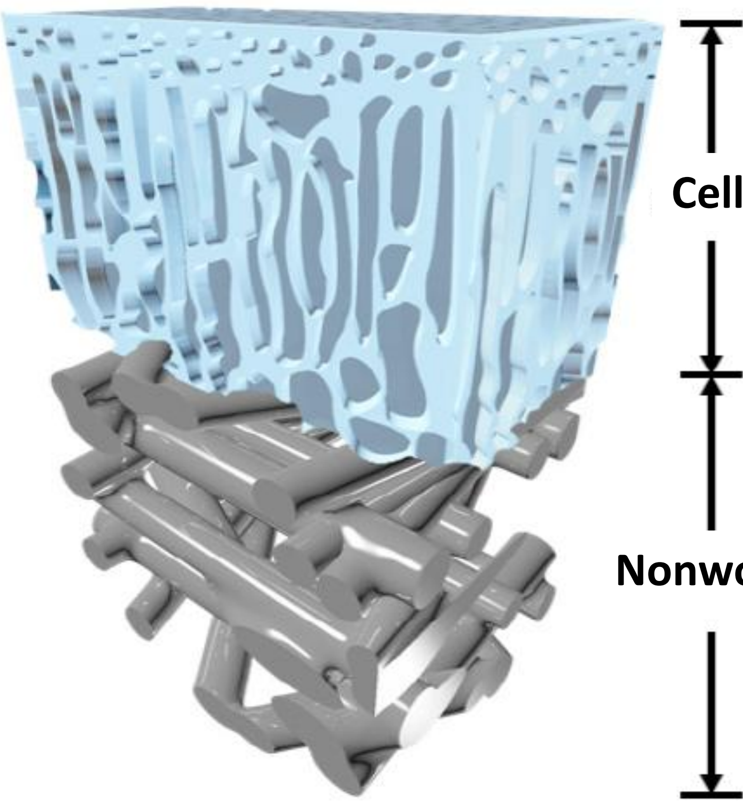
Cellulose Triacetate



Cellulose Diacetate

The middle porous structure was created by phase-inversion Method. The top skin layer of cellulose acetate membrane was generated by solvent evaporation to have a dense layer. This combination is used for the selective separation of water molecules and sodium/ chloride ions.

PET: Polyester (e.g., polyethylene terephthalate, PET) non-woven substrate to provide the mechanical strength. The middle and top layers are cellulose acetate fabricated by different approaches.



Phase inversion is a chemical phenomenon used for fabrication of artificial filtration membranes. Solvents are removed from a liquid-polymer solution, leaving a porous, solid membrane.

https://www.slideshare.net/9495094029/reverse-osmosis-based-desalination

Advantages:

Easy to make

Superior mechanical property/ strength

Resistant to chlorine

Disadvantages:

Tend to get hydrolyzed over time

Stable only at pH range 4 – 6.

Thermally labile

Membrane Type	CA based	Polyamide TFC
Feed (mg/L NaCl)	2000	2000
Pressure (psig)	425	225
Flux (GFD)	22	27
NaCl rejection (%)	97.5	99.5

***Source**:-fundamentals of membranes for water treatment, Alyson Sagle*

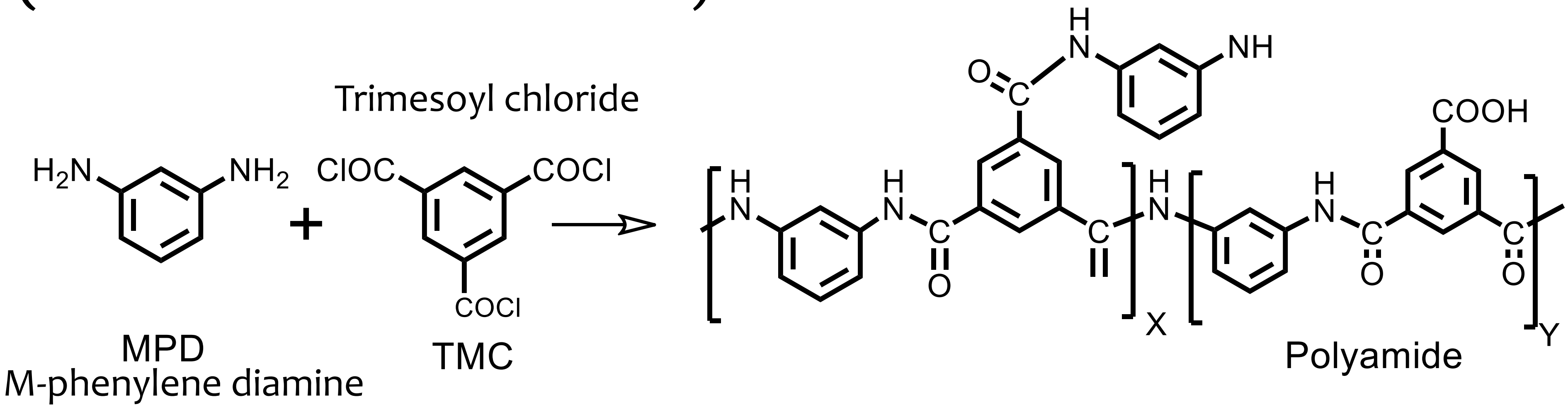
What is a TFC Membrane?

•**TFC membranes** are layered structures, typically made of:

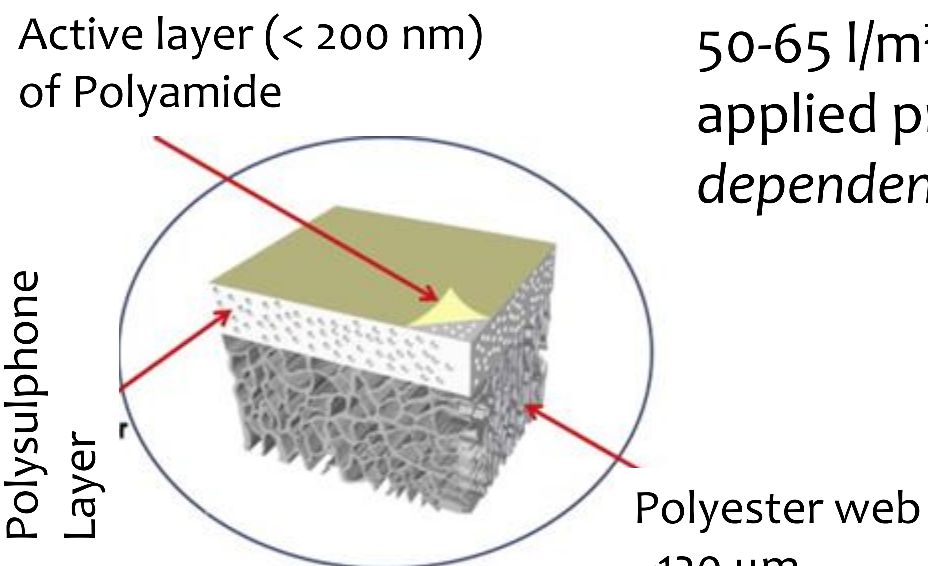
- A **polyamide thin film** (active layer)
- A **microporous polysulfone layer**
- A **polyester support fabric**

Used primarily for **RO filtration,** they are highly effective for desalination and wastewater treatment.

Thin Film Composite membranes (for Flat Sheet Membrane)



Membrane performance under BW condition: 50-65 l/m²hr, salt rejection 97-98% at 225-250 psi applied pressure……*feed water quality dependent*



Steps:

Ultrafiltration membrane casting on polyester fabric following phase separation method

Polyamide coating following *in situ* interfacial polymerization reaction

Polyamide layer in TFC membrane:

Polyamide membranes are renowned for their exceptional salt rejection performance, often achieving rates exceeding 99%. This high selectivity is primarily due to the dense, highly cross-linked polyamide layer, which minimizes pore size and enhances ion exclusion. At the same time, these membranes offer high water permeability, enabling efficient throughput during filtration. The optimized balance between selectivity and permeability is a hallmark of polyamide thin-film composite (TFC) membranes, making them a preferred choice in reverse osmosis and other advanced water treatment applications.

In a Thin-Film Composite (TFC) membrane, the polysulfone (PSf) layer acts as a porous support structure. It provides mechanical strength and stability to the overall membrane, especially under pressure. The PSf layer is typically made via phase inversion, creating a porous structure that allows for water or other permeate to pass through while supporting the thin, selective polyamide (PA) layer on top.

Role of the Polysulfone Layer in a TFC Membrane:

- ✓ Microporous Support Structure: The polysulfone layer provides mechanical strength and structural support to the ultra-thin, selective polyamide top layer, which is otherwise too fragile to function alone. Its microporous architecture allows water to pass through freely without offering significant resistance.
- ✓ Permeability Facilitator: The porous structure ensures minimal interference with water flux, enabling high permeability while maintaining the integrity of the membrane.
- ✓ Chemical and Thermal Stability: Polysulfone is known for its excellent chemical resistance, especially to oxidants and organic solvents, and for maintaining dimensional stability under elevated temperatures and pressure conditions.
- ✓ Substrate for Polyamide Layer Formation: During the interfacial polymerization process, the polyamide active layer is formed on top of the polysulfone layer. The PSf layer provides the ideal surface morphology and chemical compatibility for this reaction to occur effectively.
- ✓ Intermediate Layer Between Polyester and PolyamideThe polysulfone acts as a functional bridge between the porous polyester base layer (for overall mechanical stability) and the selective polyamide layer (for salt rejection).

In the context of membranes, convective flow refers to the transport of fluid (pure solvent or solution) across a porous membrane, which is driven by the applied pressure. Convective transport is the main mode of transport in microfiltration and ultrafiltration processes; it may also contribute to the transport in diffusion dialysis if the pressure is applied.

[Encyclopaedia of Membranes; doi.org/10.1007/978-3-642-40872-4_1994-1]