Water

Figures current as of October 2026

Where fresh water comes from and how much there is, the aquifers, rivers, and climate that decide its future, the systems that deliver it, its economics and politics, and the crises of the drought decade.

MODULE 1 — Foundations: The Water Cycle and the Numbers

Goal: Establish how much water exists, how much is usable, and who uses it.

The stock and the flow, withdrawals by sector and by country, virtual water, the two measures of stress and scarcity, and why scarcity is local when abundance is global.

MODULE 2 — Where Clean Water Comes From

Goal: Follow water from source to tap and back.

Surface water and groundwater, the treatment train with its costs, distribution and the leaks, wastewater, and who had safe water in 2024.

MODULE 3 — Groundwater: The Invisible Reserve

Goal: Cover the resource being drawn down fastest.

The great aquifers in a table, what satellites and 170,000 wells show, subsidence and intrusion, fossil water, and the few governance models.

MODULE 4 — Climate Change and the Water Cycle

Goal: Explain how warming is rearranging where and when water arrives.

The intensified cycle, glaciers and snowpack, the Colorado worked through its 2026 decision, drought and flood elsewhere, and the projections.

MODULE 5 — Europe's Rivers in 2026

Goal: Examine the drought summer as a case study, with the gauge data.

The Rhine's record low and the other gauges, the corridor from the Rhine to the Danube, power, shipping, and industry, and what 2018, 2022, and 2026 revealed together.

MODULE 6 — Hydropower and Its Problems

Goal: Assess the largest renewable and its exposure to drought.

Capacity by country, the drought episodes in a table, methane, sediment, displacement, downstream conflict, dam safety, and pumped storage.

MODULE 7 — Water Conflicts and Geopolitics

Goal: Map the shared rivers where scarcity becomes strategy.

The contested basins in a table, the Indus after India's 2025 abeyance and the 2026 award, the Aral Sea, and water as a weapon from Kakhovka to the Gulf's desalination plants.

MODULE 8 — The Cost of Water

Goal: Explain what water costs to produce and what it is priced at.

Source costs, what households pay in a table, the underpricing problem, the infrastructure gap, and affordability worked.

MODULE 9 — The Water Industry

Goal: Profile the companies and models that deliver water.

Public and private models, the argument over private ownership, the utilities in a table, Thames Water's crisis, the equipment makers, and water as an asset.

MODULE 10 — Desalination

Goal: Analyze the technology turning seawater into supply.

Thermal versus reverse osmosis, capacity by country, the cost history, brine, the 2026 attacks on Gulf plants, and the limits.

MODULE 11 — Bottled, Packaged, and Filtered Water

Goal: Analyze the business of selling water by the liter.

The market by country, the companies and Nestlé's 2026 sale of half its waters business, the economics worked, the critiques, sachets and kiosks, and home filtration.

MODULE 12 — Agriculture: The Largest Use

Goal: Give the largest use its own module.

Irrigation methods and their efficiency, the water inside food, virtual-water trade, the reallocations from farms to cities, and the Saudi alfalfa case.

MODULE 13 — Industry, Energy, and Data Centers

Goal: Explain the water-energy nexus and the newest demand.

Cooling power plants, fracking, mining, and chipmaking; data centers' water with the companies' 2025 figures; and the energy inside water.

MODULE 14 — Water Quality and Contamination

Goal: Cover what is in the water and the rules that govern it.

The contaminants in a table, Flint and its lead lines, PFAS and the argument over the 2026 rollback, and the developing world's sewer problem.

MODULE 15 — Floods, Stormwater, and Too Much Water

Goal: Cover the other half of the crisis.

Flood losses, the floods of 2021-26 in a table, defenses and the Dutch model, insurance's retreat, and managed retreat from Jakarta to the deltas.

MODULE 16 — Water Law, Rights, and Markets

Goal: Explain who is allowed to use water and how it is allocated.

The doctrines, transboundary law, the argument over water markets, the Murray-Darling market worked, and Chile's reform.

MODULE 17 — Reuse, Efficiency, and the Technology Frontier

Goal: Cover the solutions on the demand side.

Reuse leaders in a table, potable reuse, leaks and meters, Cape Town's Day Zero, managed recharge, and the cost ladder of new supply.

MODULE 18 — Six Regions

Goal: Profile the places where the crisis is already here.

The US West, India with Chennai's 2019 shortage, China, the Middle East and North Africa, Sub-Saharan Africa, and Latin America, each with its balance and its decision.

MODULE 19 — Where Things Stand, and What to Watch

Goal: Close with the argument, the turning points, and a dated watch list.

Demand and the projections, seven turning points and one lesson, five contradictions, the dates from October 2026 on, and a last word.

A note on the ground. Water is measured unevenly. Most countries do not meter groundwater, global totals rest on national reports made years apart, and the same word, use, can mean water withdrawn or water consumed. The course gives figures as the agencies publish them, names the source and release of each headline figure in the table before Module 1, and dates every figure that moves. Where the field argues, over private ownership of utilities, the 2026 rollback of American drinking-water limits, and markets in water rights, each side's case is put as its advocates make it, followed by the evidence. Figures are dated to October 2026.

Key Numbers, as of October 2026

The stocks, flows, prices, and records the course relies on

Measure	Figure	Period	Source and release
Fresh water withdrawn	About 4,000 cubic kilometers (km³) a year, or 3.2 billion acre-feet; agriculture 72%, industry 15%, municipal and household use 13%	Latest national data, 2023 shares	UN Food and Agriculture Organization (FAO): AQUASTAT, the FAO's global water database, and its Sustainable Development Goal (SDG) data portal (2025); UN *World Water Development Report 2026* (March 19, 2026)
Water stress, UN measure	17.6% of renewable supply withdrawn worldwide, after setting aside what rivers and wetlands need; 25 countries above 75%, home to about a tenth of humanity	2023; country count 2021	FAO, SDG indicator 6.4.2; UN-Water, *Progress on the Level of Water Stress* (2024)
Extreme stress, Aqueduct measure	25 countries, home to a quarter of humanity, withdraw 80% or more of their renewable supply in a typical year; about 4 billion people face high stress for at least a month a year	Baseline to 2019	World Resources Institute (WRI), Aqueduct 4.0 (August 2023)
Drinking water	74% of people have safely managed drinking water, up from 68% in 2015; 2.1 billion lack it, and 106 million drink untreated surface water	2024	World Health Organization (WHO) and UN Children's Fund (UNICEF) Joint Monitoring Programme (JMP) (August 26, 2025)
Sanitation and hygiene	3.4 billion lack safely managed sanitation, 354 million of them defecating in the open; 1.7 billion lack basic hygiene at home	2024	JMP (August 26, 2025)
Wastewater	56% of household wastewater safely treated, 332 billion cubic meters (m³)	2024	UN, *Sustainable Development Goals Report 2025*
Rivers and glaciers	One of the driest years for rivers in 35 years, with only 34-38% of basins near normal flow against 46% on average in 1991-2020; glaciers lost 408 billion tonnes, adding 1.1 millimeters to sea level	2025	World Meteorological Organization (WMO), *State of Global Water Resources 2025* (September 17, 2026)
Groundwater	Water tables falling more than 10 centimeters (4 inches) a year in 36% of 1,693 aquifer systems, and declines accelerating in 30% of the systems with long records	Records from 170,000 wells, mostly 2000-2022	Jasechko and colleagues, *Nature* (January 2024)
The Colorado River	Lake Mead at a record low of 1,037.60 feet; Lake Powell at 3,518.97 feet, just above its September 15 record of 3,516.62; Lower Basin use cut to 6.25 million acre-feet (MAF) a year for 2027-28	October 9, 2026; decision of August 21, 2026	US Bureau of Reclamation; Interior Department Record of Decision
The Rhine	4 centimeters (1.6 inches) at the Kaub gauge on September 24, the lowest since records began in 1880, and provisionally −3 cm on September 26; the previous record was 25 cm in October 2018	2026	German waterways administration, via Swissinfo (September 24, 2026)
Hydropower	1,469 gigawatts (GW) installed, including just over 200 GW of pumped storage, which pumps water uphill to store power; 28 GW added in 2025; about 14% of the world's electricity, roughly 4,480 terawatt-hours (TWh)	End of 2025	International Hydropower Association (IHA), *World Hydropower Outlook 2026* (June 24, 2026); Ember

Measure	Figure	Period	Source and release
Desalination	About 95 million m³ (25 billion US gallons) a day from nearly 16,000 plants, with about 1.5 liters of brine for every liter of fresh water; seawater and brackish capacity growing about 5.6% a year	2018 inventory; growth forecast for 2024-30	Jones and colleagues, *Science of the Total Environment* (2019); Global Water Intelligence (GWI) DesalData, via Oliver Wyman (December 2025)
Household prices	Denmark 88.46 kroner per m³ (about $13.60) for water and wastewater; England and Wales £639 a year (about $860) on average; US water and sewer bills up 5.1% in 2025; tariffs worldwide up 6.2% in the year to 2025	2025-27	DANVA, the Danish water utilities' association, *Vand i tal 2025*; Water UK (January 2026); Bluefield Research (March 2026); GWI tariff survey (September 2025)
Data centers	Google consumed 10.9 billion US gallons (41 billion liters), up 34%; Microsoft 8.2 billion liters, up 22%	2025; Microsoft's fiscal year to June 2025	Google Environmental Report (July 2026); Microsoft Environmental Data Fact Sheet 2026
US drinking-water rules	Limits of 4 parts per trillion (ppt) stand for two of the per- and polyfluoroalkyl substances (PFAS) called forever chemicals, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS); on May 18, 2026 the Environmental Protection Agency (EPA) proposed rescinding the limits for four others; lead service lines are due out by 2037 under a rule now in court	October 2026	EPA; US Court of Appeals for the D.C. Circuit
Cholera	614,828 cases and 7,598 deaths reported from 33 countries	2025	WHO (January 27, 2026)
Disaster losses	Natural catastrophes cost about $244 billion, $108 billion of it insured; floods, storms, and wildfires caused $166 billion	2025	Munich Re (January 13, 2026)
Water and violence	420 recorded incidents of violence over or involving water, up from 355 in 2023	2024	Pacific Institute, *Water Conflict Chronology*

A cubic meter (m³) is 1,000 liters, or 264 US gallons; a cubic kilometer (km³) is a billion m³, about 810,000 acre-feet. An acre-foot (AF), the unit of the American West, is 1,233 m³, roughly a year's water for two or three households. A tonne is 1.10 US short tons. Withdrawal is water taken from a source; consumption is the part not returned, lost to evaporation or built into crops and products. Prices convert at September 2026 averages (Federal Reserve): $1.15 per euro, $1.34 per pound, 6.50 kroner, 6.71 yuan, 95.5 rupees, and 5.14 reais to the dollar, and $0.71 per Australian dollar (A$).

Module 1 — Foundations

The Water Cycle and the Numbers

Recommended Reading / Reference

Book: Charles Fishman, *The Big Thirst: The Secret Life and Turbulent Future of Water* (2011)

Reference: UN *World Water Development Report 2026: Water for All People: Equal Rights and Opportunities* (March 2026); FAO AQUASTAT; WRI Aqueduct 4.0 (2023)

1a. The Stock and the Flow

Reservoir	Volume (thousand km³)	Share of all water	Residence time	Usable?
Oceans	1,338,000	96.5%	About 3,000 years	Only by desalination
Ice caps and glaciers	24,064	1.74%	Centuries to millennia	No, though their melt feeds rivers
Groundwater, fresh	10,530	0.76%	Decades to millennia	Yes: the largest usable store
Groundwater, saline	12,870	0.93%	Long	No
Ground ice and permafrost	300	0.02%	Long	No
Lakes, fresh	91	0.007%	Years to centuries	Yes
Soil moisture	16.5	0.001%	Weeks to months	Feeds crops as green water
Atmosphere	12.9	0.001%	About 9 days	Falls as rain and snow
Rivers	2.1	0.0002%	About 2 weeks	Yes: most city supply
All fresh water	About 35,000	2.5%		
Fresh lakes, rivers, soil, and air together	About 122	Under 0.01% (0.35% of fresh water)	Days to centuries	Supplies almost all human use

US Geological Survey (USGS), after Shiklomanov (1993). A cubic kilometer (km³) is a trillion liters, about 264 billion US gallons or 810,000 acre-feet.

The earth holds about 1.39 billion cubic kilometers of water, and almost none of it is available to use. About 97.5% is salt water, and of the 2.5% that is fresh, 69% is ice and 30% is groundwater. Less than 1% of the fresh water is in the rivers, lakes, soil moisture, and air that supply almost all human use.

The usable resource is therefore the flow rather than the stock: about 110,000-120,000 km³ of rain and snow fall on land each year, and plants and soils return about three-fifths to two-thirds of it to the air. The remaining 40,000-45,000 km³ runs off into rivers or soaks down into aquifers, and perhaps 12,500 km³ of that is within reach of people when and where they need it, on the estimate of Sandra Postel and colleagues.

Humanity withdraws about 4,000 km³ a year, roughly a third of that accessible flow, and the total has grown about 1% a year since the 1980s, according to the UN's *World Water Development Report*. Much of what is withdrawn returns to rivers and aquifers, so consumption, the part that evaporates or is built into crops and products and so leaves the local basin, is smaller, perhaps 1,500-2,000 km³ a year on most estimates.

1b. Who Uses It

Country	Renewable water per person (m³ a year)	Withdrawals per person (m³ a year)	Withdrawals as a share of renewable supply	Farming's share of withdrawals	Note
Canada	About 72,000	About 900	About 1%	About 10%	Abundance; much of it flows north, away from people
Brazil	About 41,000	About 320	About 1%	About 60%	The Amazon; São Paulo ran short in 2014-15 anyway
Russia	About 31,000	About 440	About 1%	About 20%	Siberian rivers flow to the Arctic
United States	About 8,800	About 1,200	About 15%	About 37%; power-plant cooling 41%	The Southwest uses nearly all it has
China	About 2,000	About 420	About 20%	About 62%	A dry north and a wet south
India	About 1,300	About 500	About 40%	About 90%	The world's largest user of groundwater
Egypt	About 490, nearly all from the Nile	About 650	About 135%, with reused drainage water and fossil groundwater	About 80%	Almost no rain of its own
Israel	About 180	About 230, desalinated and recycled water included	Above 100% of natural supply	About 55%	Desalination and reuse fill the gap
Saudi Arabia	About 70	About 680	About ten times its renewable supply	About 80%	Mined its fossil aquifers for wheat
Kuwait	About 4	About 250	Far above 100%	About half	Almost all drinking water desalinated
Germany	About 1,800	About 240	About 13%	About 3%	Withdrawals fell as coal and nuclear plants closed
Sub-Saharan Africa	About 4,000	About 100	About 3%	About 80%	Water exists; the pipes do not
World	About 5,200	About 490	About 9% of the runoff; a third of the accessible flow	72%	

Approximate. Renewable supply is FAO AQUASTAT's long-term average and withdrawals its latest national year, mostly 2015-2022, both divided by the UN's 2025 population estimates. A cubic meter (m³) is 264 US gallons. National averages hide stressed basins.

Agriculture takes 72% of the world's freshwater withdrawals, industry 15%, and municipal and household use 13%, on the FAO's 2023 figures, and farming's share passes 90% in poor, dry countries such as Pakistan and Afghanistan. The proportions surprise people who think of water in terms of showers: a person drinks two or three liters a day, under a gallon, but eats 2,000-5,000 liters (530-1,320 gallons) embedded in food.

That embedded water is called virtual water, the water it took to grow or make something. It crosses borders in grain, meat, cotton, and manufactured goods, so a water-poor country can import water by importing food. Water is also sorted by where it sits: blue water is in rivers, lakes, and aquifers, green water is rain held in the soil, which feeds most of the world's crops, and grey water is the volume needed to dilute pollution.

1c. Why Scarcity Is Local

There is enough fresh water on earth for everyone, but it is in the wrong places at the wrong times. Canada, Brazil, and Russia hold a large share of the world's runoff and use little of it, while the Middle East, North Africa, northern China, northern India, Mexico, and the American Southwest hold little and use nearly all of it.

Rain falls in monsoons and snow melts in spring floods while demand stays steady, so storage in reservoirs, snowpack, and aquifers is what turns a flow into a supply. Water is also heavy and cheap: a cubic meter weighs a tonne, 1.1 US short tons, and sells for a dollar or two, so it cannot be shipped far the way oil is, and every water problem is regional.

The course uses two measures. The first, water stress, comes in two versions that differ: WRI's compares withdrawals with renewable supply basin by basin, calling 40% high and 80% extremely high, and on that count 25 countries holding a quarter of humanity, India among them, are extremely stressed. The UN's measure first sets aside the water rivers and wetlands need, and it put the world at 17.6% in 2023, with about a tenth of humanity in countries above 75% in 2021.

The second measure is water per person, for which the Swedish hydrologist Malin Falkenmark set stress below 1,700 m^3 a year, scarcity below 1,000, and absolute scarcity below 500. Egypt, Israel, Saudi Arabia, and Kuwait sit below the last line, and India, at about 1,300, sits between the first two.

Module 1 Key Points

Foundations

• The earth holds 1.39 billion km³ of water; under 1% of the fresh part is the surface water that supplies almost all use.

• The usable resource is the flow: 40,000-45,000 km³ runs off each year, and perhaps 12,500 km³ is within reach.

• Humanity withdraws about 4,000 km³ a year; agriculture takes 72%, industry 15%, and households and cities 13%.

• Renewable water per person runs from about 72,000 m³ a year in Canada to about 4 in Kuwait.

• Scarcity is local: a cubic meter weighs a tonne and sells for a dollar or two, so water cannot be shipped far.

• On WRI's count, 25 countries holding a quarter of humanity withdraw 80% or more of their renewable water.

Module 1 Quiz

Check Your Understanding

1. Of the earth's fresh water, what share is in rivers, lakes, soil moisture, and the air?

A) About 30%
B) About two-thirds
C) About 10%, most of it in the world's great lakes
D) Under 1%, though it supplies almost all use

2. Why does the module treat the flow rather than the stock as the usable resource?

A) Because most of the stock is salt water, ice, or deep groundwater
B) Because the flow is larger than the stock
C) Because the stock is falling by about 1% a year as aquifers are drawn down
D) Because most fresh water is in lakes that are too polluted to drink

3. On the FAO's 2023 figures, how are the world's freshwater withdrawals divided?

A) Households 50%, industry 30%, farms 20%
B) Industry 45%, agriculture 40%, households 15%
C) Agriculture 72%, industry 15%, municipal and household use 13%
D) Agriculture 40%, power plants 40%, households 20%

4. What is virtual water?

A) Rain held in the soil that feeds most of the world's crops
B) Water embedded in traded food and goods
C) Water from desalination plants, sold to ships and islands
D) Water lost from city pipes before it reaches a customer's meter

5. Why is every water problem regional, according to the module?

A) Water is heavy and cheap, so it cannot be shipped far
B) Treaties forbid moving water across borders
C) Most rivers stay within one country
D) Pipelines lose most of their water to evaporation over long distances

Module 2 — Where Clean Water Comes From

From Source to Tap and Back

Recommended Reading / Reference

Reference: WHO/UNICEF JMP, *Progress on Household Drinking Water, Sanitation and Hygiene 2000-2024* (August 2025); American Water Works Association (AWWA), *Water Treatment Plant Design*; Liemberger and Wyatt, 'Quantifying the Global Non-Revenue Water Problem' (2019)

2a. Sources

City water comes from two main places, and the first, surface water from rivers, lakes, and reservoirs, supplies most large cities: New York draws from Catskill and Delaware reservoirs, London from the Thames, and Los Angeles by aqueduct from the Sierra Nevada and the Colorado River. It is plentiful where it exists, varies with the seasons, and is exposed to whatever happens upstream.

Groundwater, pumped from aquifers through wells, provides about half of the water people use at home, including the drinking water of most rural people. The rock it sits in filters it, and it stays steady across seasons, but it recharges slowly, which makes it both the more reliable source and the more easily exhausted (Module 3).

Two newer sources are growing: desalinated seawater supplies about 1% of the world's withdrawals but most of the Gulf's drinking water (Module 10), and recycled wastewater is small but expanding fastest in dry cities (Module 17).

2b. The Treatment Train

Step	What it does	Cost ($/m³, typical)	Notes
Screening and intake	Removes debris, fish, and weeds	Under 0.01	
Coagulation and flocculation	Aluminum or iron salts make suspended particles clump	0.01-0.03	The chemistry step
Sedimentation	Clumps settle in basins	0.01-0.02	Hours of residence
Filtration	Sand, gravel, anthracite, or membranes remove what remains	0.02-0.05 (sand); 0.05-0.15 (membrane)	Membranes stop parasites such as Cryptosporidium
Disinfection	Chlorine, chloramine, ozone, or ultraviolet light kill pathogens	0.01-0.03	Helped end waterborne cholera and typhoid; residual chlorine protects the pipes
Advanced treatment, where needed	Activated carbon, ion exchange, advanced oxidation, or reverse osmosis remove PFAS, pesticides, drugs, and salts	0.05-0.50	Needed at thousands of US utilities to meet the 2024 limits on PFOA and PFOS
Corrosion control, pH, fluoride	Orthophosphate coats old pipes so lead does not leach; fluoride protects teeth	Under 0.01	The step Flint skipped (Module 14)
Total treatment		0.05-0.25 conventional; up to 0.80 with advanced steps	The pipes cost far more than the treatment

Approximate. A cost of $0.10 per m³ is about 0.04 cents per US gallon.

Raw water becomes drinking water through a sequence that is a century old and still standard: coagulation, sedimentation, filtration, and disinfection. Filtration and then chlorination, used in the United States from 1908, ended the waterborne typhoid and cholera that had killed city dwellers into the twentieth century, and chlorination did more for city life expectancy than any other public-health measure.

Newer steps answer newer threats: activated carbon and advanced oxidation remove pesticides and pharmaceuticals. Since the United States set limits in 2024 on six forever chemicals, two of which the EPA now proposes to keep, utilities have been adding carbon, ion exchange, and reverse osmosis, which forces water through salt-blocking membranes (Module 10). The whole train costs a few cents to a few dimes per cubic meter, and the pipes that deliver the result cost far more.

2c. Distribution and the Leaks

City or system	Non-revenue water (leaks, theft, and unbilled use)	Pipes	Note
Tokyo	About 3%	Aggressively replaced and metered	The world's benchmark
Singapore	About 5%	Modern	Leak detection and full pricing
Berlin	About 4-5%	Renewed	
Copenhagen	About 7%	Renewed	High tariffs pay for it
London (Thames Water)	About a fifth to a quarter	Victorian mains	Roughly 570 million liters (150 million gallons) a day lost
United States (average)	About 15-20%	Many mains past their design life	About 6 billion gallons a day lost, on the 2021 estimate of the American Society of Civil Engineers (ASCE)
Mexico City	About 40%	Cracked by subsidence	The ground sinks under the pipes
Johannesburg	About 40-45%	Neglected	Repeated outages since 2023
Lagos, Nairobi, Karachi	About half	Informal connections common	Half the supply never reaches a meter
World	About 30%		126 billion m³ a year, worth about $39 billion

Approximate; utilities, the International Water Association, and Liemberger and Wyatt (2019).

Treated water travels through networks that are the largest and oldest capital asset most cities own, much of it laid a century ago and much of it leaking. Water that is treated but never billed, called non-revenue water, averages about 30% worldwide, or 126 billion cubic meters a year. Tokyo has driven its losses to about 3%, while London loses roughly a fifth, Mexico City 40%, and many cities in poor countries half.

What goes down the drain flows to wastewater treatment, where it is screened, settled, digested by bacteria, and disinfected before it returns to a river or, increasingly, is reused. On the UN's count, 56% of household wastewater was safely treated in 2024, so nearly half still reaches rivers and seas without proper treatment, and in many cities the sewer is the river.

2d. Who Has It

Service level	2015	2024	People without it in 2024	Note
Safely managed drinking water (on the premises, available when needed, free of contamination)	68%	74%	2.1 billion	Rural coverage rose from 50% to 60%
Untreated surface water as the main drinking source			106 million	Rivers, ponds, and canals
Safely managed sanitation	48%	58%	3.4 billion	Waste safely contained and treated or disposed of
Open defecation			354 million	The bottom rung
Basic hygiene (soap and water at home)	66%	80%	1.7 billion	611 million with no facility at all

WHO/UNICEF JMP (August 26, 2025); UN, Sustainable Development Goals Report 2025.

In 2024, 74% of the world's people had safely managed drinking water, up from 68% in 2015, according to the Joint Monitoring Programme of the WHO and UNICEF. That still leaves 2.1 billion people without it, among them 106 million who drink untreated water from rivers, ponds, and canals. Coverage is lowest in Sub-Saharan Africa, at about a third of people, and in fragile and conflict-affected countries, where it runs 38 percentage points below the rest.

Sanitation lags further: 3.4 billion people lack safely managed sanitation, and 354 million defecate in the open. The program's August 2025 report judged that universal safely managed services by the UN's 2030 deadline appear increasingly out of reach. The WHO once put the cost of the gap at about $260 billion a year in lost work, schooling, and health, a 2012 estimate.

Access is, in the end, an infrastructure and governance problem more than a hydrological one. The water usually exists, while the pipes, the treatment plants, and the institutions that pay for them do not.

Module 2 Key Points

Where Clean Water Comes From

• Surface water supplies most big cities; groundwater provides about half of household water and most rural drinking water.

• Treatment costs $0.05-0.25 per m^3; chlorination, used from 1908, did more for city life expectancy than any other measure.

• About 30% of treated water is lost or unbilled worldwide, from Tokyo's 3% to half in many poor cities.

• Only 56% of household wastewater was safely treated in 2024, so nearly half reaches rivers and seas untreated.

• 74% of people had safely managed drinking water in 2024, up from 68% in 2015; 2.1 billion still lacked it.

Module 2 Quiz

Check Your Understanding

1. About how much of the water people use at home comes from groundwater?

A) Nearly all of it, everywhere
B) About half, and most rural supply
C) About a tenth, mostly in the largest cities
D) Very little, because aquifers are too polluted to drink

2. Which treatment step did more for city life expectancy than any other?

A) Sedimentation in settling basins
B) Filtration through sand and gravel
C) Coagulation with aluminum salts
D) Disinfection, chiefly chlorination, from 1908 in the United States

3. How do Tokyo's and London's water losses compare?

A) Tokyo about a quarter; London about 3%
B) Both lose about 30%, the world's average
C) Tokyo about 3%; London about a fifth
D) Both lose under 5%, thanks to modern meters

4. What share of household wastewater was safely treated in 2024, on the UN's count?

A) About 90%, as in Europe
B) About a fifth, mostly in China
C) About 56%
D) Almost none outside the rich countries

5. Why does the module call access an infrastructure and governance problem more than a hydrological one?

A) Because most of the world's water is contaminated
B) Because treatment costs more than most cities can pay
C) Because rainfall has fallen in every region
D) Because the water usually exists, but the pipes, treatment, and institutions do not

Module 3 — Groundwater

The Invisible Reserve

Recommended Reading / Reference

Reference: Jasechko and colleagues, 'Rapid groundwater decline and some cases of recovery in aquifers globally' (*Nature*, January 2024); the Gravity Recovery and Climate Experiment (GRACE) satellite studies (Famiglietti and others); USGS reports on the High Plains aquifer; California's State Water Resources Control Board on groundwater probation

3a. What an Aquifer Is

An aquifer is not an underground lake but a layer of porous rock, gravel, or sand saturated with water, more like a sponge than a bathtub. Rain filtering down from the surface recharges it slowly while springs, rivers, and wells drain it, and shallow aquifers recharge in years where deep ones take centuries or millennia.

Fossil aquifers under the Sahara and Arabia hold water that fell when the climate was wetter, more than ten thousand years ago, and it will not be replaced. Groundwater is 30% of all fresh water and about 99% of the liquid fresh water not locked in ice.

Because it is invisible, unmetered in most of the world, and often governed by rules that let landowners pump what lies beneath them, groundwater has been the resource of last resort in every drought, pumped hardest exactly when it recharges least.

3b. The Great Aquifers

Aquifer	Where	Area and storage	Trend	What it supports	Status (2026)
Ogallala (High Plains)	Eight US states, South Dakota to Texas	450,000 km² (174,000 square miles); about 3,900 km³ before pumping	Down about 9% overall by 2015; levels more than 150 feet (46 m) lower in parts of Kansas and Texas	Irrigated corn, wheat, cotton, and cattle feed	Depleting; Kansas districts cap pumping
Indus basin	Pakistan and India (Punjab, Haryana)	Tens of thousands of km²	Water tables falling 0.5-1 meter (2-3 feet) a year in parts	Wheat, rice, and cotton for hundreds of millions	Critical; millions of wells on cheap power
North China Plain	Hebei, Henan, Shandong, Beijing	Shallow and deep aquifers	Shallow water table at a record depth in 2019, then rising, back to 2005 levels by 2024	Half of China's wheat; Beijing and Tianjin	Recovering after pumping limits and the South-North transfer
Central Valley	California	About 50,000 km²	Ground sank up to about 8.5 meters (28 feet) in the twentieth century; pumped hardest in the 2012-16 and 2020-22 droughts	A quarter of US food by value	Two subbasins on state probation
Guarani	Brazil, Argentina, Paraguay, Uruguay	1.2 million km²; about 37,000 km³	Stable; local declines	Cities including parts of São Paulo state	Shared by treaty (2010)

Aquifer	Where	Area and storage	Trend	What it supports	Status (2026)
Nubian Sandstone	Libya, Egypt, Chad, Sudan	2 million km²; about 150,000 km³ of fossil water	Mined, not recharged	Libya's Great Man-Made River, built to draw about 6.5 million m³ (1.7 billion gallons) a day	Non-renewable
Arabian (Saq, Wasia)	Saudi Arabia, Jordan, Iraq	Fossil	Largely exhausted by wheat irrigation in the 1980s-2000s	Once Saudi wheat	Depleted; grain is imported
Iran's central basins (Tehran, Isfahan, Mashhad)	Iran	Many basins	Parts of the central plateau sinking more than 35 cm (14 inches) a year	Most of Iran's water	Critical; moving the capital discussed
Valley of Mexico	Mexico City	Overdrawn	Parts of the city sinking up to 50 cm (20 inches) a year	About 22 million people	Critical; surface reservoirs refilled in 2025-26
European aquifers	Spain, France, Germany, Italy's Po valley	Many	Declining in parts after the droughts of 2018-26	River flow in dry summers	Under watch

USGS; GRACE studies; China's Ministry of Water Resources via Caixin (June 2026); California State Water Resources Control Board (April 2026). Approximate.

3c. What the Satellites and the Wells Show

Since 2002 the twin GRACE satellites and, from 2018, their successor GRACE-FO have measured the earth's gravity precisely enough to weigh the water underground. They showed northern India losing groundwater faster than almost anywhere, to tens of millions of wells irrigating the crops that feed the country. They also showed the North China Plain, Iran, the Middle East, and California's Central Valley draining.

In January 2024 a study in *Nature* by Scott Jasechko and colleagues combined records from about 170,000 wells in more than 40 countries. Water tables were falling more than 10 centimeters (4 inches) a year in 36% of the 1,693 aquifer systems studied, more than 50 centimeters a year in 12%, and the decline was accelerating in 30%.

The same study found recoveries where policy changed, and Chinese data since show one of the largest, on the North China Plain. Hebei began capping pumping in 2014, the South-North Water Transfer began delivering Yangtze water the same year, and a national plan followed in 2019. By 2025 overdrawn groundwater had fallen 85.8% from 2015, and the shallow water table, at a record average depth of 14 meters in 2019, had risen back to its 2005 level by 2024.

Recovery has costs of its own: Beijing's subways recorded 2,214 leaks in 2022, up from 847 in 2019, as groundwater rose around tunnels built when it was low, and buildings now need anchors against the uplift.

3d. The Consequences

- **Subsidence:** as water is withdrawn, clay layers compact and the ground sinks, permanently shrinking the aquifer and cracking roads, canals, and buildings. Jakarta, Mexico City, and Tehran are sinking by centimeters a year.

• **Saltwater intrusion:** pumping near a coast draws seawater into the aquifer and ruins wells, from Florida to Bangladesh to the Gaza Strip, whose aquifer is almost entirely unfit to drink.

• **Dry rivers and wetlands:** groundwater feeds rivers' dry-season flow, so pumping dries the streams and springs that depend on it long before the wells fail.

• **Fossil water mined:** Saudi Arabia pumped fossil aquifers to grow wheat in the desert, ended the program in 2016, and now imports grain and grows fodder abroad, including in Arizona, where the state ended a Saudi-owned farm's lease in 2024 and sued over its pumping (Module 12).

• **The equity problem:** deeper wells cost more, so as water tables fall the richer farmers drill deeper and the poorer ones go dry.

3e. Managing It

Groundwater governance is where water policy is weakest: most countries do not meter it, and India subsidizes the electricity that pumps it. The American rule that a landowner may pump what lies beneath, called the rule of capture, has produced a race to the bottom in every shared aquifer where it applies.

Among the few recent reforms, California's Sustainable Groundwater Management Act (SGMA) of 2014 requires overdrawn basins to reach balance by about 2040, and the Public Policy Institute of California expects at least 500,000 acres (2,000 km²) of San Joaquin Valley farmland to leave production. Two basins are on state probation, the Tulare Lake subbasin since April 2024 and the Tule subbasin since September 2024, and their pumpers must report their pumping and pay $300 a well and $20 an acre-foot.

Arizona has regulated pumping in its active management areas since 1980, though most of its rural land lies outside them. Managed aquifer recharge, which spreads or injects surplus surface water to refill aquifers, is spreading (Module 17), and Australia and parts of Europe cap and price groundwater. The resource that carries the world through drought is the one it manages least.

Module 3 Key Points

Groundwater

• An aquifer is saturated porous rock, a sponge rather than a lake; fossil aquifers under the Sahara and Arabia will never refill.

• Groundwater holds about 99% of the liquid fresh water not locked in ice, and droughts make it the resource of last resort.

• In a 2024 study of 170,000 wells, water tables fell over 10 cm a year in 36% of aquifer systems.

• The North China Plain shows recovery: after pumping caps and Yangtze water, its shallow water table regained 2005 levels by 2024.

• Pumping brings subsidence, salt intrusion, dry rivers, and an equity race in which deeper wells favor the rich.

• California's 2014 law requires balance by about 2040; two basins have been on state probation since 2024.

Module 3 Quiz

Check Your Understanding

1. What is an aquifer?

A) A layer of porous rock, gravel, or sand saturated with water
B) An underground lake filling a cavern
C) A reservoir held behind a dam
D) A river's floodplain, refilled each spring by the overflowing river channel

2. What did the 2024 study of 170,000 wells find?

A) Levels rising in most of the world's aquifers
B) Levels falling over 10 cm a year in 36% of systems
C) No clear trend, because records were too short to compare
D) Declines confined to the Middle East and North Africa, nowhere else

3. What has happened to the North China Plain's shallow groundwater since 2019?

A) It fell further
B) It dried up completely across Hebei province
C) It turned saline as seawater moved inland from the Bohai Sea
D) It has risen, back to 2005 levels by 2024

4. What is subsidence?

A) Ground sinking as pumped aquifers compact
B) Seawater pushing inland into coastal wells as they are pumped
C) The slow natural refilling of an aquifer by rain
D) A drop in a river's flow when nearby wells draw it down

5. What does California's 2014 groundwater law require, and where does it stand in 2026?

A) A ban on new wells statewide, enforced from 2015
B) Meters on every well, with no limit on what is pumped
C) Balance by about 2040; two subbasins, Tule and Tulare Lake, are on state probation
D) State purchase of all farmland over an overdrawn aquifer

Module 4 — Climate Change and the Water Cycle

How Warming Is Rearranging Where and When Water Arrives

Recommended Reading / Reference

Reference: Intergovernmental Panel on Climate Change (IPCC), *Sixth Assessment Report*, water cycle chapter (2021); WMO, *State of Global Water Resources 2025* (September 2026); Congressional Research Service, 'Responding to Drought in the Colorado River Basin' (updated August 2026); Global Commission on the Economics of Water (October 2024)

4a. An Intensified Cycle

Warmer air holds about 7% more water vapor for each degree Celsius (1.8°F) of warming. The consequence is not simply more or less rain but a more violent cycle: more evaporation from soils and reservoirs, longer and hotter droughts where it is dry, and heavier downpours where it rains, often in the same place in the same year.

Wet regions are generally getting wetter and dry ones drier: the Mediterranean, southwestern North America, southern Africa, and southern Australia are drying most, storm tracks are shifting toward the poles, and rain is arriving in fewer, larger storms that run off rather than soak in.

The World Meteorological Organization (WMO) found 2025 one of the driest years for the world's rivers in 35 years, with only 34-38% of river basins near normal flow, against an average of 46% in 1991-2020. It was the seventh year running in which most basins were abnormally high or low, and Europe's drought summer of 2026 is the latest exhibit (Module 5).

4b. Ice and Snow

Nearly two billion people depend on water stored as ice and snow: glaciers act as reservoirs that release water in the dry season, and the Himalaya and Hindu Kush, sometimes called the third pole, feed the Indus, Ganges, Brahmaputra, Mekong, Yangtze, and Yellow rivers.

As glaciers melt they release more water at first, a temporary abundance that masks the loss, and then less, permanently. The world's glaciers lost 408 billion tonnes of ice in 2025, the fourth year running of widespread loss across all regions, on the WMO's count. Switzerland's lost 24% of their volume in the decade to 2025, and the tropical glaciers of the Andes that supply Lima and La Paz may be largely gone within decades.

Snowpack stores winter precipitation and releases it in spring, and it is shrinking as more precipitation falls as rain, which runs off in winter when it is not needed and leaves summers dry. The American West, the Alps, and Central Asia all face the shift, and reservoirs designed for a snowmelt calendar are the wrong shape for a rain one.

4c. The Colorado, Worked

The American Southwest is the case study: the Colorado River supplies about 40 million people and about 5 million acres (20,000 km²) of farmland in seven states and Mexico. It has been in a megadrought since

2000, the driest 22-year stretch in at least 1,200 years of tree-ring records on one widely cited reconstruction (Williams and colleagues, 2022).

Worked example — The Colorado's Arithmetic

The 1922 Colorado River Compact divided 15 million acre-feet (MAF) a year, about 18.5 km³, between the Upper Basin (Colorado, Wyoming, Utah, New Mexico) and the Lower Basin (California, Arizona, Nevada). A 1944 treaty promised Mexico another 1.5 MAF, for 16.5 MAF in all. The river averaged about 14.6 MAF a year from 1906 to 2024 and only 12.4 MAF from 2000 to 2024, according to the Congressional Research Service. Promising 16.5 MAF against a supply of 12.4 leaves a gap of about 4 MAF a year, a quarter of the water promised and a third of the river's flow, and for two decades it was covered by draining Lakes Mead and Powell, which hold about 50 MAF when full. In mid-2026 the system was about 36% full. Water year 2026 was among the worst on record: the spring inflow forecast for Lake Powell in May was about 0.8 MAF, 13% of average, below the previous low of 2002. Lake Powell fell to a record 3,516.62 feet on September 15, 2026, and on October 9 Lake Mead stood at 1,037.60 feet, below its 2022 record. Each 1 MAF of cuts is roughly 150,000-200,000 acres of irrigated alfalfa, or the household use of 5-8 million people.

The rules that governed shortages since 2007 expire at the end of 2026, and the seven states failed to agree on their successor, so on August 21, 2026 the Interior Department decided for them. Its record of decision sets a framework through 2036 and operating rules for 2027-28 that cut Lower Basin use to 6.25 MAF a year, 1.25 MAF below the normal 7.5.

Under the decision Arizona's share falls 27.1% to 2.04 MAF, California's 10% to 3.96 MAF, and Nevada's 16.7% to 250,000 acre-feet, with at least 700,000 acre-feet of further conservation required. Glen Canyon Dam's release can fall to 5.0 MAF if Lake Powell is projected below 3,500 feet, and Mexico's share is being negotiated separately. Nevada and its water agencies sued in federal court on August 24, 2026.

4d. Drought and Flood Elsewhere

The pattern repeats elsewhere: multi-year droughts in the Mediterranean, southern Africa, the Horn of Africa, southern Brazil, Iran, and Iraq, alternating with floods that the infrastructure of the last century was not built for (Module 15). Pakistan's 2022 floods put a third of the country under water, Libya's Storm Daniel broke two dams above Derna in 2023, and a glacier collapse in Nepal's Langtang valley in August 2026 killed at least 1,455 people.

Sea-level rise adds a coastal dimension, pushing salt water into deltas and aquifers from the Nile to the Mekong to Bangladesh, where it is already ruining farmland.

4e. The Projections

Source	Projection	Horizon
WRI, Aqueduct 4.0 (2023)	25 countries holding a quarter of humanity face extremely high water stress now; about another billion people by 2050; 31% of world output, about $70 trillion, exposed to high stress	2050
Global Commission on the Economics of Water (October 2024)	Without action, more than half of world food production is at risk, in areas where water storage is projected to decline; output losses of about 8% in high-income countries and up to 15% in poorer ones	2050
UN *World Water Development Report*	Global water use, rising about 1% a year since the 1980s, keeps rising at a similar pace	2050
IPCC, *Sixth Assessment Report* (2021-22)	More intense rainfall extremes nearly everywhere; more land in drought with each degree of warming; glacier-fed rivers peak and then decline this century	2050-2100
WMO (September 2026)	2025 one of the driest years for rivers in 35 years; glaciers lost 408 billion tonnes	Now
World Bank, *High and Dry* (2016)	Water scarcity could cost some regions up to 6% of output by 2050	2050

The water cycle is not running out of water but becoming less predictable, and every system that depends on it, from reservoirs and crops to cities and treaties, was built on the assumption that the past was a guide to the future.

Module 4 Key Points

Climate Change and the Water Cycle

• Warmer air holds about 7% more vapor per degree Celsius, so droughts run hotter and downpours heavier.

• Glaciers lost 408 billion tonnes in 2025; melt rises at first, then falls for good as the ice runs out.

• The Colorado's users are promised 16.5 MAF a year, but the river averaged 12.4 MAF from 2000 to 2024.

• On August 21, 2026 Interior cut Lower Basin use to 6.25 MAF for 2027-28; Nevada sued three days later.

• Lake Powell hit a record low on September 15, 2026; Lake Mead stood below its 2022 record in October.

• More than half of world food production lies where water storage is projected to decline, on the 2024 Global Commission's count.

Module 4 Quiz

Check Your Understanding

1. Why does warming make both droughts and floods worse?

A) Warming adds rain everywhere
B) Warmer air holds about 7% more vapor per degree Celsius
C) Warming slows evaporation from soils and lakes
D) Glaciers melt faster, so rivers carry more water in every season everywhere

2. Why is glacier melt described as a temporary abundance?

A) Melt stops every winter
B) Melt rises at first, then falls as the ice runs out
C) Glaciers are growing again in Asia
D) Glacier water is too salty to use until it mixes with river water downstream

3. In the Colorado worked example, what is the structural gap?

A) Only a dry-year gap, closed when Lake Mead refills in spring
B) About 1 MAF a year, covered by the Mexican treaty
C) About 10 MAF a year, half the river
D) About 4 MAF a year

4. What did the Interior Department's decision of August 21, 2026 do?

A) Cut Lower Basin use to 6.25 MAF a year for 2027-28, with Arizona's share falling about 27%
B) Cut Upper Basin use by half and left the Lower Basin whole
C) Extended the 2007 shortage rules unchanged through 2036
D) Approved a deal the seven states signed in July 2026

5. What does the Global Commission on the Economics of Water warn about for 2050 without action?

A) A tenth of food production at risk
B) A doubling of irrigated land in Africa and Asia
C) Over half of food production at risk
D) Output losses of up to half in the poorest countries

Module 5 — Europe's Rivers in 2026

The Drought Summer as a Case Study, With the Gauge Data

Recommended Reading / Reference

Reference: Germany's Federal Institute of Hydrology (BfG) and waterways administration gauge data; pv magazine's analysis of modelled river discharge (August 10, 2026); the Central Commission for the Navigation of the Rhine; the European Commission's Water Resilience Strategy (June 2025)

5a. The Gauges

River and gauge	Normal	Earlier droughts	2026	Consequence
Rhine at Kaub (water level)	Barges load fully when the gauge reads about 1.5 m (5 feet) or more	25 cm in October 2018, the old record; 41 days below 78 cm in 2022	6 cm on August 14; 4 cm on September 24, the lowest since 1880; provisionally −3 cm on September 26; 74 days below 78 cm	Barges sailed light; freight costs more than doubled
Rhine at Rheinfelden, Switzerland (flow)	1,185 m³/s August average		418 m³/s in early August	Basel's ports and shippers warned of supply risks
Rhine at Lobith, Netherlands (flow, % of 2019-25 norm)	100%		81% April; 66% May; 58% June; 37% July	Dutch water intakes and salt intrusion
Danube at the Iron Gates (flow, % of norm)	100%		58% May; 54% June; 48% July	Hydro output cut; Cernavodă's reactors shut
Garonne (July flow, % of norm)	100%		5%	Irrigation bans in southwest France
Loire (July flow, % of norm)	100%		13%	River-cooled reactors at risk
Rhône (July flow, % of norm)	100%		41%	Cooling limits
Po at Pontelagoscuro (flow)			About 206 m³/s in August; seawater more than 20 km (12 miles) up the delta	Irrigation intakes failing

Kaub: German waterways administration via Swissinfo (September 24, 2026) and Ports Europe (August 25, 2026). Lobith, Iron Gates, and French rivers: modelled discharge from the Global Flood Awareness System, analyzed for pv magazine (August 10, 2026). Rheinfelden: Swiss federal data via Bluewin (August 6, 2026). Po: Euronews (August 12, 2026). The Kaub gauge measures the water available for loading, not the depth to the riverbed.

The Rhine is Europe's economic artery, carrying coal, oil, chemicals, grain, and steel to Germany's industrial heartland and Switzerland, and in 2026 it fell twice to levels never recorded. The Kaub gauge, which governs how much a barge can load on the Middle Rhine, read about 6 centimeters (2.4 inches) on August 14, below the previous record of 25 centimeters from October 2018.

Rain lifted the river to about 60 centimeters by August 24, but the respite was short. Kaub read 4 centimeters on September 24, the lowest since records began in 1880, and a provisional −3 centimeters two days later. By then the river had spent 74 days below 78 centimeters, the level at which barges must cut their loads by about 30%, against 41 such days in 2022.

Downstream at Lobith, where the Rhine enters the Netherlands, modelled flow fell from 81% of the 2019-25 norm in April to 37% in July. Upstream at Rheinfelden in Switzerland, the flow in the first days of August averaged 418 cubic meters a second against a long-term August average of 1,185.

5b. The Corridor

The drought ran from the Rhine delta to the lower Danube, where flow through the Iron Gates, the Danube's largest hydropower complex, fell to 48% of normal in July. Romania shut the first reactor at Cernavodă, its only nuclear plant and the source of about a fifth of its power, in July, and the second on August 13, only the second such shutdown since the plant opened, after one in 2003.

Hungary's Paks plant, which supplies about a third of the country's power, cut output from late July for lack of cool Danube water, and Prime Minister Péter Magyar ordered a weir built to hold the river up at the intake. France dried from the south: on modelled data the Garonne ran at 5% of its normal July flow, the Loire at 13%, and the Rhône at 41%.

Italy's Po fell to about 206 cubic meters a second at Pontelagoscuro in August, with seawater pushing more than 20 kilometers up the delta and into the irrigation intakes of the rice and maize country.

5c. Power, Shipping, and Industry

System	2026 impact	Cost or response
Hydropower	Corridor output about 13 TWh, a fifth, below norm in April-July; Germany's down 37% and France's 28% against 2019-25 by September	Replaced by gas, coal, and imports at higher prices
Nuclear	Both Cernavodă reactors shut; Paks cut output	A weir ordered for Paks; cooling upgrades studied
Rhine shipping	Loads cut by about 30% below 78 cm at Kaub, and to a fraction of capacity near record lows	Diesel freight from Rotterdam to Karlsruhe more than doubled in September; one 1,500-tonne barge needs about 60 trucks to replace it
Industry	thyssenkrupp Steel halted its own barge shipments; chemical makers ran lighter vessels built for low water	EnBW expected coal-delivery costs to cut earnings by a low double-digit-million-euro sum
Agriculture	Irrigation bans in France; Po valley intakes failing	Losses feeding into 2026-27 food prices

Reuters via Swissinfo (September 24, 2026); Bloomberg via gCaptain (August 11, 2026); Ports Europe (August 25, 2026); pv magazine (August 10, 2026).

The costs ran through every system that depends on the rivers: barges sailed light, freight rates soared, and companies shifted what cargo they could to road and rail. The chemical maker Covestro calculated that replacing one barge carrying 1,500 tonnes takes about 60 trucks. Hydropower fell by about a fifth across the corridor, and German and French output was down 37% and 28% by September, with gas and imports filling the gap at higher prices.

5d. What 2018, 2022, and 2026 Revealed

Three drought summers in nine years have shown that 2018 was not an exception but the beginning of a new range. Europe's water system was built for a continent with reliable rain: shipping on free-flowing rivers,

reactors cooled by river water, hydropower fed by Alpine snowmelt, and farms watered by rain and shallow aquifers, and each assumption has now failed more than once.

The responses are under way but slow: Germany plans to deepen the channel at the Middle Rhine's bottlenecks by 20 centimeters, from 1.90 to 2.10 meters, a €225 million project listed as an urgent need in the federal transport plan of 1992. Its first approval procedure began in November 2025, and completion is targeted for about 2033, while shippers add barges built for low water. The EU's water-reuse rules have applied since June 2023, and its Water Resilience Strategy of June 2025 aims to raise water efficiency by at least 10% by 2030.

The responses run into a hydrological fact: the aquifers that keep rivers flowing through dry summers are themselves low across Central and Eastern Europe, the WMO reported for 2025, so each drought starts from a lower base. Europe, which spent the 2010s treating water as a southern problem, has learned that it is a northern one too.

Module 5 Key Points

Europe's Rivers in 2026

- The Rhine at Kaub read 4 cm on September 24, 2026, the lowest since records began in 1880.
- Kaub spent 74 days below 78 cm, where barges cut loads about 30%, against 41 days in 2022.
- Romania shut both Cernavodă reactors and Hungary's Paks cut output for lack of cool Danube water.
- Hydropower in the corridor fell about a fifth in April-July; Germany's was down 37% against 2019-25.
- 2018, 2022, and 2026 showed that river shipping, river-cooled power, and snowmelt hydropower assume a wetter climate.

Module 5 Quiz

Check Your Understanding

1. How low did the Rhine fall at Kaub in 2026?

A) To 25 cm, the same as in 2018
B) To about 60 cm in August
C) To about 1 meter, normal for late summer
D) To 4 cm on September 24, the lowest since records began in 1880

2. What happened to Romania's Cernavodă nuclear plant in 2026?

A) It cut output by a tenth
B) Both reactors shut for lack of cooling water
C) It raised output to replace lost hydropower from the Iron Gates
D) It was closed for good after a safety review in Bucharest

3. On modelled data, what share of its 2019-25 norm did the Rhine at Lobith carry in July 2026?

A) About 80%, near normal
B) Above normal, after storms in the Alps
C) About 37%
D) About 5%, as on the Garonne

4. How did the low Rhine hit industry and transport in 2026?

A) Barges sailed light, freight costs rose, and some cargo moved to road and rail
B) Rail took all the cargo at no extra cost
C) Freight costs fell as factories closed for the summer
D) Barge traffic stopped entirely for the whole summer, closing the ports of Duisburg, Basel, and Rotterdam

5. What did the droughts of 2018, 2022, and 2026 reveal together?

A) That the system is resilient
B) That shipping, river-cooled power, snowmelt hydropower, and rain-fed farming were built for a wetter climate
C) That only southern Europe is at risk
D) That the aquifers are recovering after each drought

Module 6 — Hydropower and Its Problems

The Largest Renewable and Its Exposure to Drought

Recommended Reading / Reference

Reference: IHA, *World Hydropower Outlook 2026* (June 2026); World Commission on Dams, *Dams and Development* (2000); Ember's electricity data; the Zambezi River Authority's hydrological outlooks

6a. Scale

Country	Hydro capacity (GW)	Share of electricity	Largest projects	2025-26 note
China	About 380, plus 66 of pumped storage	About 13%	Three Gorges 22.5 GW; Baihetan 16 GW	Began the 60 GW Medog project in Tibet in July 2025, upstream of India's Brahmaputra
Brazil	About 110	About half	Itaipu 14 GW (shared with Paraguay); Belo Monte 11 GW	Rationing in 2001; near-rationing in 2021
Canada	About 83	About 60%	Robert-Bourassa 5.6 GW	Quebec and Manitoba export to the US
United States	About 80, plus 22 of pumped storage	About 6%	Grand Coulee 6.8 GW	Glen Canyon's 1.3 GW at risk if Lake Powell falls further; four Klamath dams removed in 2024
Russia	About 56	About 17%	Sayano-Shushenskaya 6.4 GW	A 2009 turbine disaster killed 75
India	About 50	About 9%	Tehri 2.4 GW	A glacial-lake flood destroyed the Teesta III dam in Sikkim in 2023
Norway	About 34	About 90%		Put refilling reservoirs ahead of exports in the 2022 drought
Turkey	About 32	About a fifth	Atatürk 2.4 GW	Controls the Tigris and Euphrates headwaters (Module 7)
Alpine and Nordic systems (Switzerland, Austria, Sweden, France, Italy)	15-30 each	10-60%	Alpine storage and run-of-river plants	French output down 28% in 2026 against 2019-25
Ethiopia	Grand Ethiopian Renaissance Dam (GERD) 5.15 GW	Most of its power	GERD, inaugurated September 2025	The Nile dispute
Zambia and Zimbabwe	About 2.1 at Kariba	Most of their power	Kariba North and South	Blackouts up to 20 hours a day in 2024; the lake refilled to about 47% by July 2026
World	1,469, including just over 200 of pumped storage	About 14%, roughly 4,480 TWh		28 GW added in 2025, a record 11.6 GW of it pumped storage

IHA (June 2026); China's National Energy Administration and hydropower planning institute (2025); Ember; Zambezi River Authority (July 2026). Approximate. A gigawatt (GW) measures capacity; a terawatt-hour (TWh), a billion kilowatt-hours, measures the energy produced.

Hydropower generated about 14% of the world's electricity in 2025, roughly 4,480 terawatt-hours, more than any other renewable source. The International Hydropower Association counted 1,469 gigawatts installed at the end of 2025, just over 200 of them pumped storage, and China alone has close to a third.

Brazil, Canada, the United States, Russia, India, and Norway follow, and a set of countries, from Norway and Ethiopia to Zambia, Paraguay, and Nepal, depend on it for most of their power. It can be dispatched at will, is cheap once built, lasts a century, and provides the storage and balancing that wind and solar need, which is why it remains the backbone of many decarbonization plans.

6b. The Drought Problem

Episode	Where	Cause	Effect
2001	Brazil	Reservoirs empty after drought	Nine months of rationing
2021	Brazil	Worst drought in about 90 years	Reservoirs near 20%; gas imports and tariff surcharges
2022	China (Sichuan)	Heat and drought on the Yangtze	Hydro output roughly halved in August; factories shut
2022	Norway, the Alps	A dry winter	Norway put reservoir levels ahead of exports; Alpine output down sharply
2023	Worldwide	El Niño and drought	Hydro output fell steeply; coal and gas filled the gap and power-sector emissions rose
2024	Zambia and Zimbabwe	Kariba near its minimum level	Blackouts up to 20 hours a day; copper mines and the economy hit
2024	Ecuador	Drought on the Paute system	Nationwide blackouts of up to 14 hours
2023-24	Colombia, Panama	El Niño drought	Bogotá rationed water; the Panama Canal cut transits
2026	Europe	The drought from the Rhine to the Danube	Corridor output down about a fifth in April-July
2026-27	US Southwest	Lake Powell at record lows	Glen Canyon Dam's power at risk; 2026 releases cut and Flaming Gorge water sent downstream

Hydropower's fuel is rain, and the fuel has become unreliable, which is the paradox: the renewable most relied on to balance the grid is the one most exposed to the climate it is meant to protect. Countries that depend on it, from Brazil and Zambia to Ecuador and Norway, have learned that a dry year is a power crisis, and the response everywhere has been to build gas or coal plants as backup, which is why emissions rose in the 2023 drought.

Wet years reverse the story: Kariba, which fell near its minimum in 2024 and stood at 23.9% of usable storage in July 2025, was at 47.47% on July 21, 2026, and the Zambezi River Authority raised the 2026 allocation for power to 36 billion cubic meters.

6c. The Other Problems

- **Methane:** reservoirs in warm climates emit methane from decaying vegetation, and some shallow tropical reservoirs have carbon footprints approaching those of fossil plants, while cold, deep ones emit little.

• **Sediment:** dams trap the silt that built deltas and fed floodplains. The Nile delta has eroded since the Aswan High Dam, the Mekong delta is sinking and salting as upstream dams hold back its sediment, and reservoirs themselves fill with silt over decades.

• **Displacement and ecology:** the Three Gorges Dam displaced about 1.3 million people, and dams block fish migration. Four dams on the Klamath River in California and Oregon came down in 2024, the largest dam removal in American history, to restore salmon runs.

• **Downstream conflict:** a dam upstream is a lever over everyone below it, as with Ethiopia's dam on the Nile, China's on the Mekong, Turkey's on the Tigris and Euphrates, and China's Medog project above India (Module 7).

• **Safety:** the failure of two neglected dams above Derna, Libya, in 2023 killed thousands, a saddle dam in Laos collapsed in 2018, a glacial flood swept away a dam in Sikkim in 2023, and in July 2026 Typhoon Maysak breached the Liulan Reservoir's earth dam in China, killing 26.

6d. Pumped Storage and the Future

The growth in hydropower is shifting from new rivers to storage, and pumped storage uses two reservoirs at different heights: water is pumped up when power is cheap and released through turbines when it is dear. It still holds more than 90% of the world's stored electricity by energy, and its capacity passed 200 GW in 2025, when a record 11.6 GW was added, about two-fifths of all new hydropower.

China accounted for more than 40% of the world's new hydropower in 2025 and has more than 300 GW under construction, 218 GW of it pumped storage, while retrofitting old dams with turbines and modernizing old plants are the other growth areas. Large new dams are contested almost everywhere outside China, Africa, and the Himalaya, and the climate that makes storage more valuable also makes the water behind each dam less certain.

Module 6 Key Points

Hydropower and Its Problems

• Hydropower supplied about 14% of the world's electricity in 2025 from 1,469 GW, including just over 200 GW pumped storage.

• Its fuel is rain: droughts cut output in Brazil, Sichuan, Zambia, Ecuador, and Europe, and gas or coal filled the gap.

• Kariba fell near its minimum in 2024 and refilled to about 47% of usable storage by July 2026.

• Dams trap delta-building sediment, emit methane in the tropics, displace people, and fail when neglected, as at Derna in 2023.

• Pumped storage passed 200 GW in 2025; China is building 218 GW more.

Module 6 Quiz

Check Your Understanding

1. What share of the world's electricity did hydropower supply in 2025?

A) About 14%
B) About 40%, more than coal
C) About 3%, behind solar and wind
D) About half, mostly in China and Brazil

2. What happened to Lake Kariba between 2024 and 2026?

A) It stayed near its minimum through 2026
B) It filled to 90% in 2025
C) It stayed above 90% throughout, so Zambia and Zimbabwe exported surplus power
D) It fell near its minimum in 2024, then refilled to about 47% by July 2026

3. What is the paradox of hydropower that the module describes?

A) It is too slow to balance wind and solar
B) It produces most of the world's electricity but little of its storage
C) Its fuel is rain, which is growing less reliable
D) Its reservoirs emit more methane than coal plants emit carbon in every climate

4. How do dams affect the deltas below them?

A) They enlarge them with extra silt
B) They make no measurable difference
C) They trap the sediment that built the deltas, which then sink and salt
D) They raise the sea level at the river mouth

5. How large was the world's pumped storage at the end of 2025?

A) Just over 200 GW
B) About 2 GW
C) About 1,469 GW, all of hydropower
D) About 500 GW, a third of hydropower

Module 7 — Water Conflicts and Geopolitics

The Shared Rivers Where Scarcity Becomes Strategy

Recommended Reading / Reference

Reference: Pacific Institute, *Water Conflict Chronology*; the Permanent Court of Arbitration's Indus Waters Treaty proceedings (awards of 2025-26); the UN Watercourses Convention (1997); the UN Environment Programme (UNEP) and the World Bank on the Aral Sea; the Stimson Center's Mekong Dam Monitor

7a. Upstream and Downstream

About 60% of the world's freshwater flow crosses a border, in some 310 river basins shared by two or more countries, and the physics of a river makes the upstream state the sovereign of everyone below. Of the 153 countries that share rivers, lakes, or aquifers, only 43 had arrangements in force covering at least 90% of their shared waters, the UN reported in 2025.

The 1997 UN Watercourses Convention, which codifies equitable use and the duty not to cause significant harm, came into force only in 2014 and has about 40 parties, none of them China, India, Turkey, Ethiopia, or Egypt. Wars fought purely over water are rare, because states have usually found war costlier than negotiation, but water is a constant instrument and casualty of conflict, and the 2020s have seen the worst deterioration in a generation.

7b. The Basins

Basin	States	The dispute	Treaty	Status, October 2026
Indus	India (upstream), Pakistan	The rivers on which most of Pakistan's farming depends; Indian dams and timing on the western rivers	1960 Indus Waters Treaty, put in abeyance by India on April 23, 2025, after a terrorist attack in Kashmir	A Court of Arbitration ruled on August 31, 2026 that the treaty stands; India rejected the ruling
Nile	Ethiopia, Sudan, Egypt, and eight upstream states	Ethiopia's 5.15 GW GERD against Egypt's near-total dependence on the river	A colonial-era agreement of 1929 and the Egypt-Sudan agreement of 1959; a 2010 upstream framework; no basin-wide treaty	GERD inaugurated September 9, 2025; its releases peaked later that month, floods followed in Sudan and Egypt, and Egypt called the operation reckless
Mekong	China, Myanmar, Laos, Thailand, Cambodia, Vietnam	China's 11 mainstream dams and Laos's cascade alter flows and hold back sediment	Mekong River Commission (1995), without China	Cambodia's Funan Techo canal, begun in 2024, worries Vietnam; the delta is salting
Tigris-Euphrates	Turkey, Syria, Iraq, Iran	Turkish and Iranian dams control the headwaters	No basin treaty	Iraq's reserves fell to about 10 billion m^3 in May 2025, the lowest in 80 years; a deal with Turkey of November 2025 pays for water projects with oil sales

Basin	States	The dispute	Treaty	Status, October 2026
Colorado	Seven US states, Mexico	Allocations exceed the river's recent flow by about a third	1922 Compact; 1944 treaty with Mexico	Interior imposed cuts for 2027-28 on August 21, 2026; Nevada sued; Mexico's share under separate talks
Rio Grande (Río Bravo)	US, Mexico	Mexico's deliveries owed under the 1944 treaty	1944 treaty	Mexico delivered about 0.88 of 1.75 MAF in the cycle to October 2025; it committed in February 2026 to at least 0.35 MAF a year
Amu Darya and Syr Darya	Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan, Kazakhstan, Afghanistan	Upstream dams against downstream cotton; Afghanistan's 285 km Qosh Tepa canal could take up to a fifth of the Amu Darya	Soviet-era quotas; Afghanistan party to none	Qosh Tepa due for completion in late 2026
Jordan	Israel, Jordan, Syria, the Palestinians	The most stressed basin on earth	1994 Israel-Jordan treaty	A water-for-energy deal shelved after October 2023; Gaza's water system largely destroyed
Brahmaputra (Yarlung Tsangpo)	China, India, Bangladesh	China's 60 GW Medog project in Tibet, upstream of India	None	Under construction since July 2025; India plans a large dam of its own downstream
Ganges	India, Bangladesh	Dry-season flows below India's Farakka barrage	1996 treaty, which expires in December 2026	Talks to go through the countries' Joint Rivers Commission had not begun by August 2026

Permanent Court of Arbitration; UN, Sustainable Development Goals Report 2025; Iraq's water ministry via AFP (May 2025); US Bureau of Reclamation and International Boundary and Water Commission; India's Ministry of External Affairs (August 4, 2026).

The Indus is the most dangerous of these disputes, because it lies between two nuclear powers. A day after the attack in Pahalgam on April 22, 2025, India held the 1960 treaty in abeyance, and a four-day conflict followed in May. India stopped sharing data through the two countries' Indus commission, and began flushing and filling its dams on its own schedule. Pakistan declared that any attempt to stop or divert its share would be an act of war.

When the monsoon flooded Punjab in August 2025, India warned Pakistan through diplomatic channels rather than the commission the treaty provides. On August 31, 2026 a Court of Arbitration under the treaty ruled unanimously that the treaty remains fully in force and that abeyance is not permitted by it; India rejected the award within hours, calling the court illegally constituted.

7c. The Aral Sea

The Aral Sea was the world's fourth-largest lake until the 1960s, when Soviet planners diverted the Amu Darya and the Syr Darya to irrigate cotton across Central Asia, and it lost about 90% of its volume. The southern basin is now largely a desert of salt and pesticide residue, the Aralkum, whose dust storms carry the residue across the region, and the fishing towns stand far from any water.

A partial recovery shows what policy can do: Kazakhstan's Kok-Aral dam, finished in 2005 with World Bank support, holds the Syr Darya's flow in the northern basin, where the water rose by several meters and fish returned. The south has not recovered, and Afghanistan's Qosh Tepa canal will draw more from the Amu Darya. The lesson is that a river diverted to a single crop with no cap on use can be lost almost entirely within one lifetime.

7d. Water as a Weapon

The 2020s have seen water infrastructure targeted in war as it had not been for decades. The Kakhovka dam on the Dnipro in occupied southern Ukraine was destroyed on June 6, 2023, an act most investigations attribute to Russia. Its 18 km³ reservoir drained, flooding downstream towns and killing dozens, cutting off irrigation for more than half a million hectares, and leaving the Zaporizhzhia nuclear plant to cool its reactors from a pond.

Gaza's water and sanitation system was largely destroyed in the 2023-25 war, and Sudan's warring factions have struck each other's water and power works. The war with Iran that began on February 28, 2026 brought the Gulf's desalination plants into the line of fire. A plant on Iran's Qeshm Island was hit on March 7, cutting off 30 villages, and Iran blamed the United States, which denied it; an Iranian drone damaged a plant in Bahrain the next day.

Debris damaged Kuwait's Doha West plant, strikes fell near Dubai's Jebel Ali complex, and in June American strikes destroyed two reservoirs in Iran's Hormozgan province serving more than 20,000 people. In countries that desalinate most of their drinking water, as Kuwait, Bahrain, and Qatar do, a plant is as strategic as a power station (Module 10).

The Pacific Institute recorded 420 incidents of violence over or involving water in 2024, up 18% from 355 in 2023. Most were within states, over allocation between farms, cities, and ethnic groups, rather than between them.

Module 7 Key Points

Water Conflicts and Geopolitics

• About 60% of freshwater flow crosses a border; only 43 of 153 sharing countries have arrangements covering 90% of their shared waters.

• India put the Indus treaty in abeyance in April 2025; an August 2026 arbitral award said it stands, and India rejected it.

• Ethiopia inaugurated the GERD in September 2025; floods in Sudan and Egypt followed its releases.

• Cotton irrigation shrank the Aral Sea by about 90%; a 2005 dam revived only its northern basin.

• The 2026 Iran war brought strikes on desalination plants and reservoirs on both sides of the Gulf.

• The Pacific Institute counted 420 violent water incidents in 2024, up 18%, most of them within states.

Module 7 Quiz

Check Your Understanding

1. What share of the world's freshwater flow crosses a border?

A) About 10%, in a few basins
B) About 90%, in the great rivers
C) About a third, mostly in Africa and Asia
D) About 60%

2. What did the Court of Arbitration's award of August 31, 2026 find on the Indus?

A) That the treaty had lapsed
B) That the treaty remains in force and India's abeyance is not permitted
C) That Pakistan owes India compensation
D) That the treaty should be renegotiated within one year under World Bank supervision

3. What happened on the Nile after Ethiopia inaugurated the GERD in September 2025?

A) Egypt and Ethiopia signed a basin treaty
B) Releases peaked later that month, and floods followed in Sudan and Egypt, which called the operation reckless
C) The turbines were shut for repairs
D) Sudan withdrew from the Nile Basin Initiative

4. What shrank the Aral Sea by about 90%?

A) Hydropower dams on the Syr Darya
B) A century of falling rainfall
C) Cotton irrigation
D) Climate change alone, with no human diversion

5. Which water infrastructure came under attack in the 2026 war with Iran?

A) Desalination plants on both sides of the Gulf
B) Only dams in Turkey
C) The Kakhovka dam on the Dnipro in southern Ukraine
D) The Aswan High Dam and the Nile's irrigation canals in Egypt

Module 8 — The Cost of Water

What Water Costs to Produce and What It Is Priced At

Recommended Reading / Reference

Reference: Organisation for Economic Co-operation and Development (OECD), *Pricing Water Resources and Water and Sanitation Services* (2010); GWI's annual tariff survey (September 2025); EPA, *7th Drinking Water Infrastructure Needs Survey and Assessment* (April 2023); Bluefield Research's US water and sewer bill survey (March 2026)

8a. What It Costs to Produce

Source	Production cost ($/m³)	Energy (kWh/m³)	Notes
River or lake water, conventional treatment	0.10-0.50	0.2-0.5	The cheapest; depends on intake distance and pollution
Groundwater	0.30-1.00	0.3-1.0, rising with depth	Lifting from 100 m (330 feet) takes ten times the energy of lifting from 10 m
Rainwater harvesting	0.15-1.50	Near zero	Limited by storage
Long-distance transfer (aqueducts)	0.50-2.00	1-4 when pumped over mountains	California's State Water Project; China's South-North transfer
Recycled wastewater, non-potable	0.30-0.80	0.5-1.0	Irrigation and industry
Recycled wastewater, potable	0.60-1.20	1.0-1.5	Singapore, Orange County
Brackish desalination	0.40-0.90	1.0-2.5	Inland, in Texas, Arizona, and Israel
Seawater desalination, large Gulf plants	0.37-0.60	2.8-3.5	Hassyan's record tariff of $0.365 (2023)
Seawater desalination elsewhere	0.50-3.00	3.5-5.0	Large plants at the low end; smaller plants, dearer power, and stricter rules at the high end
Bottled water at retail	500-3,000	About 1,500-2,800, mostly for the bottle and transport	About a thousand times tap water (Module 11)

Approximate; bottled water's energy from Gleick and Cooley (2009). Energy is in kilowatt-hours (kWh) per cubic meter. One dollar per m³ is about 0.4 cents per US gallon, or about $1,230 per acre-foot.

The cost of water depends almost entirely on where it comes from, and the figures above are only production costs: the pipes, pumps, storage, and treatment plants that deliver water are capital costs that dwarf them, and the energy to move water is often the largest variable operating cost.

Drinking-water and wastewater systems account for about 2% of American energy use, on the EPA's estimate. California's State Water Project, which lifts water about 600 meters (2,000 feet) over the Tehachapi Mountains to Los Angeles, is the largest single user of electricity in the state.

8b. What It Is Priced At

Place	What households pay	Basis	Note
Denmark	88.46 kroner per m³, about $13.60 (5 cents a gallon)	National average for water and wastewater, taxes and value-added tax (VAT) included; 2025, provisional	Up about 20% from 2020 to 2025
Germany (Saxony)	€5.12 per m³ plus about €257 a year in fixed charges, about $8 per m³ for a household using 144 m³ a year	State averages for water and wastewater, 2025	Full cost recovery
England and Wales	£639 a year on average, about $860	Combined water and sewerage bill, 2026-27	Up 5.4%, after a 26% rise in 2025-26
London (Thames Water)	£658 a year on average	2025-26	Bills fund a company in crisis (Module 9)
United States	Northeast $147 a month and West $143, on average	Combined water and sewer bills in 50 cities, 2025	Up 5.1% in 2025 and 24.2% in five years
Beijing	5 yuan per m³, about 75 cents, for the first 180 m³ a year, then 7 and 9 yuan	Tiered household tariff, wastewater included	Tiers introduced in 2014
Delhi	Free up to 20 m³ a month	Metered households, since 2015	Tankers fill the gaps at many times the price
Unconnected households in poor cities	Often 5-20 times the piped rate	Tanker trucks and kiosks	The affordability paradox, worked below
US farmers on federal project water	About $20-100 per acre-foot, a few cents per m³	Long-term contracts	Why alfalfa grows in deserts
Indian farmers	Pumping power free or nearly free in many states	State electricity subsidies	Why Punjab's aquifer is failing

DANVA, *Vand i tal 2025*; Statistical Office of Saxony (2026); Water UK and company figures via MoneyToTheMasses (January 2026); Bluefield Research (March 2026); Beijing Municipal Commission of Development and Reform; Delhi Jal Board. Converted at September 2026 averages.

Tariffs bear little relation to costs: Danish households pay more than $13 per cubic meter for water and wastewater together, and German and British households pay $5-10. American bills vary widely and are rising fastest, up 5.1% in 2025 alone, and GWI's survey of utilities worldwide found tariffs up 10.7% in the year to mid-2024, a record, and 6.2% in the year after.

India, Egypt, Mexico, and much of the developing world charge a few cents or nothing, with the difference paid by governments or by service that fails. Farmers, who use most of the water, pay least of all, often only the cost of pumping and in much of India not even that, which is why water grows alfalfa in deserts and rice in drought zones.

The OECD's judgment is that water is underpriced almost everywhere: underpricing drives overuse, starves utilities of investment, and makes the price of a necessity one of the hardest things in politics to change.

8c. The Infrastructure Gap

Because tariffs often do not cover costs, infrastructure decays, and the EPA's 2023 survey put America's drinking-water needs at $625 billion over 20 years. The country has about 9 million lead service lines, the pipes that poisoned Flint, Michigan, in 2014-15, and a 2024 rule requires utilities to replace them by 2037, though the rule is being challenged in court (Module 14).

England's privatized utilities, Thames Water above all, piled up debt and paid dividends while their pipes leaked and their sewers overflowed into rivers, and Thames carried £19.1 billion of debt at the end of March 2026 (Module 9). Worldwide, the OECD and the World Water Council estimated in 2015 that water infrastructure would need $6.7 trillion of investment by 2030 and $22.6 trillion by 2050.

Contamination adds cost on top: the EPA put the cost of meeting its 2024 PFAS limits at about $1.5 billion a year, and utilities' own estimates run far higher.

8d. Affordability, Worked

Worked example — The Affordability Paradox in Two Households

A family of four in Delhi connected to the city system uses 15 cubic meters a month. The first 20 are free, so it pays nothing. A family of four in an unconnected settlement two kilometers away buys the same 15 cubic meters from tankers, at up to about 500 rupees (about $5) per cubic meter when supply is short. That is about 7,500 rupees, roughly $80 a month, a large share of a laborer's income, for water of worse quality. In Nairobi's informal settlements kiosk water often costs several times the piped tariff. The paradox of underpricing is that the subsidy goes to the connected, who are better off, while the poor pay five to twenty times the piped tariff.

In rich countries the collision is different: utilities often treat a water bill above 4.5% of household income as unaffordable, and Bluefield's 2025 average for the Northeast, $147 a month, is 4.5% of an income of about $39,000. As tariffs rise to pay for pipes, a growing share of households cross that line, which is how shutoffs in Detroit and Baltimore became national stories.

The design problem every utility faces is to charge enough to maintain the system and little enough that the poor can drink. The usual answer, a cheap lifeline block for basic use with rising prices above it, is easier to describe than to run, and it does nothing for the household with no pipe.

Module 8 Key Points

The Cost of Water

• Production costs run from $0.10 per m³ for river water to $0.50-3 for seawater desalination outside the Gulf.

• Energy is often water's largest variable cost; US drinking-water and wastewater systems use about 2% of the nation's energy.

• Households pay over $13 per m³ in Denmark, about $8 in Saxony, and little or nothing in Delhi.

• US water and sewer bills rose 5.1% in 2025 and 24.2% in five years; farmers pay least.

• The EPA puts US drinking-water needs at $625 billion over 20 years, with about 9 million lead lines.

• Underpricing subsidizes the connected while unconnected households pay five to twenty times the piped rate.

Module 8 Quiz

Check Your Understanding

1. What is often the largest variable cost in delivering water?

A) Chlorine
B) Labor at treatment plants
C) Insurance against floods, drought, and contamination claims at every plant
D) Energy for pumping and treatment

2. What did Danish households pay for water and wastewater in 2025, on DANVA's provisional figures?

A) About $1 per m³, like Spain
B) 88.46 kroner per m³, about $13.60, taxes and VAT included
C) About 50 kroner per m³
D) About $4 per m³, the European average

3. Who pays least for water, and why does it matter?

A) City households, so they waste it
B) Industry, because it recycles most of its water on site
C) Farmers, so crops like alfalfa grow in deserts
D) Golf courses, which irrigate with untreated river water for free

4. What is the affordability paradox in the worked example?

A) The unconnected poor pay the most
B) Tariffs fall fastest for the poorest households in every city
C) Delhi's free allowance reaches every household, piped or not
D) The rich pay the most per liter because they use more

5. What does the US need for drinking-water infrastructure, on the EPA's 2023 survey?

A) $62.5 billion in all
B) Only lead-pipe replacement, about $1 billion
C) $6.7 trillion
D) About $625 billion over 20 years

Module 9 — The Water Industry

The Companies and Models That Deliver Water

Recommended Reading / Reference

Reference: GWI, *Global Water Market*; the companies' 2025 annual reports (Veolia, Suez, American Water Works, Xylem); UK Department for Environment, Food and Rural Affairs (Defra), *A New Vision for Water* (January 2026); the House of Commons Environment, Food and Rural Affairs Committee on Thames Water (September 2026); Bel, Fageda, and Warner, 'Is Private Production of Public Services Cheaper Than Public Production?' (2010)

9a. Public and Private

Model	How it works	Where	Record
Municipal or public utility	A city or regional authority owns and runs the system; tariffs set politically	Most of the world: the US (about 85% of people), Germany, Japan, most of Asia	From Tokyo's excellence to Jackson, Mississippi's collapse; underinvestment where tariffs are political
National utility	A state company	Israel's Mekorot, Singapore's Public Utilities Board (PUB), many African and Middle Eastern states	Israel and Singapore are among the world's best; many others fail
Full privatization	Private companies own the assets under an economic regulator	England and Wales since 1989, the only large example	Investment rose; so did debt, dividends, and sewage spills, and Thames Water is in crisis
Concession (the French model)	A private firm runs public assets under a 20-30 year contract	France historically, Spain, Latin America, Manila	Exported by Veolia and Suez; Paris (2010) and Berlin (2013) took their water back
Management contract or public-private partnership	A private operator works for a fee; the assets stay public	The Middle East, Africa, parts of Asia	Depends on the contract
Corporatized public utility	Public ownership run on commercial lines with an independent regulator	The Netherlands, Scotland, Australia	Often the best performers

Most of the world's water is delivered by public utilities, and the roughly one person in ten served by a private operator generates most of the argument, which is sharpest in England, where the whole industry was sold in 1989.

9b. The Argument Over Private Ownership

The case for private ownership. Its advocates say private capital invests where governments will not, because a regulated company can borrow against its tariffs while a city's water budget competes with schools and police. England's companies invested heavily after 1989 and cut leakage by about two-fifths from its mid-1990s peak. Brazil's 2024 sale of Sabesp, which serves about 28 million people in São Paulo state, came with a contract to invest 68 billion reais (about $13 billion) and reach universal water and sewage service by 2029, four years ahead of the national target.

The case against. Its critics say a natural monopoly with captive customers rewards financial engineering more than service. England's companies took on tens of billions of pounds of debt and paid out dividends while sewers overflowed into rivers, and Thames Water now faces collapse. More than 300 cities, including Paris in 2010 and Berlin in 2013, have taken their water back into public hands since 2000, and Cochabamba's revolt in 2000 against a private concession became the movement's founding story.

The evidence. Comparisons find no systematic cost advantage either way: a 2010 review of the studies by Germà Bel, Xavier Fageda, and Mildred Warner found no cost savings from private production of water and waste services. What separates good systems from bad is regulation, tariffs that cover costs, and governance. England's regulator, Ofwat, allowed debt to pile up for two decades, and the government announced its abolition in July 2025.

The course's reading. Ownership matters less than the rules around it. The corporatized public utility, publicly owned, commercially run, cost-recovering, and independently regulated, is the model most of the best systems share, and private owners do well or badly according to how tightly their finances are regulated.

9c. The Utilities

Company	Country	Revenue	People served	Notes
Veolia	France	€44.4 billion in water, waste, and energy (2025)	The largest private water operator	Absorbed most of Suez in 2022; builds desalination plants
Suez	France	€9.5 billion (2025)	67 million with drinking water	The remnant after Veolia's takeover, owned by a consortium of investors
American Water Works	US	About $5 billion	More than 14 million people in 14 states	Merging with Essential Utilities (5.5 million people in 9 states); closing expected by the end of March 2027
Thames Water	UK	About £2.5 billion	16 million	£19.1 billion of debt at the end of March 2026; creditors' rescue undecided
Severn Trent, United Utilities, Pennon	UK	£1-2.5 billion each	Millions each	Listed; bills rising under the 2025-30 price review
Sabesp	Brazil	Tens of billions of reais	About 28 million (São Paulo state)	Privatized in 2024, with Equatorial as reference shareholder
Beijing Enterprises Water, China Water Affairs	China, Hong Kong	Billions of dollars each	Tens of millions	China's build-and-operate giants
ACWA Power	Saudi Arabia	Several billion dollars	Desalination for tens of millions	Holds record-low desalination tariffs (Module 10)
Manila Water, Maynilad	Philippines	About $1 billion each	Millions each	Concessions since 1997
Mekorot, PUB	Israel, Singapore	Billions of dollars	National	The reference systems

Company reports and filings; American Water and Essential Utilities joint release (February 10, 2026) and 8-K (September 15, 2026); Parliament's Environment, Food and Rural Affairs Committee (September 18, 2026). Revenues approximate where no figure is given.

9d. Thames Water

London's supplier was sold debt-free in 1989. A succession of owners, the infrastructure fund Macquarie above all between 2006 and 2017, loaded it with borrowing and paid out dividends, and it reached £19.1 billion of debt by March 2026 while leaking about a fifth of its water and spilling sewage into the Thames. In May 2025 the regulator fined it a record £122.7 million over sewage failures and dividend rules.

A court-approved emergency loan of up to £3 billion from its senior creditors, at close to 10% interest, kept it running, and the private-equity firm KKR abandoned a rescue in June 2025. The creditors' consortium, London & Valley Water, then offered £3.35 billion of new equity, a write-off of up to 30% of the debt, and no dividends before 2035. The government rejected a version in June 2026, and the creditors added a golden share for the state in July.

On September 18, 2026 the House of Commons environment committee, a cross-party panel of members of Parliament (MPs), urged ministers to reject the creditors and prepare for special administration, the temporary public takeover the law provides, and gave the government until mid-November to respond. The emergency loan was expected to run out by the end of 2026, and as of early October 2026 no decision had been announced.

The crisis is reshaping the industry's rules: Sir Jon Cunliffe's review recommended a new regulator in July 2025, when the government announced Ofwat's abolition, and its January 2026 white paper, *A New Vision for Water*, set out the replacement. It would fold Ofwat's water work, with that of the Environment Agency, the Drinking Water Inspectorate, and Natural England, into one regulator, and the King's Speech in May 2026 announced the bill.

9e. Equipment and Technology

A second industry sells the utilities their tools, led by Xylem, the largest firm devoted to water technology, which bought Evoqua in 2023 and had revenue of $9.035 billion in 2025 from pumps, meters, treatment systems, and analytics. Ecolab treats industrial water, DuPont, Toray, and Nitto make the reverse-osmosis membranes at the heart of desalination and reuse, Grundfos and Wilo make pumps, and Badger and Mueller make meters.

The technology frontier, from smart meters, satellite leak detection, and automated treatment to low-energy membranes and the removal of forever chemicals, is where the sector's growth and its investors' attention lie. It is the part of the water business that behaves like a technology market rather than a utility.

9f. Water as an Asset

Water rights can be bought and sold in a few places, and Module 16 works the largest market, Australia's Murray-Darling. In 2020 Nasdaq launched a futures contract on an index of California water prices, the first attempt to trade water like a commodity, which drew accusations of speculating on a human right and has traded thinly. The constraint on water as an asset class is the one that runs through this course: water cannot be shipped far, so every market is local and every price political.

Module 9 Key Points

The Water Industry

• About one person in ten is served by a private water operator; England's 1989 sale is the largest example.

• Studies find no systematic cost advantage for private operators; regulation, cost-covering tariffs, and governance decide performance.

• Thames Water had £19.1 billion of debt in March 2026; in September MPs urged preparing for special administration.

• England plans to abolish Ofwat and merge four regulators into one, under a January 2026 white paper.

• Veolia had €44.4 billion of revenue in 2025; American Water and Essential Utilities expect to merge by March 2027.

Module 9 Quiz

Check Your Understanding

1. What model do the best-run water systems tend to share, on the course's reading?

A) Full private ownership
B) Free water paid for from taxes
C) Long concessions to foreign operators, renewed every thirty years under contract
D) Publicly owned, commercially run, and independently regulated

2. What did a 2010 review of studies by Bel, Fageda, and Warner find about private water and waste services?

A) No systematic cost savings from private production compared with public production
B) Private operators cut costs by half
C) Public utilities always cost less
D) Private operators raised quality but not prices

3. How much debt did Thames Water carry at the end of March 2026?

A) About £1 billion, after repayments
B) About £3 billion, the emergency loan
C) £19.1 billion
D) About £60 billion, the whole industry's

4. What did the UK government's January 2026 white paper propose?

A) Nationalizing all utilities
B) Abolishing Ofwat for a single regulator
C) Splitting Ofwat into separate water and sewage regulators
D) Capping all bills at 2024 levels until the new regulator starts

5. When is the merger of American Water and Essential Utilities expected to close?

A) It closed in December 2025
B) It was blocked by Pennsylvania
C) By the end of March 2027
D) Never, because both boards rejected it in February 2026

Module 10 — Desalination

Turning Seawater Into Supply

Recommended Reading / Reference

Reference: Jones and colleagues, 'The state of desalination and brine production: A global outlook' (*Science of the Total Environment*, 2019); the International Desalination and Reuse Association; GWI DesalData; ACWA Power's project disclosures

10a. The Technology

Technology	How it works	Energy (kWh/m³)	Cost ($/m³)	Share of new capacity	Where
Multi-stage flash (MSF)	Seawater flashed to steam through stages of falling pressure, then condensed	10-15, heat and power combined	1.0-2.0	Under 5%	Older Gulf plants on cheap gas
Multi-effect distillation (MED)	Evaporation through a series of vessels at falling pressure	6-10	0.8-1.5	About 5%	The Gulf, often beside power plants
Seawater reverse osmosis (SWRO)	Seawater pushed at 55-70 bar through membranes that pass water and block salt; devices recover the pressure	3-4; the best plants under 3	0.37-1.50	90% and more	Everywhere; the standard since the 2000s
Brackish reverse osmosis	Lower pressure on brackish groundwater	1-2.5	0.40-0.90	Inland	Texas, Arizona, Israel, Australia
Electrodialysis	Ions pulled through membranes by an electric field	1-3 on brackish water	0.5-1.0	Small	Brackish and industrial water
Forward osmosis, membrane distillation, graphene membranes	Research and pilots				No commercial breakthrough yet

Approximate. A bar is about 14.5 pounds per square inch, so 60 bar is about 870 psi.

Two families of technology take salt out of seawater, and the first, thermal desalination, boils seawater and condenses the vapor, an energy-hungry process that made sense only where fuel was nearly free, which is why the Gulf built it. Reverse osmosis forces seawater through membranes whose pores pass water molecules and block salt ions, using a third to a fifth of thermal's energy, about 3-4 kilowatt-hours per cubic meter in modern plants, and it has taken nearly all new capacity.

The output is so pure that it corrodes pipes and tastes flat, so minerals are added back before it is distributed. The waste is brine, concentrated and often warm and chemically treated, which is returned to the sea and harms marine life where it is poorly dispersed.

10b. Scale and Geography

Country	Capacity and share of supply	Largest plants	Notes
Saudi Arabia	More than 11 million m³ (2.9 billion gallons) a day, the world's largest; about 70% of drinking water	Ras Al-Khair, about 1 million m³ a day	Its state water agency is the world's largest producer
United Arab Emirates (UAE)	Most drinking water	Taweelah, about 909,000 m³ a day, the largest reverse-osmosis plant when it opened; Hassyan, about 818,000 m³ a day	Record-low tariffs on cheap solar and gas power
Kuwait, Qatar, Bahrain, Oman	Kuwait about 90% of drinking water, Oman 86%, Bahrain almost all		The most dependent; within range of the 2026 war
Israel	About 80% of drinking water	Sorek, about 620,000 m³ a day; Hadera; Ashkelon	The model of large, low-cost reverse osmosis
United States	Large capacity, mostly brackish, industrial, and reuse plants	Carlsbad, about 190,000 m³ (50 million gallons) a day, the largest seawater plant in the US; El Paso's inland brackish plant	California's permits are slow and strict
Spain	About 60% of the EU's capacity	Torrevieja	Europe's leader; much of it for farms
Australia	Large plants for every major mainland city	Perth (two plants), Sydney, Melbourne (Wonthaggi), Adelaide	Built after the Millennium Drought; some held in reserve
China	Growing	Tianjin, Qingdao	Industry and coastal cities
Egypt, Morocco, Algeria	Growing fastest	Casablanca's plant, about 300 million m³ a year at full size	The growth market
World	About 95 million m³ (25 billion gallons) a day from 15,906 plants in 2018; seawater and brackish capacity growing about 5.6% a year		About 1% of withdrawals; 48% of output in the Middle East and North Africa

Jones and colleagues (2019); GWI DesalData via Oliver Wyman (December 2025); the Associated Press (AP) on Gulf supply shares (March 2026); EU Blue Economy Observatory; company data. Approximate.

The world had 15,906 desalination plants producing about 95 million cubic meters a day in 2018, the latest full global inventory, and 48% of that came from the Middle East and North Africa. Industry trackers expect seawater and brackish capacity to grow about 5.6% a year from 2024 to 2030, with more than half of the new capacity in the Middle East and North Africa.

For the Gulf, desalination is the water supply itself: on AP's March 2026 figures, it provides about 90% of Kuwait's drinking water, 86% of Oman's, 70% of Saudi Arabia's, and nearly all of Bahrain's, and about 80% of Israel's. Outside the Gulf it is a supplement: about 1% of the world's withdrawals.

10c. Cost

Year	Best large plant ($/m³)	Typical ($/m³)	Driver
1990	About 2.50	3-5	Early membranes; no energy recovery
2000	About 1.00	1.5-2.5	Better membranes; energy-recovery devices
2005	About 0.53 (Ashkelon, Israel)	1.0-1.5	Large plants
2013	About 0.58 (Sorek, Israel)	0.8-1.2	Scale
2019	About 0.49 (Taweelah, Abu Dhabi)	0.7-1.0	Cheap power and finance in the Gulf
2023	0.365 (Hassyan, Dubai), the record	0.5-1.0 in the Gulf	Cheap solar power, scale, low-cost finance
2026	About 0.37-0.60 in Gulf tenders	0.50-3 elsewhere	Energy a third to a half of operating cost

Contracted tariffs, which include capital and finance, from project announcements. $0.365 per m³ is about 0.14 cents per US gallon, or about $450 per acre-foot.

The price of desalinated water from the best plants has fallen by about two-thirds since 2000. Large seawater plants now deliver it for $0.50-1.50 a cubic meter in most places and less in the Gulf, where ACWA Power's bid for Dubai's Hassyan plant set the record of $0.365 in 2023 on cheap solar power, scale, and low-cost finance. Smaller plants with dearer power and stricter environmental rules cost $1-3.

That is 1.5 to 4 times the cost of conventional sources, which is why desalination serves cities, industry, and the Gulf rather than farms: no crop except high-value greenhouse produce can pay for it. Energy is a third to a half of operating cost, so the economics track the price of power, and the shift to solar-powered plants in the Gulf, Morocco, and Australia drives the recent decline.

10d. The Limits

Desalination is a coastal, urban, and industrial solution, and its limits are structural: it needs a coast or a long pipeline from one, as Riyadh's supply shows, and energy at scale, which makes it a source of emissions unless the power is clean.

It also produces brine, about 142 million cubic meters a day worldwide on the 2019 estimate, or about 1.5 liters for every liter of fresh water, and Saudi Arabia, the UAE, Kuwait, and Qatar produce 55% of it. California regulates its disposal tightly, and studies report the Persian Gulf's salinity rising near the largest outfalls.

The 2026 war added a limit of its own: plants on both sides of the Gulf were hit, and a country that desalinates nine-tenths of its drinking water has a single point of failure in every plant (Module 7). Desalination will supply a growing share of the world's coastal cities and almost none of its farms, at a price that the rich and the desperate pay.

Module 10 Key Points

Desalination

• Reverse osmosis uses a third to a fifth of thermal desalination's energy and takes 90% or more of new capacity.

• The world desalinated about 95 million m³ a day in 2018, 48% of it in the Middle East and North Africa.

• Desalination supplies about 90% of Kuwait's drinking water, 70% of Saudi Arabia's, and 80% of Israel's.

• ACWA Power's Hassyan bid set the record low tariff, $0.365 per m³, in 2023.

• Each liter of fresh water leaves about 1.5 liters of brine; four Gulf states produce 55% of it.

• The 2026 war showed that a plant supplying most of a country's drinking water is a strategic target.

Module 10 Quiz

Check Your Understanding

1. Why has reverse osmosis displaced thermal desalination?

A) It needs no membranes
B) It uses a third to a fifth of the energy
C) It produces no brine, so it can be built on any coast
D) It needs no coastline, because it runs on river water and treated sewage

2. What did Jones and colleagues estimate about brine in their 2019 study?

A) About 142 million m^3 a day, roughly 1.5 liters per liter of fresh water
B) Modern plants produce almost none
C) About 1 million m^3 a day, all of it reused
D) Brine output roughly equals fresh-water output, almost all of it from American plants

3. What is the record-low tariff for desalinated seawater, and where was it set?

A) $2 per m^3 in California
B) $0.10 per m^3 in Oman
C) $5 per m^3 in Israel
D) About $0.365 per m^3, at Dubai's Hassyan plant in 2023

4. Why can desalination not solve farming's water shortages?

A) Few crops can pay its price
B) Farms are too far from the coast in every country
C) Its brine would poison the fields
D) Governments reserve all of it for cities by law

5. What share of the world's desalinated water came from the Middle East and North Africa, on the 2018 inventory?

A) About 5%
B) About 48%, the largest share
C) Nearly all of it
D) About a fifth, mostly in Israel, with the rest in North Africa

Module 11 — Bottled, Packaged, and Filtered Water

The Business of Selling Water by the Liter

Recommended Reading / Reference

Book: Peter Gleick, *Bottled and Sold: The Story Behind Our Obsession with Bottled Water* (2010)

Reference: Beverage Marketing Corporation's US bottled-water reports (May 2025); company reports for Nestlé, Danone, Coca-Cola, PepsiCo, Primo Brands, and Nongfu Spring; the French Senate's 2025 inquiry into mineral-water treatment; Qian and colleagues on nanoplastics in bottled water (*Proceedings of the National Academy of Sciences*, January 2024)

11a. The Market

Country	Bottled water (billion liters a year)	Per person (liters a year)	Why	Leading brands
China	About 110	About 80	Distrust of tap water; convenience; the largest market	Nongfu Spring, C'estbon, Ganten, Wahaha
United States	About 61	About 179 (47.3 US gallons) in 2024, a record	Convenience; distrust after Flint; bigger than soda since 2016	Primo Brands (Poland Spring), Dasani, Aquafina, Smartwater
Mexico	About 35	About 270	Tap water widely unsafe or distrusted; refillable 20-liter jugs	Bonafont (Danone), Ciel (Coca-Cola), Epura
Indonesia	About 30	About 110	No reliable tap water	Aqua (Danone)
Thailand	About 20	About 280	Habit and distrust of the tap	Singha, Crystal
Italy	About 15	About 250	A mineral-water tradition	San Pellegrino, Levissima, Sant'Anna
Germany	About 14	About 170	Sparkling mineral water	Gerolsteiner, Volvic
India	About 12, plus an informal sachet trade	About 8 in the formal market	Growing fast as a stand-in for piped water	Bisleri, Kinley, Aquafina
Gulf states	About 10	About 170	Little tap-drinking tradition	Masafi, Al Ain, Aquafina
West Africa	Large informal trade		'Pure water' sachets sold for pennies	Local
World	About 400-500	About 50-60	A market of roughly $300 billion	Nongfu, Danone, Nestlé, Coca-Cola, PepsiCo

Beverage Marketing Corporation (May 2025) for the United States; industry estimates for the rest, approximate. A liter is 0.26 US gallons.

Bottled water is a market of roughly $300 billion selling 400-500 billion liters a year, on industry estimates, and it has been one of the fastest-growing drinks for two decades. In the United States it has outsold carbonated soft drinks by volume since 2016, and Americans drank a record 47.3 gallons (179 liters) each in 2024, against 34.8 gallons of soda.

Consumption per person is highest in Mexico, Thailand, Italy, and the Gulf, places where tap water is distrusted, unavailable, or culturally secondary. It is growing fastest in China, India, Indonesia, and Africa,

where it substitutes for public supply that does not exist or cannot be trusted. In rich countries bottled water is a convenience; in poor ones it is infrastructure by the bottle.

11b. The Companies

- **Nongfu Spring:** China's largest bottler, whose founder Zhong Shanshan regained the top place on Hurun's China rich list in 2025, at 530 billion yuan (about $79 billion), on bottled water and tea.
- **Danone:** Evian, Volvic, Badoit, Aqua in Indonesia, and Bonafont in Mexico, the leader in premium and emerging-market water.
- **Nestlé:** Pure Life, Perrier, S.Pellegrino, Acqua Panna, and Vittel. It sold its North American mass brands, Poland Spring among them, in 2021, and they became part of Primo Brands, now the largest American seller. On July 23, 2026 it agreed to sell half of its remaining waters business to the private-equity firm Platinum Equity, in a venture valued at €4.9 billion, for about €3 billion in cash, with closing expected in the first half of 2027.
- **Coca-Cola and PepsiCo:** Dasani, Smartwater, Ciel, Kinley, and Aquafina, many of them purified municipal water resold at a premium, the model that made bottled water a mass product in the 1990s.
- **The regionals and the sachet sellers:** thousands of local brands, and in West Africa and South Asia the plastic sachet of 'pure water' sold for pennies, which is the real drinking-water supply of much of the urban poor.

11c. The Economics, Worked

Worked example — What a Bottle Costs and What It Sells For

An American bottler fills a half-liter bottle, about 17 ounces. The water, bought at a city rate of $1.50 per cubic meter, costs $0.00075, less than a tenth of a cent, and a spring-water bottler pays a state extraction fee of similar size or nothing. The plastic bottle and cap cost $0.03-0.05, filling, labeling, and packing $0.02-0.04, trucking to a store $0.05-0.10, and marketing $0.02-0.05, and the retailer takes $0.20-0.50. The bottle sells for $1.00-2.00 at a convenience store; in a supermarket 24-pack it sells for $0.15-0.25, because bulk shipping and thin retail margins strip most of those costs out. The water is about 0.05% of the price of the convenience-store bottle, while the bottle, the truck, and the shelf are the product. At $1.50 a half-liter, or $3,000 per cubic meter, the markup over tap water is about 2,000-fold, for water that consumers in blind tests cannot reliably tell from tap. The margin is why Nongfu Spring made its founder a billionaire and why every beverage company sells water.

11d. The Critiques and the Defense

The first critique is plastic: drinks are sold in roughly 500 billion plastic bottles a year, most of them never recycled. A 2024 study by Naixin Qian and colleagues counted about 240,000 plastic particles in a typical liter of bottled water, most of them nanoplastics too small for earlier methods to detect.

The second is extraction: companies pumping springs and aquifers in dry regions, Nestlé in California, Michigan, and Ontario, Coca-Cola in India, and Danone in Mexico, have faced protests over taking water from communities that then buy it back.

The third is regulation: bottled water is usually regulated as a food, more loosely than tap water, and France's Perrier affair showed what a label can hide. Authorities found that Nestlé had treated its Perrier and

Vittel sources with filtration and ultraviolet light that natural mineral water may not undergo, and in 2024 the company paid €2 million in a settlement with prosecutors. A Senate inquiry in 2025 accused the state of covering up the practice.

Perrier kept its label: in November 2025 a court in Nanterre allowed it to go on selling natural mineral water, and in December the prefect of the Gard department authorized production from two of its boreholes and closed three others. The industry's defense is that it sells convenience and, in much of the world, the only safe water available, which in Mexico, Indonesia, and West Africa is true.

11e. Filtration at the Tap

The alternative to the bottle is the filter, a fast-growing business of its own. Pitcher and faucet filters such as Brita, under-sink reverse-osmosis units, whole-house systems, and the water-cooler business serve households that distrust their tap. In poor countries, ceramic and membrane filters and community kiosks with reverse-osmosis units sell treated water at a fraction of the bottled price.

The 2024 American limits on forever chemicals spurred home filtration, and its technology of activated carbon, reverse osmosis, and ultraviolet light is the treatment train of Module 2 shrunk to the kitchen. Its logic is the bottle's: where the public system is trusted, the market is small, and where it is not, the household pays to finish the utility's job.

Module 11 Key Points

Bottled, Packaged, and Filtered Water

• Bottled water sells roughly 400-500 billion liters a year; Americans drank a record 179 liters each in 2024.

• Nongfu Spring's founder topped Hurun's China rich list in 2025; Nestlé agreed in July 2026 to sell half its waters.

• In a $1.50 convenience-store bottle, the water costs less than a tenth of a cent, about 0.05% of the price.

• A 2024 study found about 240,000 plastic particles in a typical liter of bottled water.

• France let Perrier keep its natural mineral water label in late 2025 after the scandal over illegal treatment.

• Bottles and home filters grow where the public system is distrusted; households pay to finish the utility's job.

Module 11 Quiz

Check Your Understanding

1. Which is the largest bottled-water market by volume?

A) India
B) The United States, by a wide margin
C) Mexico, among the highest per person
D) China, at about 110 billion liters

2. What did Nestlé announce for its waters business on July 23, 2026?

A) It bought Danone's water brands
B) It closed the Perrier source
C) A sale of half the business to Platinum Equity in a venture valued at €4.9 billion
D) A full listing of the waters business in Zurich

3. In the worked example, what share of a convenience-store bottle's price is the water itself?

A) About half
B) About 10%
C) Nearly all of it
D) About 0.05%, less than a tenth of a cent

4. What did a 2024 study find in bottled water?

A) About 240,000 plastic particles per liter, mostly nanoplastics
B) Hardly any plastic
C) Less plastic than in tap water
D) Lead above legal limits in most of the brands tested across the United States

5. What happened to Perrier's natural mineral water status in late 2025?

A) It was revoked
B) It was kept for two boreholes, and three were closed
C) It was suspended until Nestlé removes all of its filters
D) It was granted only for the bottles sold outside of France

Module 12 — Agriculture: The Largest Use

Seven-Tenths of the World's Withdrawals

Recommended Reading / Reference

Reference: FAO, *The State of the World's Land and Water Resources for Food and Agriculture* (2021); Mekonnen and Hoekstra's water-footprint studies (Water Footprint Network); the Public Policy Institute of California on the San Joaquin Valley; the Arizona Attorney General's suit against Fondomonte

12a. Irrigation

Method	How it works	Share of water reaching the crop	Share of irrigated area	Cost to install ($ per hectare)	Where
Flood or furrow (surface)	Water released across fields or between rows by gravity	40-60%	About 80-85%	Low, $200-500	Most of Asia and Africa; the American West's alfalfa
Center pivot or sprinkler	Water sprayed from rotating booms or fixed heads	65-80%	About 10-15%	$1,500-3,000	The Great Plains' green circles, Brazil, Saudi Arabia
Drip or micro	Water delivered to the roots through tubing and emitters	85-95%	About 5%	$2,000-5,000	Israel (about three-quarters of its irrigation), Spain, California orchards, India
Subsurface drip	Buried drip lines	90-95%	Under 1%	$3,000-6,000	High-value crops
Precision scheduling	Sensors and forecasts apply less water at the right time	Adds 10-20% to any method	Growing	Mostly software	Large farms in rich countries

Approximate. A hectare is 2.47 acres.

Irrigated land is about a fifth of the world's cropland and grows about 40% of its food. Agriculture takes 72% of freshwater withdrawals and about nine-tenths of the water consumed, the water that evaporates or is transpired by plants rather than returned to rivers and aquifers.

Most irrigated land is still flooded, a method thousands of years old that can lose half its water to evaporation and runoff, because flood water is usually cheap and better equipment is not. Drip irrigation, developed commercially by Israel's Netafim from 1965, cuts water use by 30-50% and raises yields, and Israel waters about three-quarters of its irrigated land this way, while India and China subsidize its spread.

The arithmetic of efficiency is less simple than it looks: water 'lost' from a flooded field often recharges the aquifer or flows back to the river for the next farm, so the savings across a basin are smaller than those on one field. Farmers who save water also tend to plant more rather than pump less, unless the water saved is taken out of the basin.

12b. The Water Inside Food

Product	Water footprint (liters per kg)	Where the water comes from	Notes
Beef	About 15,400	Mostly rain on pasture and feed crops	The largest footprint among the meats
Lamb	About 10,400	Mostly rain on pasture	
Almonds (shelled)	About 16,000	Much of it irrigation; California grows about 80% of the world's almonds	Very high per calorie where irrigated
Pork	About 6,000	Mostly rain on feed	
Cheese	About 5,000		
Chicken	About 4,300	Mostly rain on feed	The lowest of the meats
Rice	About 2,500	A large irrigation share in Asia's flooded paddies	
Wheat	About 1,800	Mostly rain, with irrigated wheat in India and Pakistan	
Maize	About 1,200	Mostly rain in the US Corn Belt	
Potatoes	About 290		
Cotton (lint)	About 10,000	Heavy irrigation in India, Pakistan, Uzbekistan, and the US	Behind the Aral Sea's collapse (Module 7)
A cup of coffee	About 130 liters per cup	Mostly rain	Brazil, Vietnam, Colombia

Global averages from Mekonnen and Hoekstra (2011-12) and the Water Footprint Network. A liter per kilogram is about 0.12 US gallons per pound.

The water inside food explains the geography of scarcity: a kilogram of beef embeds about 15,400 liters, most of it rain on pasture and feed, while a kilogram of shelled almonds embeds about 16,000, much of it pumped or diverted in California, and a kilogram of potatoes about 290. Diets shifting toward meat and dairy raise water demand faster than population does.

Trade moves that virtual water: the United States, Brazil, Australia, and Argentina export it in grain, meat, and cotton, and the Middle East, North Africa, and East Asia import it. Egypt, among the largest wheat importers, buys about 12-13 million tonnes a year, grain that took roughly 20-23 km³ of water to grow, about two-fifths of the 55.5 km³ a year the 1959 Nile agreement allots it. For a dry country, importing food is importing water, which is why food security and water security are one policy.

12c. The Great Reallocations

Because farming uses most of the water at the lowest price, every serious water reform is a transfer from farms to cities and rivers, and the 2020s have begun it. On the UN's 2022 figures, a cubic meter used in farming produced about $0.70 of value added, against $38.50 in industry and $114 in services.

California's groundwater law is expected to take at least 500,000 acres of San Joaquin Valley farmland out of production. The Lower Basin states of the Colorado expected to conserve about 1.3 MAF in 2026, about 770,000 acre-feet of it paid for by the federal government, with deals made in 2023 at up to $400 an acre-foot, before the cuts imposed for 2027-28 (Module 4).

Spain and Italy cut irrigation allocations first in drought, and India's Punjab is trying to move farmers off flooded rice. The transfers are explosive because farmers hold the senior rights, the oldest claims that are

served first in a drought (Module 16), and the rural votes, and they are hard to stop because the water is worth so much more elsewhere.

Worked example — The Saudi Alfalfa Case

In 2014 Fondomonte, a subsidiary of the Saudi dairy company Almarai, began farming about 3,500 acres (1,400 hectares) of Arizona state trust land in the Butler Valley, at a low rent, and pumping groundwater that Arizona law left unmetered and unlimited outside its management areas. It grew alfalfa, baled and shipped to feed Saudi cows, because Saudi Arabia had banned growing such fodder at home after exhausting its own aquifers. Desert alfalfa takes 2-2.5 meters (7-8 feet) of water a year, about 25,000 cubic meters per hectare, so the lease alone could use about 35 million cubic meters (28,000 acre-feet) a year, roughly the household use of 150,000-200,000 Americans. Neighbors' wells went dry. The state ended the Butler Valley lease, effective in 2024, and declined to renew Fondomonte's other leases. Arizona's attorney general later sued the company under public-nuisance law over its pumping on private land in the Ranegras Plain, where it used about 31,000 acre-feet in 2023, more than 81% of the basin's groundwater pumped that year. The company denies the claims. The case crystallized three facts: a water-scarce country will farm other countries' aquifers if the law allows; unmetered groundwater is free until it is gone; and Saudi Arabia had run the same experiment at home, growing wheat on fossil water from the 1980s until it ended the program in 2016.

Module 12 Key Points

Agriculture: The Largest Use

- Irrigated land is a fifth of cropland but grows about 40% of the world's food.
- Most irrigated land is still flooded because water is cheap; drip reaches 85-95% efficiency on about 5%.
- Saved water is often replanted, so basin-wide savings from drip are smaller than savings on one field.
- A kilogram of beef embeds about 15,400 liters of water; a kilogram of potatoes about 290.
- Farming produced about $0.70 of value per cubic meter in 2022, against $38.50 in industry.
- Arizona ended a Saudi-owned farm's lease and sued over its pumping: 31,000 acre-feet in 2023.

Module 12 Quiz

Check Your Understanding

1. Why is most of the world's irrigated land still flooded rather than dripped?

A) Flooding is the most efficient way to water any crop
B) Drip lines clog in the silty water most farms use
C) Flood water is cheap; drip is not
D) Drip cannot water grain crops such as wheat or rice at all

2. Why are basin-wide savings from drip irrigation smaller than field-level savings?

A) Evaporation from drip lines is higher than from canals
B) Drip lines leak more than open canals
C) Water lost from flooded fields often recharges aquifers or returns to the river, and farmers who save water tend to plant more
D) Field savings are measured in dry years only

3. On the UN's 2022 figures, about how much value does a cubic meter of water produce in farming?

A) About $0.70
B) About $38.50, as in industry
C) About $114, as in services
D) About $5, the same as in every other sector

4. About how much water does Egypt's imported wheat embody each year, on the module's arithmetic?

A) Almost none
B) About 20-23 km^3, roughly two-fifths of its Nile share
C) More than the whole Nile
D) About 100 km^3, twice the Nile's flow through the Aswan High Dam each year

5. What did Arizona do about Fondomonte's alfalfa farming?

A) Raised its rent and kept the lease
B) Sold it the state land outright for a new dairy in the Butler Valley
C) Required it to switch to drip irrigation within five years
D) Ended its lease and sued over its pumping

Module 13 — Industry, Energy, and Data Centers

The Water-Energy Nexus and the Newest Demand

Recommended Reading / Reference

Reference: International Energy Agency (IEA), *Water-Energy Nexus* (2016) and its data-center analyses; USGS water-use estimates; Google Environmental Report (July 2026); Microsoft Environmental Data Fact Sheet 2026; Taiwan Semiconductor Manufacturing Company (TSMC) sustainability reports

13a. Energy's Water

Use	Water withdrawn (liters per MWh)	Water consumed (liters per MWh)	Notes
Coal plant, once-through cooling	80,000-200,000	About 1,000	Takes river water and returns it warmer
Coal or gas steam plant, cooling tower	2,000-4,000	1,500-3,000	Consumes by evaporation
Gas combined cycle, cooling tower	800-1,500	500-1,000	About half of coal's
Nuclear, tower or once-through	3,000-4,000; 100,000 and more once-through	2,000-3,000	River-cooled reactors are the drought casualties (Module 5)
Solar photovoltaic, wind	Under 100	Under 50	Panel washing only
Hydropower, reservoir evaporation		5,000-70,000, depending on climate	The largest consumer per MWh where reservoirs are shallow and hot
Fracking	Tens of millions of liters per well; Permian wells often about 40 million (more than 10 million gallons)	Most of it	Disposal of the salty water that returns is a growing problem
Hydrogen by electrolysis	About 9-10 liters per kilogram, plus cooling	About 9 per kilogram	Green hydrogen at scale is a water question

Approximate; IEA, USGS, and US national laboratories. A megawatt-hour (MWh) is 1,000 kilowatt-hours, about what an American home uses in a month; 1,000 liters is 264 US gallons.

Energy production withdraws about a tenth of the world's fresh water, and in the United States the cooling of power plants was the largest single withdrawal for decades, 41% of the total in the last national survey of 2015. The nexus runs both ways: it takes water to make power, for cooling, fracking, and hydropower's evaporation, and power to make water, for pumping, treatment, and desalination.

The energy transition changes the balance: solar and wind use almost no water, the largest hidden water saving in the transition, while green hydrogen, biofuels, and the cooling of new nuclear plants add demand. Drought now curtails power directly, as Europe's rivers showed in 2026.

13b. Industry and Chips

Industry withdraws about 15% of the world's fresh water, on the FAO's 2023 figures, concentrated in pulp and paper, steel, chemicals, textiles, food processing, and mining. Concentrating copper takes roughly a cubic meter of water per tonne of ore, or hundreds per tonne of copper, which is why Chile's copper mines pump desalinated seawater more than 3,000 meters (10,000 feet) up the Andes.

Chipmaking needs ultrapure water, filtered to parts per trillion, in large volumes for rinsing wafers, and a large fab can use tens of millions of liters a day. Taiwan's 2021 drought forced TSMC to truck water to its fabs and to push its recycling higher. Its new fabs in Arizona, and Intel's, sit in a desert on stressed aquifers and are building their own water-reclamation plants.

13c. Data Centers

Facility or company	Water use	Cooling	Note
A large evaporative-cooled data center of about 100 megawatts (MW)	1-5 million liters (0.3-1.3 million gallons) a day	Evaporative cooling towers	Comparable to the household use of a town of about 3,000-15,000 Americans
Google, 2025	10.9 billion US gallons (41 billion liters) consumed, up 34%; 7.7 billion gallons replenished	About two-thirds of its data centers use evaporative cooling	Issued water standards for the industry on June 3, 2026
Microsoft, fiscal year to June 2025	8.2 billion liters consumed, up 22%; 13.3 billion withdrawn; 48% of consumption in water-stressed areas	A design introduced in 2024 uses no water for cooling in operation	Pledged to be water positive, replenishing more than it uses, by 2030
Amazon Web Services, Meta	Billions of liters each	Mixed	Water-positive pledges for 2030
Closed-loop or direct-to-chip liquid cooling	Near zero on site, at the cost of more electricity	Dry coolers; liquid piped to the chips	The shift in dry regions since 2024
Indirect water in the power supply	Several liters per kWh where coal or gas plants with cooling towers supply the power		Often larger than direct use

Google Environmental Report via DatacenterDynamics (July 1, 2026) and Axios (June 3, 2026); Microsoft Environmental Data Fact Sheet 2026.

Data centers use water to reject heat, because evaporative cooling is the cheapest way to cool a building full of servers, and the buildout for artificial intelligence (AI) has made water a siting constraint. Google's water consumption rose 34% in 2025 to 10.9 billion gallons, and Microsoft's 22% in its 2025 fiscal year to 8.2 billion liters, nearly half of it in water-stressed areas.

Dry places have pushed back: Google redesigned its Uruguay data center for air cooling after the 2023 drought, a Chilean court sent its Santiago project back for review, and towns from Arizona to Texas to Spain have fought over permits and aquifer draws.

The industry's answer is closed-loop and direct-to-chip cooling, which uses almost no water on site at the cost of more electricity, along with pledges to replenish more water than it uses by 2030. On June 3, 2026 Google proposed industry standards, including avoiding water-intensive cooling in stressed regions and disclosing water use every year.

The indirect water, evaporated at the power plants that supply the electricity, is often larger than the direct use. A data center on evaporative cooling in a coal-and-gas region is water-intensive twice over, while one on solar power with dry cooling is nearly water-free, and which kind it is getting is the question every state courting the investment faces.

Module 13 Key Points

Industry, Energy, and Data Centers

• Energy production withdraws about a tenth of the world's fresh water; US power-plant cooling took 41% in 2015.

• Solar and wind use almost no water, the largest hidden water saving in the energy transition.

• Industry takes about 15% of withdrawals; chip fabs need ultrapure water by the tens of millions of liters a day.

• Google's water consumption rose 34% in 2025 to 10.9 billion gallons; Microsoft's rose 22%.

• A data center's indirect water, evaporated at its power plants, often exceeds the water it uses on site.

Module 13 Quiz

Check Your Understanding

1. Why does the energy transition save water?

A) New coal plants use dry cooling
B) Gas plants need no cooling water
C) Solar and wind use almost no water, while coal and nuclear plants evaporate large volumes for cooling
D) Hydropower replaces fossil plants everywhere

2. How much water did Google's operations consume in 2025?

A) 41 billion liters
B) About 1 billion liters, a small town's use
C) About 400 billion liters, ten times its 2024 use
D) Almost none, because all its sites are air-cooled

3. Why can a data center's indirect water use exceed its direct use?

A) Its chips need ultrapure water
B) Its cooling towers recycle all their water
C) Its cooling loops lose most of their water through leaks in the buildings' pipes and tanks
D) The power plants that supply it evaporate water for cooling

4. What did Taiwan's 2021 drought force TSMC to do?

A) Close its fabs
B) Truck in water and recycle more of it
C) Move production to Japan for the rest of the year
D) Switch to cooling its fabs with seawater from the Taiwan Strait

5. What share of all US freshwater withdrawals went to power-plant cooling in the last national survey?

A) About 72%, more than farming
B) 41%, in 2015
C) About 10%, behind households and farms
D) About 2%, almost all of it for nuclear plants

Module 14 — Water Quality and Contamination

What Is in the Water, and the Rules That Govern It

Recommended Reading / Reference

Book: Anna Clark, *The Poisoned City: Flint's Water and the American Urban Tragedy* (2018)

Reference: EPA's 2024 PFAS rule and its May 2026 rescission proposal; the Lead and Copper Rule Improvements (LCRI, October 2024); WHO, *Guidelines for Drinking-water Quality*; the EU Drinking Water Directive (2020)

14a. The Contaminants

Contaminant	Source	Health effect	Where	Limit or rule	Treatment
Pathogens: cholera, typhoid, E. coli, Cryptosporidium, Giardia	Sewage and animal waste	Diarrheal disease; unsafe water, sanitation, and hygiene caused about 1.4 million deaths in 2019	Wherever water goes untreated; Milwaukee's 1993 outbreak sickened about 400,000	No fecal bacteria; limits on turbidity	Disinfection and filtration
Lead	Lead service lines and solder, leaching into corrosive water	Damage to children's brains; no safe level	The US, with about 9 million lead lines; old European cities	US 2024 rule: replace lead lines by 2037 and act at 10 parts per billion (ppb) from 2027	Corrosion control; pipe replacement
PFAS (forever chemicals)	Firefighting foam, nonstick and waterproof coatings, factories	Linked to cancers and immune and developmental effects	Near military bases, airports, and factories; found in many US systems	US: 4 ppt for PFOA and PFOS; EU: 100 nanograms per liter for 20 PFAS from January 2026	Activated carbon, ion exchange, reverse osmosis
Nitrates	Fertilizer and manure	Blue-baby syndrome; possible cancer risk	Farm regions: the US Midwest, the Netherlands, Brittany, Punjab	10 milligrams per liter as nitrogen (US); 50 as nitrate (EU)	Ion exchange; less fertilizer
Arsenic	Natural, in groundwater	Cancer and skin lesions	Bangladesh and West Bengal, Chile, Argentina, the US West	10 micrograms per liter (WHO)	Adsorption; safer wells
Fluoride, in excess	Natural	Skeletal fluorosis	India, China, East Africa	1.5 milligrams per liter (WHO)	Adsorption; blending
Pharmaceuticals and hormones	Sewage effluent	Hormone effects on fish; effects on people debated	European and American rivers	Monitoring; EU watch lists	Advanced oxidation; activated carbon
Microplastics	Textiles, tires, packaging	Under study	Everywhere, bottled water especially	No limits yet	Filtration removes most
Salt	Seawater intrusion, irrigation, road salt	Undrinkable water and failed crops	Coastal aquifers; the Indus and Nile deltas; Basra	Varies	Desalination or a new source
Disinfection byproducts	Chlorine reacting with organic matter	Cancer risk	Treated systems	80 micrograms per liter for trihalomethanes (US)	Removing organic matter first; chloramine

WHO; EPA; EU Drinking Water Directive. A part per trillion (ppt) is a nanogram per liter, roughly one drop in 20 Olympic swimming pools.

14b. Flint

In April 2014 Flint, Michigan, a shrinking industrial city run by a state-appointed emergency manager, switched its water from Detroit's system to the Flint River to save money. Its treatment plant did not add the orthophosphate that had protected the pipes, and the corrosive river water stripped the scale from the city's lead service lines.

Lead reached the water of about 100,000 people for eighteen months while officials insisted it was safe. A pediatrician's study of children's blood, a Virginia Tech engineer's sampling, and residents' organizing forced the switch back in October 2015, and a Legionnaires' disease outbreak in the same period killed at least twelve people.

The consequences ran for a decade: the state agreed to a $626 million settlement, and criminal charges against state officials were eventually dismissed. A court-supervised program replaced about 11,000 lead and galvanized lines by July 2025, and on August 3, 2026 the city announced that no active lead service lines remained, after excavating about 31,930 addresses and replacing 11,600 lines.

Flint's water has tested below the federal action level for lead since July 2016, and the city became the reference case for what happens when a water system is run for cost rather than safety and its users are poor enough to be ignored.

The national rule that followed, the Lead and Copper Rule Improvements of October 2024, requires nearly every American utility to replace its lead service lines within ten years and lowers the level that triggers action from 15 to 10 parts per billion. Utilities' associations challenged it as unaffordable and beyond the EPA's authority over pipes on private land, and the D.C. Circuit heard the case on September 30, 2026, with a ruling possible in early 2027.

14c. PFAS and the 2026 Rollback

Per- and polyfluoroalkyl substances (PFAS), thousands of synthetic chemicals used since the 1940s in nonstick pans, waterproof fabrics, firefighting foam, and food packaging, do not break down in the environment and accumulate in the blood. In April 2024 the EPA set the first enforceable national limits: 4 ppt each for PFOA and PFOS, 10 ppt each for three more, and a combined limit for mixtures of four, with compliance due in 2029.

In May 2025 the EPA said it would keep the PFOA and PFOS limits, give utilities until 2031 to meet them, and rescind the rest. A federal appeals court refused on January 21, 2026 to strike the four limits before ruling on the whole rule, and on May 18, 2026 the EPA formally proposed rescinding them, arguing that the 2024 rule had skipped steps the Safe Drinking Water Act requires. The court heard arguments on the 2024 rule on September 18, 2026, and as of early October neither the court's ruling nor the final rescission had been issued.

The case for the 2024 limits. Public-health groups and many states argue that the chemicals are persistent, widespread, and linked to kidney and testicular cancer, immune suppression, and low birth weight, so limits near the level of detection are justified. They say a combined limit is the only way to regulate chemicals that occur together, and that dropping it invites a patchwork of state rules.

The case for the rollback. The utilities' associations and the Trump administration's EPA argue that the rule's costs were understated and fall on ratepayers. A study for the American Water Works Association (AWWA) put compliance at $3.8 billion a year and up to $40 billion of capital, against the EPA's $1.5 billion a year. They add that the 2024 rule regulated four chemicals without the step-by-step findings the law requires, and that utilities need time to build treatment.

The evidence. The EPA estimated in 2024 that 6-10% of the country's 66,000 public water systems would need to act, and that the rule's benefits roughly matched its costs before counting harms it could not price. Manufacturers' settlements, 3M's of up to $12.5 billion and $1.185 billion from DuPont, Chemours, and Corteva, cover part of the treatment cost, and the rest lands on water bills. The EU's limits for 20 PFAS took effect in January 2026.

The course's reading. The heart of the 2024 rule, the PFOA and PFOS limits, survives, so the practical change is smaller than the politics suggests. What remains open is legal and financial: whether the court upholds the 2024 process, and who pays to remove chemicals that their makers put into the water.

14d. The Developing World's Sewer Problem

For most of humanity the contaminant that matters is sewage: unsafe drinking water, sanitation, and hygiene caused about 1.4 million deaths in 2019, about 395,000 of them children under five, on the WHO's 2023 estimate, about a million of them from diarrheal disease. Cholera, which rich countries had largely eliminated by the early twentieth century, sickened 614,828 people and killed 7,598 in 33 countries in 2025 as wars and floods broke water systems.

Nearly half of household wastewater worldwide is not safely treated, and stretches of rivers from the Ganges to the Citarum in Java to the Tietê in São Paulo are open sewers. Bangladesh's arsenic crisis is a warning about solving one water problem by creating another: tube wells drilled from the 1970s to escape sewage-borne disease put tens of millions of people onto groundwater naturally laced with arsenic, the largest mass poisoning in history.

The fix everywhere is what rich cities built a century ago: sewers, filtration, and chlorination. Its obstacle is money (Module 8).

Module 14 Key Points

Water Quality and Contamination

• Unsafe water, sanitation, and hygiene caused about 1.4 million deaths in 2019; cholera killed 7,598 people in 2025.

• Flint skipped corrosion control in 2014; in August 2026 the city said no active lead lines remained.

• The 2024 US lead rule requires lead lines out by 2037; utilities' challenge was argued in September 2026.

• The EPA keeps 4 ppt limits for PFOA and PFOS but proposed in May 2026 to rescind four others.

• Utilities put PFAS compliance at $3.8 billion a year; the EPA estimated $1.5 billion.

Module 14 Quiz

Check Your Understanding

1. What went wrong in Flint in 2014?

A) Corrosion control was skipped on river water
B) PFAS foam from an air base
C) A sewage plant overflowed into the river intake
D) Detroit's water was cut off when the city failed to pay its bills

2. What did the EPA propose on May 18, 2026?

A) Tighter limits on all six PFAS
B) Delaying all PFAS limits to 2040
C) Rescinding the limits for four PFAS while keeping 4 ppt for PFOA and PFOS
D) Replacing the limits with voluntary health advisories

3. What did the federal appeals court decide on January 21, 2026?

A) It struck down the whole rule
B) It upheld the 2024 rule in full
C) It ordered the EPA to write limits for all 15,000 PFAS within two years
D) It refused to vacate the four limits without a full ruling

4. What has become of Flint's lead service lines?

A) Most are still in use
B) They were coated, not replaced
C) The city reported in August 2026 that no active lead lines remained
D) They were replaced with plastic lines that failed within five years of installation

5. Which contaminant matters most for most of humanity, by deaths?

A) Microplastics
B) Sewage and the pathogens it carries, behind about 1.4 million deaths in 2019
C) PFAS in tap water
D) Lead from old service lines

Module 15 — Floods, Stormwater, and Too Much Water

The Other Half of the Crisis

Recommended Reading / Reference

Reference: Munich Re's natural-catastrophe reports (January 2026); the EM-DAT international disaster database; the Dutch Delta Programme; Congressional Research Service reports on the National Flood Insurance Program (NFIP); Indonesia's Nusantara capital authority

15a. The Floods

Event	Year	Deaths	Cause	Lesson
Germany and Belgium (the Ahr valley)	2021	About 220	A stalled storm; a month's rain in hours	Warnings issued but not acted on
China (Zhengzhou, Henan)	2021	About 400	More than 600 mm (24 inches) of rain in three days; a subway flooded	Urban drainage overwhelmed
Pakistan monsoon floods	2022	About 1,700	Record monsoon rain and glacial melt; a third of the country under water	About $30 billion of damage and losses; 8 million displaced
Libya (Derna)	2023	Thousands	Storm Daniel broke two neglected dams	Dam safety and state collapse
Brazil (Rio Grande do Sul)	2024	About 180	Weeks of rain; a state capital flooded	Levees and pumps failed
Hurricane Helene (US Southeast)	2024	About 250	Inland flooding hundreds of kilometers from landfall	About $79 billion; flood risk far from coasts
Valencia, Spain	2024	About 230	A cut-off low, called a DANA (Depresión Aislada en Niveles Altos) in Spain, dropping a year's rain in hours	Alerts came after the water
Texas Hill Country	2025	135, 116 of them in Kerr County	Overnight rain sent the Guadalupe River up by about 26 feet (8 m)	Camps and homes in the flood zone; no sirens
Pakistan monsoon	2025	About 1,000	Flash floods and swollen rivers from India	Upstream releases and warnings via diplomats, not the treaty's commission
Indonesia, Thailand, Malaysia (Cyclone Senyar)	2025	At least 1,500	A rare cyclone over the Strait of Malacca	Landslides and floods in Sumatra and southern Thailand
China (Typhoon Maysak)	2026	159, 26 of them when the Liulan Reservoir's earth dam failed	A typhoon's rain on old dams	Aging small dams
Nepal (Langtang valley)	2026	At least 1,455, with 5,285 missing	A glacier collapse on August 26	Glacial hazards in the Himalaya

Government and agency counts as reported; approximate. The Nepal search ended on October 5, 2026.

Floods are the most common natural disaster, on the EM-DAT database's count, and the same intensified cycle that lengthens droughts loads more water into each storm: air that is 1°C (1.8°F) warmer holds about

7% more moisture, and heavy rain intensifies with it. Munich Re put the world's natural-catastrophe losses at about $244 billion in 2025, of which $108 billion was insured, and floods, storms, and wildfires caused $166 billion of it.

Losses rise with warming, with exposure as cities spread onto floodplains and deltas, and with subsidence, as Jakarta, Bangkok, and the Mekong delta sink faster than the sea rises. Several of the deadliest recent floods came from the mountains, among them Pakistan's monsoon floods of 2022 and the collapse of a glacier into Nepal's Langtang valley in August 2026.

15b. Defenses

The Netherlands is the reference: a quarter of the country lies below sea level, yet it has not flooded catastrophically since 1953, when the sea killed 1,836 people, thanks to the Delta Works of dikes and storm-surge barriers. Its Room for the River program lowered floodplains and moved dikes back so rivers can spread, and its Delta Programme plans a century ahead and spends about €1.5 billion a year.

The American model is levees and the National Flood Insurance Program (NFIP), which for decades subsidized building in floodplains. It owes the Treasury about $22.5 billion and, since its Risk Rating 2.0 reform of 2021, has moved premiums toward the true risk, pricing some households out. Its authority to write policies lapsed during the federal shutdown of October-November 2025 and briefly in February 2026, and it was extended to December 11, 2026.

China's sponge cities, with permeable pavement, green roofs, wetlands, and retention basins, absorb ordinary storms but were overwhelmed in Zhengzhou in 2021. Dams control floods as well as store water and fail catastrophically when neglected, as at Derna in 2023 and Liulan in 2026.

Early warning is the cheapest defense by far, and it failed in the Ahr valley, in Valencia, where phone alerts arrived after the water, and in Texas, where Kerr County had no flood sirens. The UN's Early Warnings for All initiative aims to cover everyone on earth by the end of 2027.

15c. Insurance's Retreat and Managed Retreat

The economics of flooding arrive through insurance: private insurers have pulled back from Florida, Louisiana, and parts of California and raised premiums across Europe, and the federal program's honest pricing makes some homes too costly to insure. A home that cannot be insured cannot be mortgaged, which is how flood risk becomes a story about property values and the tax base of whole towns.

The policy that follows is managed retreat: buying out and relocating communities from floodplains and coasts. The Netherlands has done it for its rivers, American counties have bought out tens of thousands of flooded homes, and Indonesia is doing it for a capital.

Jakarta is the extreme case: about 40% of the city lies below sea level, and parts of North Jakarta have sunk by as much as 25 centimeters (10 inches) a year, because many households and businesses pump their own groundwater where piped water does not reach. In 2019 Indonesia decided to move its capital about 1,300 km to Nusantara on Borneo, held its first independence ceremony there in 2024, and now plans for it to be the political capital from 2028.

Jakarta's ten million people stay, so the city is building defenses too. Its government's 19 km sea wall along the northern coast was due to begin in September 2026, part of a national plan for a wall of about 500 km

along Java's north coast that could cost up to $80 billion over 20 years. The lesson is that subsidence from unpiped groundwater can sink a megacity, and that retreat on a national scale is now a policy.

The other half of the water crisis is that the places with too much water are often the same places, in another season, as the places with too little.

Module 15 Key Points

Floods, Stormwater, and Too Much Water

• Natural catastrophes cost about $244 billion in 2025; floods, storms, and wildfires caused $166 billion of it.

• Warmer air holds about 7% more moisture per degree Celsius, so storms dump more water in the same hours.

• The Netherlands has avoided catastrophe since 1953 with the Delta Works and Room for the River.

• Early warning is the cheapest defense; it failed in the Ahr valley in 2021 and in Valencia in 2024.

• Uninsurable homes cannot be mortgaged, so flood risk becomes a property-value and tax-base problem.

• Jakarta is sinking up to 25 cm a year; Nusantara is to be Indonesia's political capital from 2028.

Module 15 Quiz

Check Your Understanding

1. How much did natural catastrophes cost the world in 2025, on Munich Re's count?

A) About $2 trillion, mostly insured
B) About $24 billion, all of it from floods
C) About $500 billion, half from earthquakes
D) About $244 billion

2. What is the Netherlands' Room for the River program?

A) Giving rivers space to spread
B) A flood tax
C) A program to build higher concrete walls along every river and canal
D) A Dutch insurance plan for houseboats

3. Which flood measure failed in the Ahr valley in 2021 and in Valencia in 2024?

A) The upstream dams
B) Early warning
C) The sponge-city drainage systems
D) The levees built after the floods of 1953

4. Why is Indonesia moving its political capital to Nusantara?

A) For better ports
B) Because a volcano threatens Jakarta
C) Jakarta is sinking and floods
D) To claim disputed territory on Borneo

5. How does flood risk become a property and credit problem?

A) Through insurance: homes that cannot be insured cannot be mortgaged, so values and tax bases fall
B) Through higher rents in flood zones
C) Through lower property taxes in flood zones
D) Through banks lending more to riverside towns

Module 16 — Water Law, Rights, and Markets

Who Is Allowed to Use Water, and How It Is Allocated

Recommended Reading / Reference

Reference: The Murray-Darling Basin Authority's reports and the 2012 Basin Plan; the Australian Competition and Consumer Commission's water markets inquiry (2021); Getches and colleagues, *Water Law in a Nutshell*; UN General Assembly resolution 64/292 on the human right to water (2010); Chile's 2022 water code reform

16a. The Doctrines

Doctrine	Rule	Where	Consequence
Riparian rights	Owners of land along a river may use it reasonably, without impairing others' use	The eastern US, England, much of the common-law world	Suits wet places; no priority in drought
Prior appropriation	First in time, first in right: the earliest user holds the senior right wherever the land lies, and unused rights can be lost	The western US and parts of Canada	Senior rights, usually farms, get water first in drought; junior users, often cities, buy or lease; use-it-or-lose-it discourages saving
Rule of capture	A landowner may pump unlimited groundwater from beneath the land	Texas, tempered by local districts; historically much of the US and India	The race to the bottom in shared aquifers
Correlative rights	Overlying owners share groundwater in proportion	California, now managed under its 2014 groundwater law	Weak until basins were required to balance
State ownership with licenses	Water belongs to the state or the public; users hold licenses	Civil-law countries, China, Israel, Australia since its reforms, South Africa since 1998	Makes reallocation and markets possible; depends on the state's capacity
Islamic and customary law	Water as common property, with priority for drinking and animals	The Middle East, parts of Africa and Asia	Coexists uneasily with modern codes
The human right to water	Recognized by the UN General Assembly in 2010; the WHO cites 50-100 liters a person a day as the basic need	Written into the constitutions of South Africa, Kenya, Mexico, and others	Grounds lifeline tariffs and limits on shutoffs; unenforceable where the state is weak

Who may use water is decided by legal doctrines that are older than the scarcity. The American West's prior appropriation gives the senior right to whoever diverted first, usually a farmer a century ago, and cuts the junior user, often a city, first in a drought, while its use-it-or-lose-it rule punishes saving. The rule of capture lets a landowner pump what lies beneath the land, the doctrine behind the aquifer races of Texas and India.

Civil-law and reformed systems vest water in the state and license its use, which is what makes reallocation and markets possible in Australia, South Africa, Chile, and Israel, while between countries the law is thinner still. The 1997 UN convention's principles of equitable use and no significant harm bind few states, so rivers are governed by bilateral treaties such as the Indus and the US-Mexico agreements, by commissions without the upstream power, as on the Mekong, or by no basin-wide treaty at all, as on the Nile and the Tigris-Euphrates.

16b. The Argument Over Water Markets

The case for markets. Economists and many water managers argue that trading moves water from low-value to high-value uses without a regulator having to decide, pays the sellers rather than taking their water, and puts a visible price on scarcity. They point to Australia's Murray-Darling, where trade let farmers keep orchards alive through droughts, and to the American West, where cities lease water from farms that fallow fields instead of seizing it.

The case against. Critics argue that water is a human right and an ecological necessity, not a commodity, and that markets concentrate it in the hands of whoever can pay. Chile's rights ended up concentrated in a few companies and estates while villages beside export orchards were supplied by trucks, and in Australia speculators and foreign funds hold entitlements while towns downstream watched their rivers dry.

The evidence. Markets have reallocated water quickly where the rules were sound. Australia's competition regulator found in 2021 that the Murray-Darling market works but lacks integrity safeguards, including rules against insider trading, and Australia has begun legislating them. Chile's market concentrated rights because they were granted free, in perpetuity, and without a cap, and its 2022 reform made new rights temporary and put drinking water first.

The course's reading. A water market is only as good as the cap, the registry, and the share set aside for rivers and people that come before it. With them, as in Australia, it allocates scarcity efficiently, and without them, as in Chile before 2022, it turns a public resource into private wealth.

16c. The Murray-Darling Market, Worked

Australia's Murray-Darling basin, about a million square kilometers (390,000 square miles) that grow about 40% of the country's farm output, runs the world's most developed water market. It was built from the 1990s, when water rights were separated from land and made tradeable, and it expanded through the Millennium Drought of 1997-2009.

Worked example — How the Market Allocates a Drought

A rice grower in the Riverina holds a water entitlement of 1,000 megaliters (ML), about 810 acre-feet, and an almond grower downstream holds 500 ML. In a wet year allocations are 100%, and water on the temporary market trades at about A$50-100 a megaliter; the rice grower uses his water, and the almond grower buys a little extra. In a drought like 2019's, allocations fall to 30% and the temporary price rises to A$600-900 a megaliter. The rice grower's 300 ML is then worth about A$250,000 (about $178,000; A$ is the Australian dollar) on the market and would grow rice worth about A$120,000, so he sells the water and leaves the paddock fallow. The almond grower, whose trees would die without water and whose crop is worth about A$4,000 a megaliter, buys it. Water moves from the low-value annual crop to the high-value permanent one without a regulator deciding, and the rice grower is paid. The critiques are as real. The market sent water to almond plantations that a long drought could still kill. Governments spent about A$13 billion buying back and saving water for rivers and wetlands and still fell short. Towns downstream on the Darling, Wilcannia and Menindee, saw the river run dry, and at Menindee millions of fish died in 2019 and 2023, while water was traded upstream. The market allocates efficiently within the rules; it does not decide what the rules should protect.

16d. The Other Markets

Chile privatized water rights outright in its 1981 water code, separated them from land, and let them trade. Forty years later a few companies and estates held the rights to whole river basins, and rural communities lacked drinking water beside irrigated export orchards. The 2022 reform made new rights temporary, for up to 30 years, gave human consumption priority, and lets unused rights lapse, while two attempts to write a new constitution, partly over water, failed in 2022 and 2023.

The western United States trades water within states under prior appropriation, from northern Colorado's Colorado-Big Thompson shares to California's drought-year transfers and Arizona's water bank, and the federal payments to fallow Colorado River farms are a market in all but name. Nasdaq's California water futures, launched in 2020, let anyone hedge or speculate on an index of the state's water prices and have traded thinly. China has piloted water-rights trading on the Yellow River and runs a national water exchange.

Module 16 Key Points

Water Law, Rights, and Markets

• Prior appropriation gives the earliest user the senior right; in drought, junior users, often cities, are cut first.

• Markets move water to higher-value uses and pay sellers; critics say they concentrate a human necessity in few hands.

• In the worked drought, 300 ML of rice water sells for A$250,000 and keeps almond trees alive downstream.

• Chile's 1981 code concentrated water rights; its 2022 reform made new rights temporary and put drinking water first.

• A market needs a cap, a registry, and protected shares for rivers and people before trading begins.

Module 16 Quiz

Check Your Understanding

1. What is prior appropriation, and what does it do in a drought?

A) Equal sharing in drought
B) State ownership of all water
C) A market that sets every user's share by auction each spring, with the state as auctioneer
D) First in time, first in right: junior users are cut first

2. In the Murray-Darling worked example, why does the rice grower sell his water in the drought?

A) Rice prices fell
B) His allocation is worth more on the market than the rice it would grow
C) The regulator orders him to
D) His entitlement expires at the end of every drought year under the 2012 Basin Plan

3. What did Chile's 2022 water code reform change?

A) It privatized the rivers
B) It abolished all private water rights, nationalizing the farms that held them
C) New rights became temporary, and drinking comes first
D) It created a national water stock exchange in Santiago

4. What does the course say a water market needs in order to work well?

A) A cap, a registry, and protections
B) No rules beyond supply and demand, so prices can move freely
C) Federal ownership of every right, with prices set by the state each year
D) Foreign investors to supply capital and liquidity to the farms

5. What happened at Menindee and Wilcannia, according to critics of the Murray-Darling market?

A) They gained new water rights
B) They sold their water to almond growers
C) They were moved to the river's mouth
D) Their river ran dry and millions of fish died while water was traded upstream

Module 17 — Reuse, Efficiency, and the Technology Frontier

The Solutions on the Demand Side

Recommended Reading / Reference

Reference: Singapore PUB on NEWater; California's direct potable reuse regulations (2023) and Arizona's advanced water purification rules (March 2025); the Orange County Water District; the City of Cape Town's New Water Programme; the Southern Nevada Water Authority (SNWA) on conservation

17a. Reuse

Place	Reuse	What it is used for	Cost ($/m³)	Notes
Israel	About 85-90% of wastewater	Farming; about half of irrigation water	0.30-0.60	The world leader
Singapore (NEWater)	Up to 40% of demand; up to 55% by 2065	Chip fabs and industry; topping up reservoirs	0.60-0.90	Membranes and ultraviolet light to drinking standard
Windhoek, Namibia	Direct potable reuse since 1968	Drinking water	0.80-1.00	The longest-running direct potable reuse
Orange County, California	About 130 million gallons (490,000 m³) a day	Injected into the aquifer that serves about 2.5 million people	0.70-0.90	The largest potable-reuse system
Spain, Cyprus, Malta	20-90%	Irrigation, golf courses, industry	0.30-0.60	EU reuse rules since 2023
Gulf states	Much of treated wastewater	Landscaping, cooling, farming	0.40-0.80	Cheap beside desalination
El Paso, Texas	10 million gallons (38,000 m³) a day from 2028	Drinking water, piped straight into the distribution system	About $295 million to build	The first such plant in the US; Big Spring, Texas, has blended purified water since 2013
United States	Under a tenth of wastewater	Mostly irrigation and industry		Direct potable reuse rules in Colorado (2022), California (2023), and Arizona (2025)
World	About 11% of municipal wastewater			Nearly half of household wastewater is still not safely treated

Utilities; PUB; El Paso Water; Arizona Department of Environmental Quality (March 2025). Approximate.

The cheapest new water is the water already in the pipes: reuse treats sewage to a standard fit for irrigation, industry, recharging aquifers, or drinking, and at $0.30-1.20 a cubic meter it costs less than most desalination. Israel recycles about 85-90% of its wastewater, nearly all for farming, Singapore's NEWater can meet up to 40% of demand, and Orange County has run the world's largest potable-reuse system since 2008.

Direct potable reuse sends purified wastewater straight to the tap: Windhoek has done it since 1968, Colorado, California, and Arizona adopted rules for it between 2022 and 2025, and El Paso broke ground in

February 2025 on a plant, due in 2028, that will pipe purified water directly into its distribution system. The obstacle is less the technology than the public: 'toilet to tap' fails at the ballot box until the drought is bad enough, and then it passes.

17b. Cities and Networks

The water lost or unbilled in city pipes, about 30% worldwide, is the next-cheapest source. Smart meters that flag leaks as they happen, acoustic sensors in the mains, satellite radar that finds underground leaks from orbit, pressure management, and automated treatment can cut losses by half where they are used, and Tokyo's 3% shows what a century of pipe replacement and metering achieves.

Managed aquifer recharge stores surplus winter flow underground for summer: Arizona has banked more than 4 million acre-feet (about 5 km³), California captured part of its 2023 floods in Central Valley aquifers under emergency rules, and Los Angeles's spreading grounds have recharged for a century. Machines that condense water from the air work, but their cost and energy confine them to niches. None of these measures is glamorous, but together they are the largest and cheapest supply the world has.

17c. Cape Town's Day Zero

Cape Town showed how fast demand can fall: a drought from 2015 to 2017, of a severity expected about once in three centuries on one estimate, took the city's dams to about 20% of capacity in early 2018. Officials announced a Day Zero, first set for April 2018, when taps would be turned off and residents would queue at collection points for 25 liters a day.

The city raised tariffs steeply for heavy users, cut pressure across the network, and from February 2018 limited residents to 50 liters (13 gallons) a person a day. Use fell from about 1.2 billion liters a day in 2015 to about 500 million in early 2018, the last steps in a few months, and Day Zero was postponed and then cancelled when the winter rains came.

The lesson is that demand management works in months while new supply takes years. Cape Town's New Water Programme aims to add about 300 million liters a day from 2031, from purified wastewater at Faure, a desalination plant at Paarden Eiland, and three aquifers. The test came early: after an unusually dry winter, the dams stood at 75.8% on September 17, 2026, against 92% a year before, and the city planned to decide on restrictions at the end of October.

17d. The Cost Ladder of New Supply

Option	Cost ($/m³)	Scale available	Energy	Best for
Conservation and efficiency: leaks, meters, pricing	0.05-0.30, often repaid by savings	Up to 30% of city supply	Saves energy	Everywhere, first
Moving water from farms: fallowing, drip	0.10-0.50	Tens of km³ in dry basins	Low	The largest lever
Managed aquifer recharge	0.10-0.40	Where surplus flows exist	Low	Storage without dams
Non-potable reuse	0.30-0.60	Much of city wastewater	Low to medium	Stressed cities
Potable reuse, indirect or direct	0.60-1.20	A quarter or more of city demand	Medium, 1-1.5 kWh/m³	Coastal and inland cities

Option	Cost ($/m³)	Scale available	Energy	Best for
Brackish desalination	0.40-0.90	Inland brackish aquifers	Medium	Texas, Arizona
Rainwater and stormwater capture	0.30-1.50	Modest	Low	A supplement
Long-distance transfer	0.50-2.00	Basin-scale and politically fraught	High	A last resort, as in China's South-North project
Seawater desalination	0.37-3.00	Coastal cities only	High, 3-5 kWh/m³	The Gulf, Israel, Australia
Water from the air	2-10	Tiny	Very high	Remote sites

The ladder is the planner's rule: exhaust each rung before climbing to the next. Approximate.

The cost ladder is the planner's discipline: conservation, pricing, and leak repair are the cheapest and are available everywhere, moving water from farms is the largest lever, recharge and reuse come next, and desalination and long-distance transfers are the expensive top rungs.

The cities that have coped with scarcity, Singapore, Israel's cities, Perth, and Las Vegas, climbed the ladder in order. Southern Nevada cut its use per person by 58% between 2002 and 2025, and its use of Colorado River water by 40%, while adding about 876,000 residents, and from 2027 Nevada law bars Colorado River water from watering decorative grass in the Las Vegas area. Cape Town in 2018, Chennai in 2019 (Module 18), and Mexico City in 2024 had not added supply or storage in time, and found that the upper rungs take years to build.

17e. Agriculture's Frontier

Because farming uses most of the water, the largest savings are on the farm (Module 12). The frontier adds precision irrigation, satellite measurement of the water each field evaporates, which the OpenET project has mapped across the western United States since 2021, and drought-tolerant and gene-edited crops that need less.

The honest constraint, again, is that saved water is planted again unless it is retired from the basin. That is why the reforms that work, California's groundwater law, the Colorado fallowing payments, and Australia's cap on extraction, limit the total taken rather than merely raising efficiency.

Module 17 Key Points

Reuse, Efficiency, and the Technology Frontier

• Reuse costs $0.30-1.20 per m^3, less than most desalination; Israel recycles about 85-90% of its wastewater.

• Singapore's NEWater can meet up to 40% of demand; El Paso's direct potable plant is due in 2028.

• Cape Town halved its water use from 2015 to early 2018; its dams were 75.8% full in September 2026.

• Southern Nevada cut use per person 58% from 2002 to 2025 while adding about 876,000 residents.

• The cost ladder: exhaust conservation and reallocation before climbing to desalination and long transfers.

• Saved farm water is replanted unless retired, so effective reforms cap total extraction.

Module 17 Quiz

Check Your Understanding

1. What share of Singapore's water demand can NEWater meet, as of 2026?

A) Up to 40%
B) About 90%, nearly all of it
C) About 5%, mostly for industry
D) Only a test share, because the plants are still pilots

2. How did Cape Town avert Day Zero in 2018?

A) Rail tankers of water
B) Imports of water by ship
C) A pipeline from the Orange River, built by the national government in a single dry season
D) Steep tariffs, pressure cuts, and a 50-liter daily limit on each person

3. What happened to Southern Nevada's water use between 2002 and 2025?

A) It doubled
B) Use per person fell 58% and Colorado River use 40% while the population grew by about 876,000
C) It stayed flat as growth stopped
D) It rose with a new desalination plant on Lake Mead

4. What is the cost ladder's rule?

A) Desalinate first
B) Build the largest project first to secure supply
C) Climb from the cheapest option up
D) Choose whichever option uses the least energy

5. What is the main obstacle to direct potable reuse?

A) It costs more than seawater desalination everywhere
B) Public acceptance
C) There is too little wastewater in dry cities
D) No treatment can remove the pathogens reliably

Module 18 — Six Regions

The Places Where the Crisis Is Already Here

Recommended Reading / Reference

Reference: WRI Aqueduct country rankings; World Bank regional water reports; India's Central Ground Water Board; the US Bureau of Reclamation; Chennai Metropolitan Water Supply and Sewerage Board records of 2019

Region	Water balance	The core problem	The 2026 flashpoint	The decision
US West (Colorado basin, California, Great Plains)	The Colorado over-allocated by about a third; Central Valley and Ogallala aquifers depleting; snowpack shrinking	A twentieth-century allocation of a river that has shrunk, with farms holding the senior rights	Interior imposed cuts for 2027-28 in August 2026; Nevada sued; Lake Powell at record lows	Whether the states settle before 2028, and how much alfalfa the region keeps growing
India	About 1,300 m³ of renewable water per person; groundwater supplies most irrigation and rural drinking water	Cheap or free power pumping a finite aquifer to grow rice and wheat	An arbitral award on the Indus that India rejects; the Ganges treaty expiring in December 2026	Whether to meter and price groundwater pumping and move Punjab off rice
China	About 2,000 m³ per person; the north holds nearly half the people and most of the farmland but about a fifth of the water	A dry north and a wet south, bridged by the South-North transfer	The Medog dam above India; the North China Plain's water table rising after pumping caps	How far to keep moving water north rather than people and industry south
Middle East and North Africa	About 6% of the world's people and about 1% of its renewable fresh water	Fossil aquifers exhausted; the Gulf on desalination; Egypt on the Nile	A war that struck desalination plants; Tehran's reservoirs below 10% in late 2025; Iraq's reserves at an 80-year low	Whether its water systems survive its wars
Sub-Saharan Africa	Abundant rivers, from the Congo to the Zambezi, but about a third of people with safely managed drinking water and about 6% of cropland irrigated	Infrastructure and governance, not hydrology	Johannesburg's outages; cholera in war zones; Kariba back to about 47% of usable storage in 2026	Whether money goes to pipes or to the consequences of not having them
Latin America	About a third of the world's fresh water, unevenly spread	Distribution and pollution more than quantity; glacier-fed cities losing their ice	Mexico City's reservoirs at about a quarter in mid-2024 and 81% full in August 2026; Bogotá's rationing in 2024-25	Whether cities build storage and reuse before the glaciers finish melting

Approximate; sources as cited in the text.

18a. The US West

The American West is where the world's richest country meets the arithmetic of Module 4. The Colorado supplies about 40 million people and is over-allocated by about a third, California's Central Valley grows a quarter of the nation's food on aquifers that have sunk the ground by up to about 8.5 meters (28 feet), and the Ogallala under the Great Plains is far lower in Kansas and Texas than before pumping. The snowpack that all three depend on is shrinking.

The West has the money to adapt, as Las Vegas's conservation, San Diego's desalination, Orange County's reuse, and Arizona's water bank show. It also has the law that makes adapting slow: under prior appropriation the senior rights belong to farms growing alfalfa and cotton, and the junior ones to Phoenix and Los Angeles.

The decision arrived on August 21, 2026, when the Interior Department imposed cuts for 2027-28 after the seven states failed to agree. Nevada's lawsuit three days later, and Lake Powell's record low in September, show how far the basin is from a settlement, and the outcome will set the template for every over-allocated river on earth.

18b. India

India has about 18% of the world's people and about 4% of its fresh water, and it has pumped its way through the gap. Groundwater supplies most of its irrigation and rural drinking water from tens of millions of wells, and in the northwest it is falling faster than almost anywhere, because the electricity that pumps it is free or cheap and the rice and wheat it grows are bought by the state at guaranteed prices.

The monsoon delivers most of the year's rain in four months, storage is scarce, and the monsoon is growing more erratic. The reforms that would help, metering groundwater, pricing power for pumps, and moving Punjab and Haryana from rice to less thirsty crops, are among the hardest in Indian politics, because farmers are a large share of voters.

Chennai showed what the gap looks like in a city: in June 2019 the four reservoirs that supply India's sixth-largest city ran nearly dry after failed monsoons, and trains carried water from about 200 kilometers away while tankers served millions. Four years earlier, in December 2015, the same city had flooded, because it had built over the lakes and wetlands that once stored its rain.

Chennai has since mandated rainwater harvesting, added desalination, and begun restoring lakes, but the lesson stands: a city that paves its wetlands and stores nothing can flood and run dry within four years. Beyond its borders, India's abeyance of the Indus treaty and the Ganges treaty's expiry in December 2026 add a transboundary layer (Module 7).

18c. China, the Middle East, Africa, and Latin America

China's problem is geography: the north has nearly half of the people, most of the farmland, and about a fifth of the water. It has answered with the largest water transfer ever built and with years of mining the North China Plain's aquifers, and since pumping caps and Yangtze water arrived, the plain's water table has been rising (Module 3). Its open questions in 2026 are the Medog dam above India and how long a slowing economy keeps paying to move water north.

The Middle East and North Africa form the most water-scarce region on earth, and its two futures sit side by side. The Gulf's cities run on desalination, which the 2026 war showed to be exposed. Yemen, Iraq, Jordan, and Iran, meanwhile, have exhausted aquifers or rivers cut upstream: Iraq's reserves fell to an 80-year low in 2025, and in November 2025 Iran's president warned that Tehran might have to be evacuated if rationing failed.

Sub-Saharan Africa has water and lacks pipes: only about a third of its people have safely managed drinking water, about 6% of its cropland is irrigated, Johannesburg's network has failed repeatedly since 2023, and cholera returns wherever war and flood break the systems. Wet years help, as Kariba's recovery to about 47% of usable storage in 2026 showed, but they do not build pipes.

Latin America holds about a third of the world's fresh water and cannot always get it to the right places. São Paulo nearly ran dry in 2014-15 and Montevideo resorted to brackish water in 2023. Bogotá rationed water from April 2024 to April 2025, and Mexico City's main reservoirs fell to about a quarter in mid-2024 before the rains of 2025 and 2026 refilled them. Chile's central valley has been in drought since 2010, and the Andean cities that drink from glaciers are watching them shrink.

Module 18 Key Points

Six Regions

• In every region the decision is the same: price, reallocate, and store before the aquifer, glacier, or treaty runs out.

• The US West faces Interior's 2027-28 cuts and Nevada's lawsuit, with Lake Powell at record lows.

• India has about 18% of the world's people and 4% of its fresh water, and pumps groundwater on cheap power.

• Chennai flooded in 2015 and ran dry in 2019 after building over the lakes that stored its rain.

• China moves water north and is now refilling the North China Plain's aquifers.

• Sub-Saharan Africa has water but lacks pipes; Latin America has a third of the world's water, unevenly spread.

Module 18 Quiz

Check Your Understanding

1. What happened in Chennai in June 2019?

A) A cyclone flooded it
B) It opened a new dam
C) Its four reservoirs ran nearly dry, and trains brought water
D) It became the first Indian city to meter and price every well, ending the shortage for good

2. Why is India's groundwater falling so fast?

A) Cheap or free power pumps it for rice and wheat
B) The monsoon failed
C) Cities pump most of it for industry and households
D) Rivers no longer recharge it because of upstream dams in China

3. What is China's core water problem?

A) Too little rain overall
B) Pollution in the Yangtze
C) Its dams on the Mekong
D) Nearly half its people and most of its farmland are in the dry north, while most of its water is in the south

4. What shows the Middle East's two futures side by side?

A) Its rivers and its seas
B) Oil wealth alone
C) The Gulf's desalinated cities and the crises of Iran, Iraq, and Yemen
D) Its aquifers, which are refilling across the region after a decade of wet winters and new dams

5. What is Sub-Saharan Africa's water problem, in the module's reading?

A) Too little rain
B) Its rivers are too polluted for any use, so cities import bottled water
C) Most of its water is locked in glaciers
D) It has water but lacks pipes

Module 19 — Where Things Stand, and What to Watch

The Argument, the Turning Points, and the Dates

Recommended Reading / Reference

Reference: UN *World Water Development Report 2026*; WMO, *State of Global Water Resources 2025*; WRI Aqueduct 4.0; the Global Commission on the Economics of Water, *The Economics of Water* (October 2024); the governments' and agencies' published schedules

19a. The Argument

The world is not running out of water: it has as much as it ever had, but it is running out of the predictability, the storage, and the cheap abundance that its water systems were built on. Withdrawals have grown about 1% a year since the 1980s, on the UN's count, driven by population, richer diets, industry, and now data centers and chip fabs, while supply is growing less reliable as the cycle intensifies, glaciers shrink, and aquifers are drawn down.

A quarter of humanity already lives in countries that use 80% or more of their renewable water in a typical year, on WRI's count, and about another billion people are expected to join them by 2050. The Global Commission on the Economics of Water found more than half of world food production in places where water storage is projected to decline.

The 2020s have shown what that trajectory looks like: the Rhine at 4 centimeters at Kaub, Lake Powell and Lake Mead at record lows, Kariba near its minimum and then back to about half full, Tehran's reservoirs below 10%, Indonesia moving its capital from Jakarta to Borneo, and the Indus treaty held in abeyance.

Measure	Latest	What to watch next	Source
People with safely managed drinking water	74% in 2024, up from 68% in 2015; 2.1 billion without	The 2027 report on 2025-26	WHO/UNICEF JMP
River basins with normal flow	34-38% in 2025, against a 1991-2020 average of 46%	The 2026 report, due in September 2027	WMO
Glacier loss	408 billion tonnes in 2025	Whether 2026's loss tops it	WMO
Water stress (UN measure)	17.6% of renewable supply withdrawn worldwide in 2023	Whether stressed regions keep rising	FAO
Colorado River storage	About 36% of capacity in mid-2026	Whether Lake Powell stays above the level needed to generate power	US Bureau of Reclamation

19b. From Supply to Demand

The twentieth century's answer to scarcity was supply: dam the river, drill the well, build the aqueduct, and, on the coast, desalinate. That era is ending, not because the engineering failed but because the rivers are dammed, the aquifers are overdrawn, and desalination cannot reach the farm.

The twenty-first century's answer is demand. It means pricing water closer to its cost, metering and governing groundwater, moving water from low-value crops to higher-value uses, cutting the 30% of treated water lost or unbilled, reusing what is already in the pipes, and building the institutions the last century did

not need: basin agreements, groundwater law, tariffs with lifeline blocks, and markets with caps. Each of these is politically harder than a dam, and each is cheaper, in the order the cost ladder of Module 17 sets out.

The winners are the rich and the coastal: the Gulf, which buys its water from the sea, Singapore and Israel, which built reuse and pricing before the crisis, and Las Vegas and Perth, which climbed the ladder in time. The losers are the poor and the downstream: communities without basic supply, farmers whose aquifers fail, the people of the Nile, Mekong, and Ganges deltas facing salt from below and dams from above, and unconnected households paying many times the piped rate. The same drought brings a price rise in one place and a famine in another, so the distribution of the damage is a choice that institutions make.

19c. Seven Turning Points, One Lesson

Seven turning points, each taught in its home module, carry one lesson, and the first is the Aral Sea (Module 7), which lost about 90% of its water to cotton irrigation with no cap on use. Flint (Module 14) cut corrosion control to save money and poisoned its children. Jakarta (Module 15) let a megacity pump its own foundations away and is moving the capital.

Cape Town (Module 17) grew for decades on one kind of supply, then halved its use between 2015 and early 2018 as the dams ran low. Chennai (Module 18) paved its wetlands and ran dry four years after it flooded. Kakhovka (Module 7) was destroyed as an act of war, and the Rhine's record low in 2026 (Module 5) had been foreseen in 2018 and 2022.

Six of the seven were governance failures before they were hydrological ones, each with a cheaper alternative that was known at the time, and the seventh, Kakhovka, showed that in war a dam is a weapon. The hopeful corollary is that Cape Town halved its consumption in under three years, Kazakhstan revived the northern Aral, and the North China Plain's water table is rising again. Water crises are among the most predictable disasters on earth, and among the most avoidable.

19d. Five Contradictions

- **Plenty and scarcity:** the earth has as much fresh water as ever, yet a quarter of humanity lives in countries that use almost all of theirs.
- **A right with a price:** the UN recognizes water as a human right, yet underpricing subsidizes the connected while the unconnected pay five to twenty times more.
- **The fix that became a target:** desalination freed the Gulf from scarcity, and in 2026 the plants that supply most of its drinking water came under fire.
- **Efficiency that raises use:** drip irrigation saves water on every field, yet farmers who save water often plant more, so a basin's use can rise unless extraction is capped.
- **Rules written for past rivers:** the Colorado Compact and the 1944 treaty with Mexico promise 16.5 MAF from a river that averaged 12.4 MAF since 2000, and the Indus treaty, which survived three wars, was held in abeyance in 2025.

19e. The Watch List

What	When	Why it matters
Cape Town decides whether to restrict water after a dry winter; its dams stood at 75.8% on September 17	End of October 2026	Whether Day Zero's lessons hold
The UK government answers a parliamentary committee's call to reject Thames Water's creditors and prepare for special administration; the creditors' emergency loan is expected to run out by the end of 2026	By mid-November 2026	The verdict on England's private model
The EPA's final rescission of four PFAS limits, and the appeals court's ruling on the 2024 rule, argued on September 18	Late 2026 or after	How much of the 2024 rule survives
The UN 2026 Water Conference, co-hosted by the UAE and Senegal	December 8-10, 2026, Abu Dhabi	Global water commitments after the 2023 conference in New York
The National Flood Insurance Program's authority expires unless renewed	December 11, 2026	Flood cover for about 4.5 million American policies
The India-Bangladesh Ganges treaty expires	December 2026	The next test of South Asia's water diplomacy
Afghanistan's Qosh Tepa canal due for completion	Late 2026	The Amu Darya's flow to Uzbekistan and Turkmenistan
Interior's Colorado River rules for 2027-28 take effect, with Nevada's lawsuit pending and Mexico's share under negotiation	January 1, 2027	Whether imposed cuts hold or the states settle
The appeals court rules on the 2024 lead-pipe rule, argued on September 30	Possibly early 2027	Whether 9 million lead lines must go by 2037
American Water and Essential Utilities complete their merger	By the end of March 2027	Consolidation of American private water
Nestlé's waters venture with Platinum Equity closes	First half of 2027	The future of Perrier and S.Pellegrino
Lake Powell's spring low against the level needed to generate power	Spring 2027	Glen Canyon Dam's power and the release to Lake Mead
Europe's next summer: the Rhine at Kaub, Cernavodă, and Paks	Summer 2027	Whether 2026 was the new normal
The lead-rule compliance date: action at 10 parts per billion and replacement under way	November 1, 2027	Utilities' first deadline under the 2024 lead rule
El Paso's direct potable reuse plant opens; Nusantara becomes Indonesia's political capital	2028	Reuse in the US; managed retreat at national scale
Compliance with the PFOA and PFOS limits	2029, or 2031 if the extension is final	The cost of forever chemicals on water bills
Cape Town's New Water Programme targets 300 million liters a day of new supply	From 2031	Supply after demand management
Lead service lines replaced nationwide; California's groundwater basins in balance	2037; about 2040	The two longest American deadlines

19f. The Last Word

The throughline of these nineteen modules is that the world is not running out of water but out of the predictability, storage, and cheap abundance its systems were built on. Rivers that carried Europe's trade,

aquifers that carried India through drought, glaciers that carried Asia through summer, deltas that fed Egypt and Vietnam, and treaties that carried rivals through wars are each under strain in the 2020s.

The technologies that promise replacement, desalination, reuse, the filter, and the bottle, serve those who can pay. Water was treated as free for most of history because it was, and the century ahead will be defined by learning to price, govern, and share something that is no longer free but still cannot be shipped. The Rhine at 4 centimeters, the Colorado's imposed cuts, and Indonesia's moving capital measure where that learning stood in 2026.

Module 19 Key Points

Where Things Stand, and What to Watch

• The world is losing water's predictability, storage, and cheap abundance rather than the water itself.

• Water use has grown about 1% a year since the 1980s while supply grows less reliable.

• Six of seven turning points were governance failures with known cheaper alternatives; Kakhovka showed a dam is a weapon.

• The Colorado Compact and the 1944 treaty promise 16.5 MAF from a river averaging 12.4 MAF since 2000.

• Watch the UN Water Conference on December 8-10, 2026, and the Colorado's imposed rules from January 1, 2027.

Module 19 Quiz

Check Your Understanding

1. How fast has global water use grown, according to the UN's World Water Development Report?

A) About 10% a year since 2000, doubling each decade
B) About 1% a year
C) Not at all since 1980, because efficiency has offset growth
D) About 5% a year, faster than the world economy

2. What lesson do the module's turning points teach?

A) That most were governance failures before hydrological ones, foreseen and with cheaper alternatives known at the time
B) That hydrology is destiny
C) That only poor countries suffer water crises
D) That desalination solved each of them in time

3. What does the module mean by rules written for past rivers?

A) Laws that ban new dams
B) Rules that still use Roman water law
C) The Colorado Compact and the 1944 treaty promise 16.5 MAF from a river that has averaged 12.4 MAF since 2000
D) Rules that allocate water by population alone

4. What happens on December 8-10, 2026?

A) The NFIP expires
B) The UN Water Conference meets in Abu Dhabi
C) The Colorado Compact expires
D) The Colorado River's new operating rules take effect across the basin

5. What is the closing module's central claim?

A) Water will soon be shipped across oceans like oil, ending local scarcity
B) The world is running out of water in every region
C) Desalination will end scarcity within a generation
D) Predictability is running out

Answer Sheet

Answers to every module's Check Your Understanding quiz.

Module	Answers
Module 1 Quiz	1. D 2. A 3. C 4. B 5. A
Module 2 Quiz	1. B 2. D 3. C 4. C 5. D
Module 3 Quiz	1. A 2. B 3. D 4. A 5. C
Module 4 Quiz	1. B 2. B 3. D 4. A 5. C
Module 5 Quiz	1. D 2. B 3. C 4. A 5. B
Module 6 Quiz	1. A 2. D 3. C 4. C 5. A
Module 7 Quiz	1. D 2. B 3. B 4. C 5. A
Module 8 Quiz	1. D 2. B 3. C 4. A 5. D
Module 9 Quiz	1. D 2. A 3. C 4. B 5. C
Module 10 Quiz	1. B 2. A 3. D 4. A 5. B
Module 11 Quiz	1. D 2. C 3. D 4. A 5. B
Module 12 Quiz	1. C 2. C 3. A 4. B 5. D
Module 13 Quiz	1. C 2. A 3. D 4. B 5. B
Module 14 Quiz	1. A 2. C 3. D 4. C 5. B
Module 15 Quiz	1. D 2. A 3. B 4. C 5. A
Module 16 Quiz	1. D 2. B 3. C 4. A 5. D
Module 17 Quiz	1. A 2. D 3. B 4. C 5. B
Module 18 Quiz	1. C 2. A 3. D 4. C 5. D
Module 19 Quiz	1. B 2. A 3. C 4. B 5. D