2.500 Desalination and Water Purification
Spring 2009

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Spring 2009

Tuesday/Thursday 1:00-2:30

Professor John H. Lienhard V

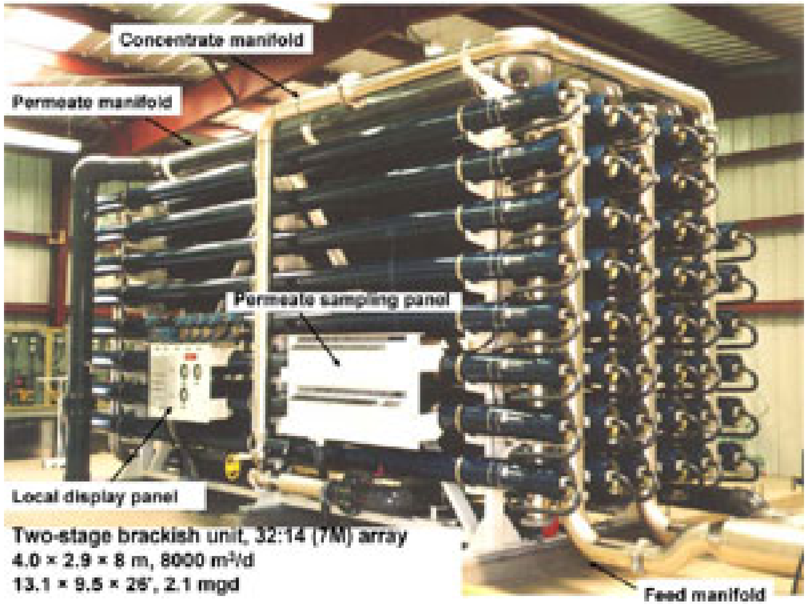

Figure from Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

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Massachusetts Institute of Technology

Ghana

Photo by Amy Smith. Used with permission.

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2.500 Desalination and Water Purification

Image from Wikimedia Commons,

Tanzania

- More than 1 billion people lack access to clean drinking water
- Half the hospital beds in the world are occupied by patients with easily prevented water-borne disease
- Half the people in the world do not have sanitation systems as good as those in Ancient Rome.
- In 2000, unsafe water mortality amounted to 80 million years of lost life (*Science*, 25 Jan 2008)
- This situation is expected to get WORSE.

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Yangon, Myanmar

May 2008
…after cyclone

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Please see http://www.nytimes.com/slideshow/2008/05/05/world/0505-MYANMAR_index.html
http://graphics8.nytimes.com/images/2008/05/05/nytfrontpage/23097528.JPG

Photo source:
The New York Times, 7 May 2008

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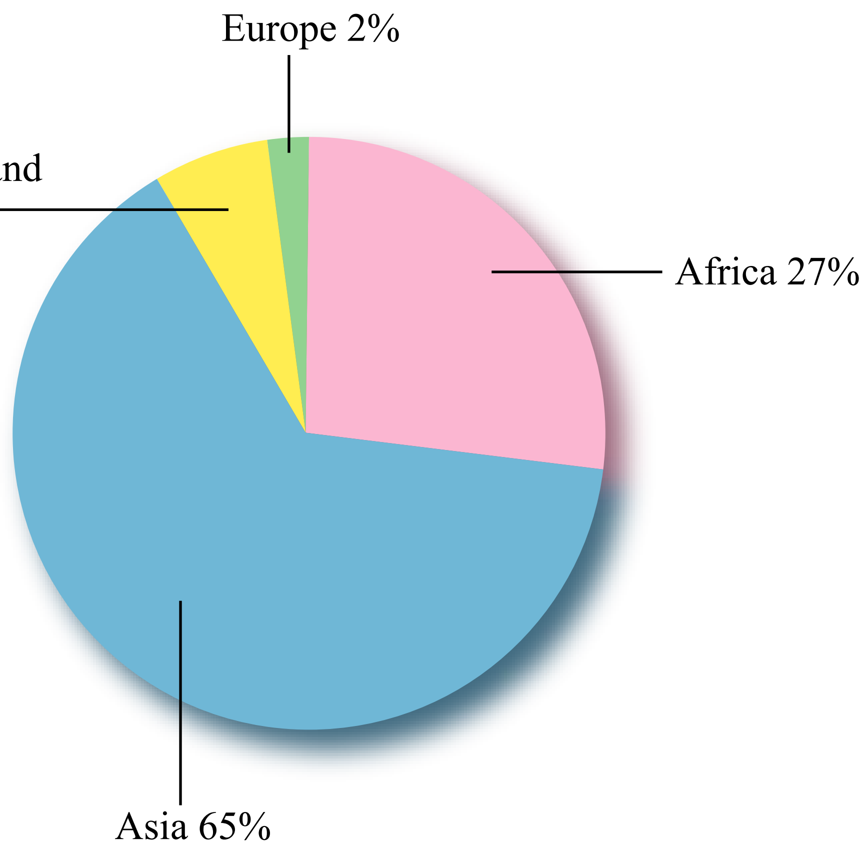
Sources: postnewsline.com; Andrew Heavens (flickr.com).



Water supply, distribution of unserved populations

Figure by MIT OpenCourseWare.

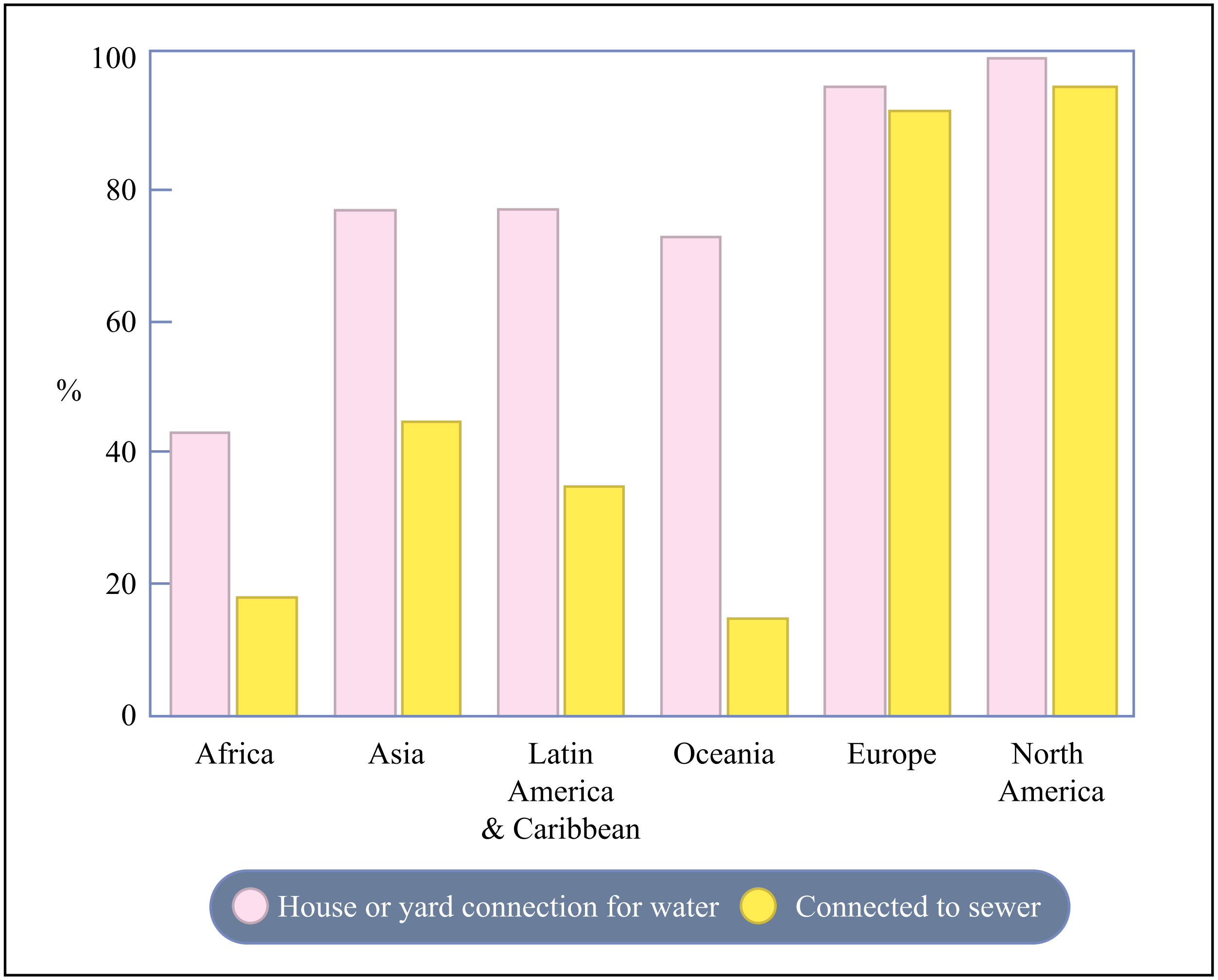
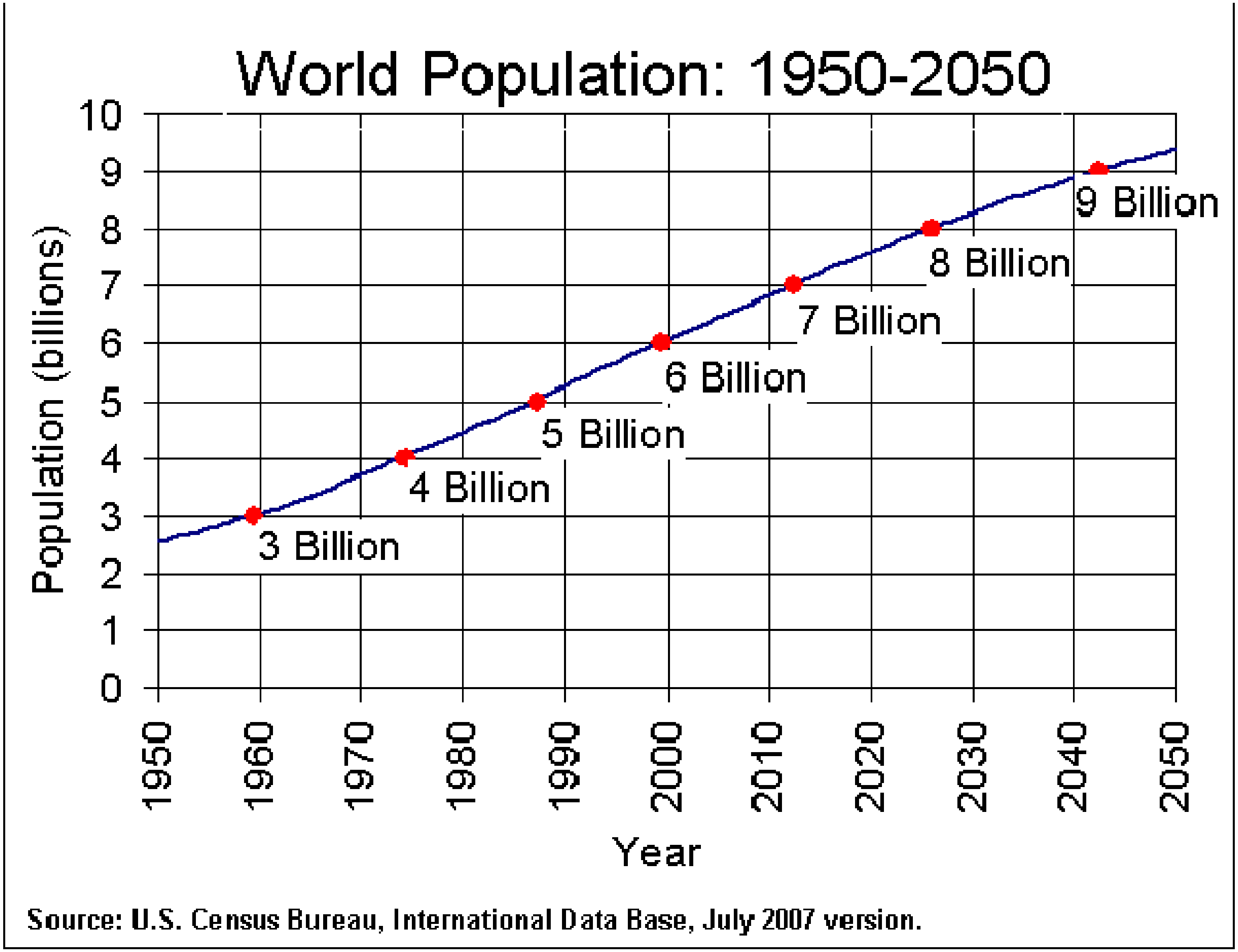
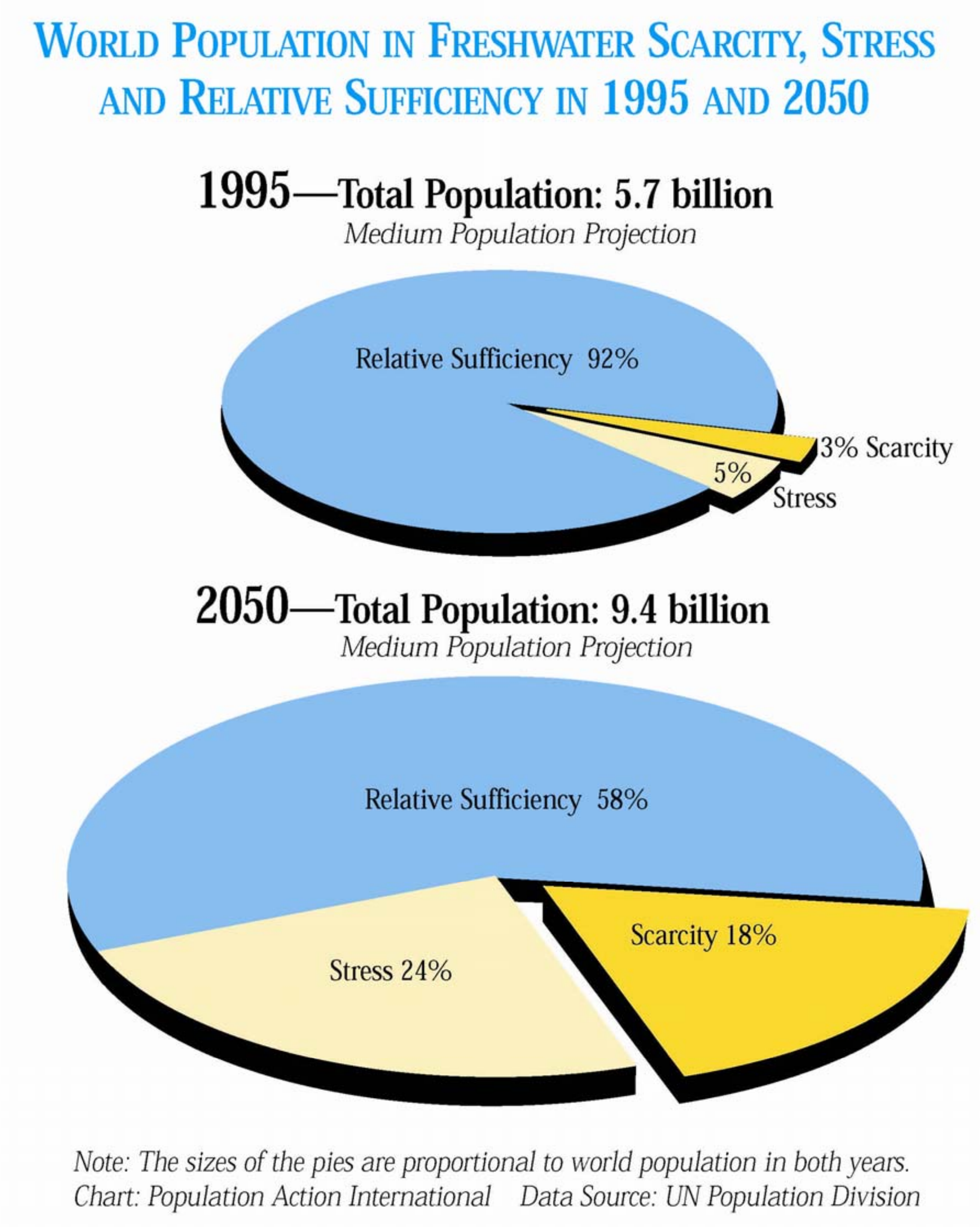


Figure by MIT OpenCourseWare.


World Population: 1950-2050
Population (billions)
10
9
8
7
6
5
4
3
2
1
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Year
3 Billion
4 Billion
5 Billion
6 Billion
7 Billion
8 Billion
9 Billion
Source: U.S. Census Bureau, International Data Base, July 2007 version.

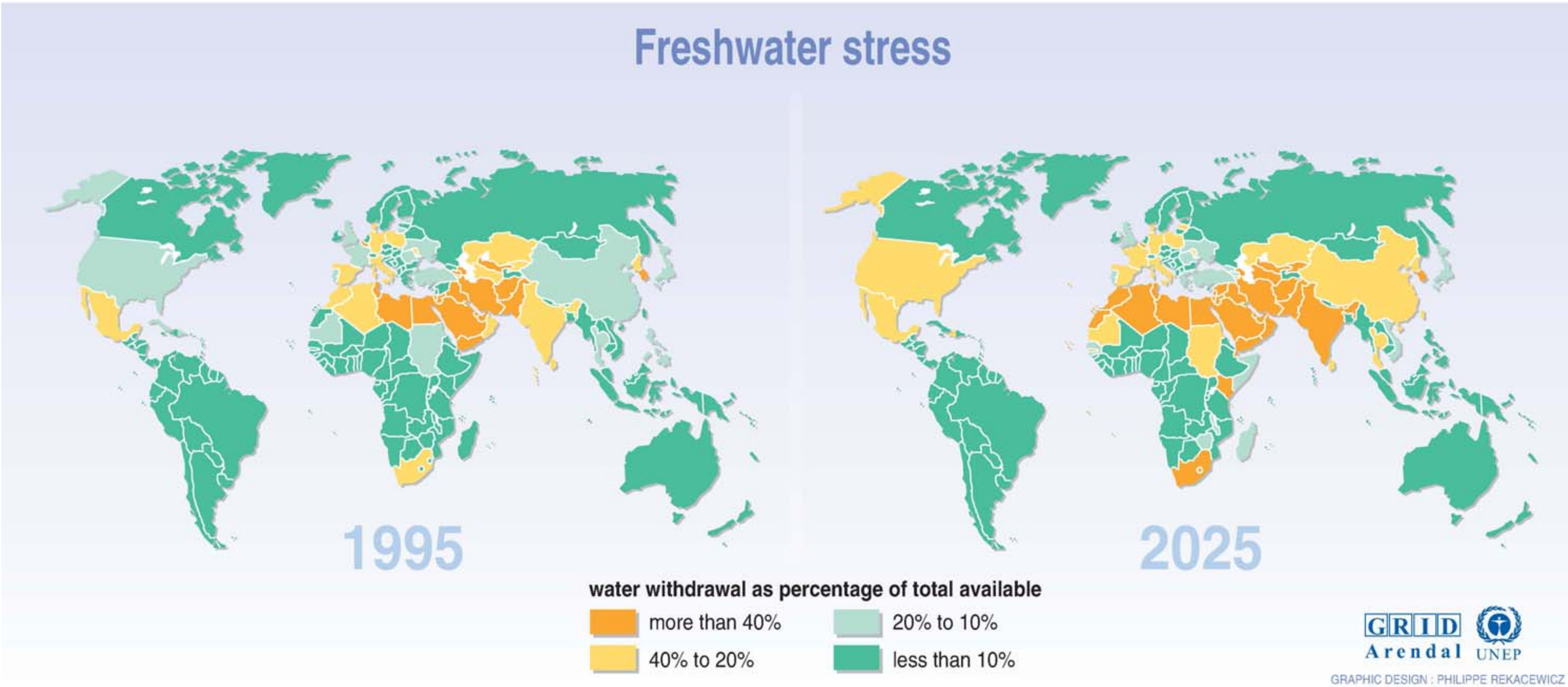


Water stress means that the annual water supply is below 1700 m^3 per person.

Water scarcity means that the annual water supply is below 1000 m^3 per person.

Source: Gardener-Outlaw & Engelman

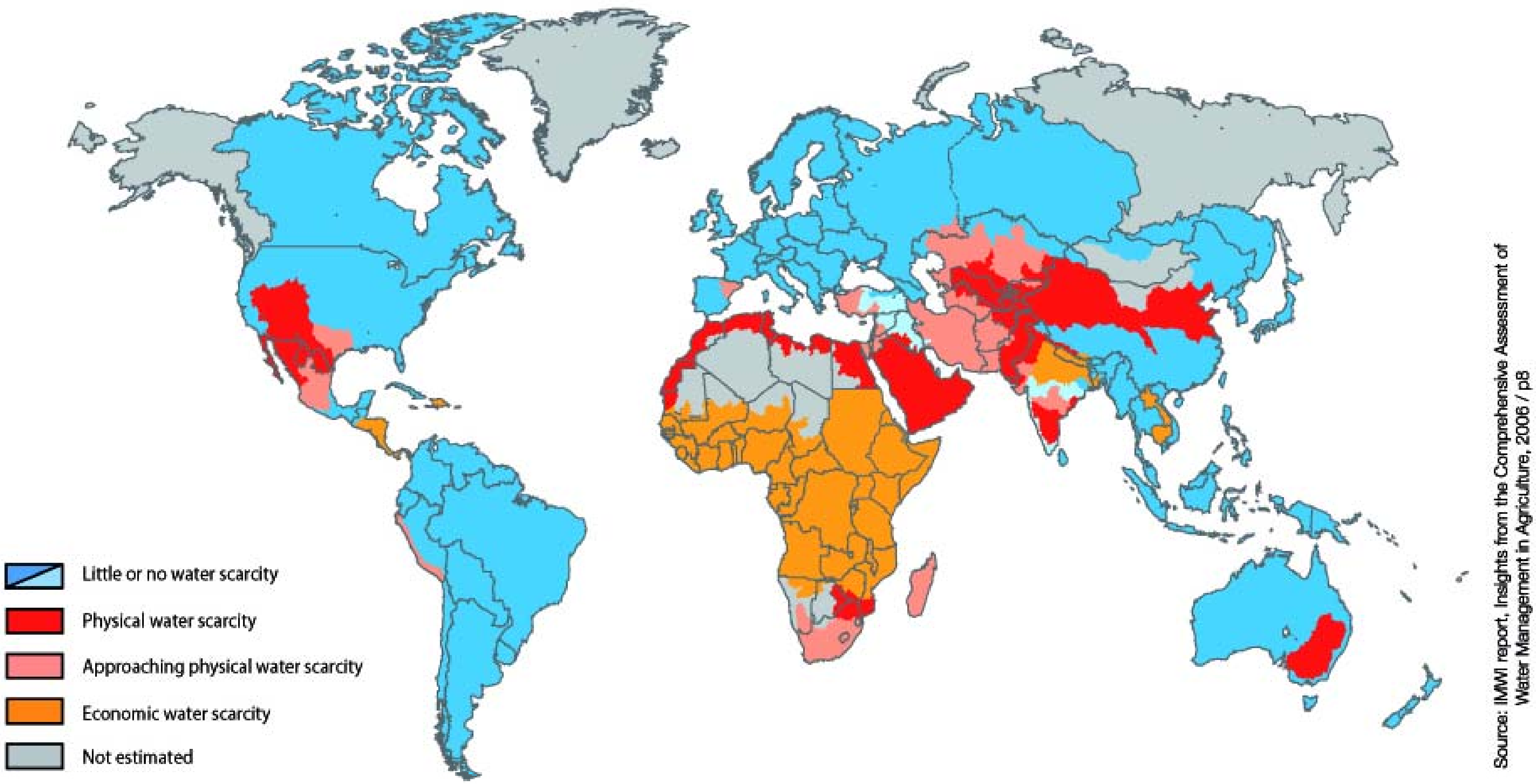
Source: Gardner-Outlaw, Tom, and Robert Engelman. "Sustaining Water, Easing Scarcity: A Second Update." *Population Action International*, May 1997. (PDF)



Source: Global environment outlook 2000 (GEO), UNEP, Earthscan, London, 1999.

Image by Philippe Rekacewicz for UNEP/GRID-Arendal. "Freshwater Stress." *UNEP/GRID-Arendal Maps and Graphics Library*. UNEP/GRID-Arendal, 2000. Accessed September 25, 2009.

Areas of physical and economic water scarcity



UNEP/GRID-Arendal. "Areas of Physical and Economic Water Scarcity."
UNEP/GRID-Arendal Map and Graphics Library. UNEP/GRID-Arendal, 2008. Accessed September 25, 2009.

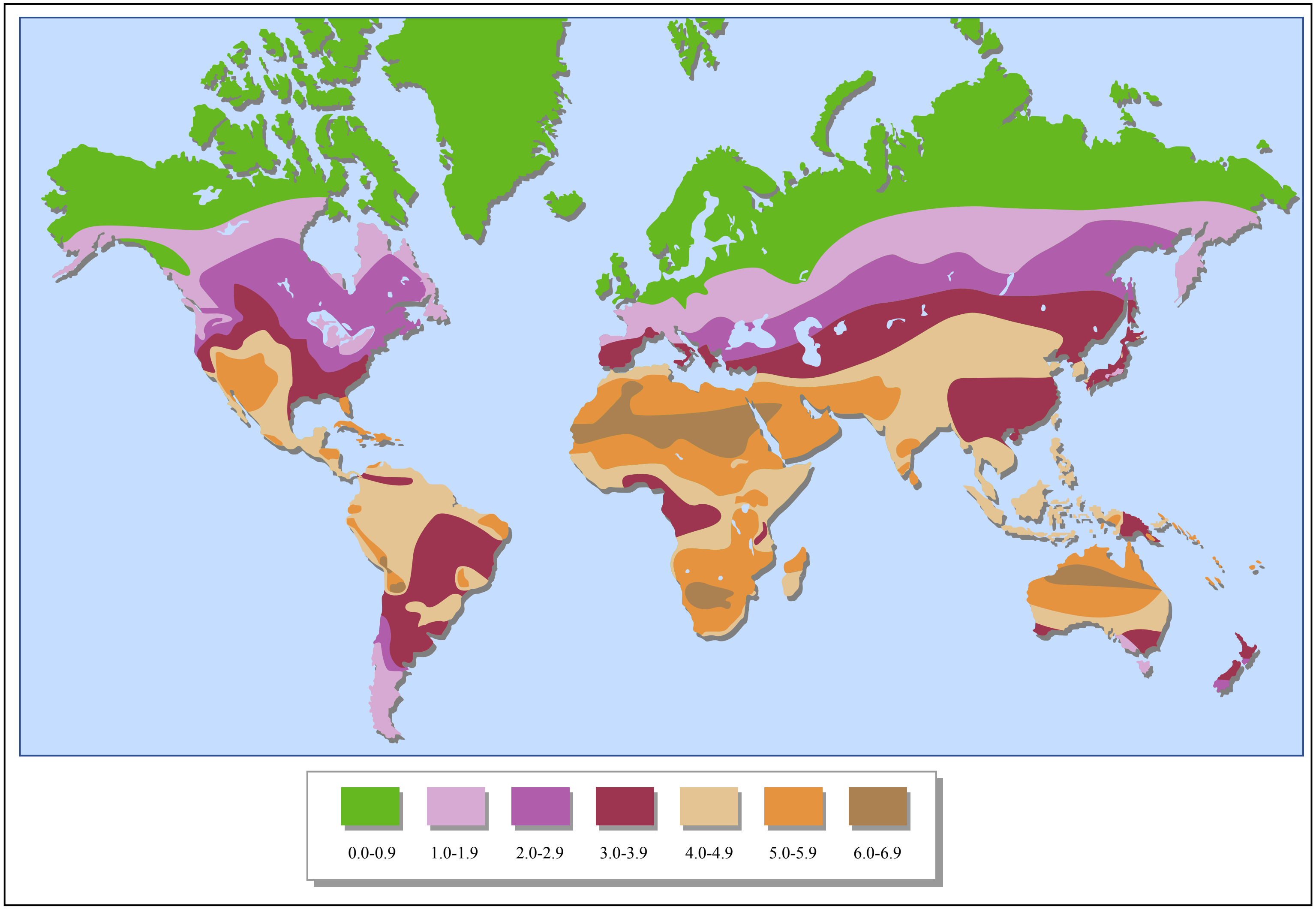
July - September, 1989   August 12, 2003

Aral Sea – water diverted for agriculture

Image from NASA Earth Observatory.

Source: infranetlab.org

World Insolation (kWh/m^2-day)



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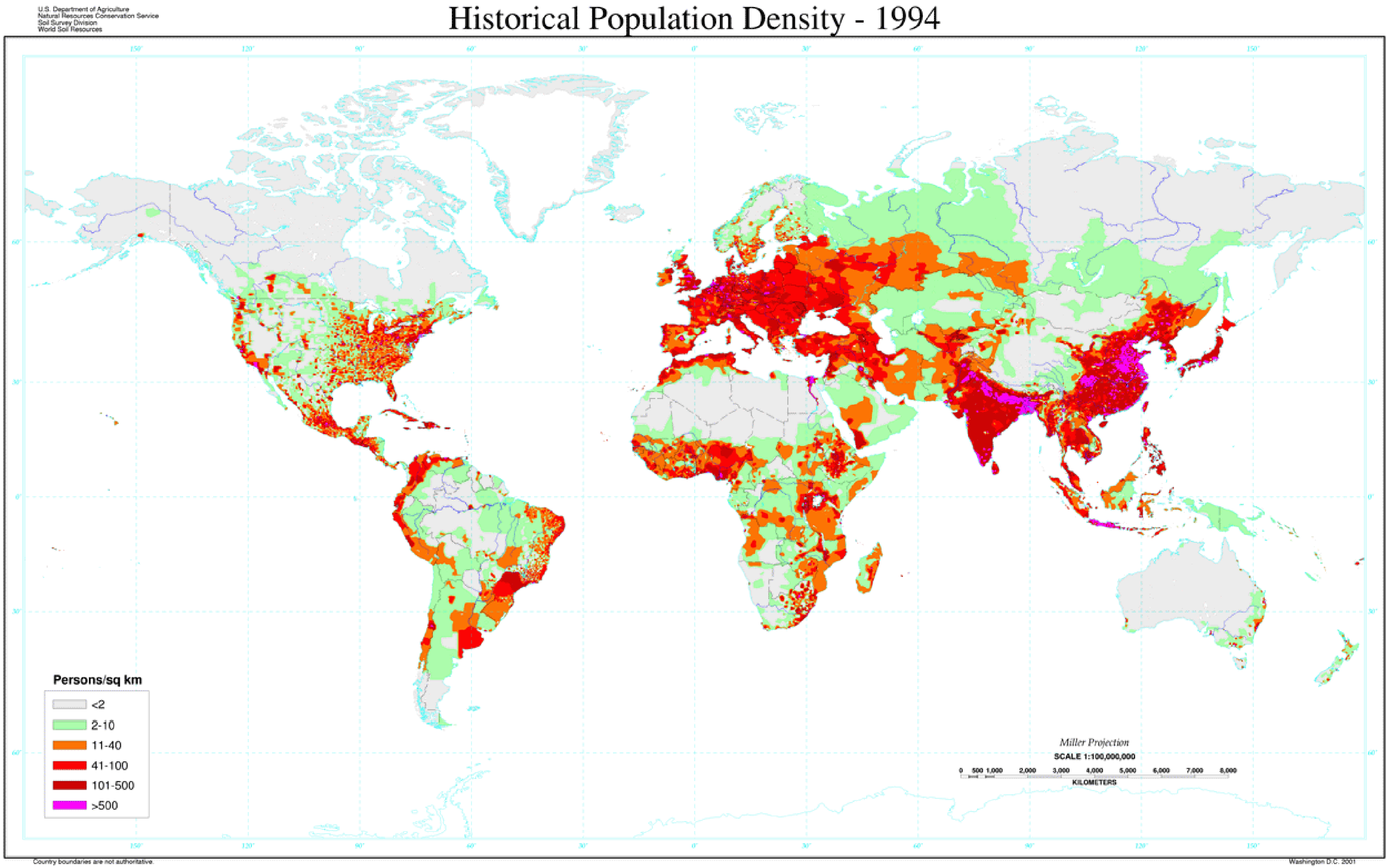
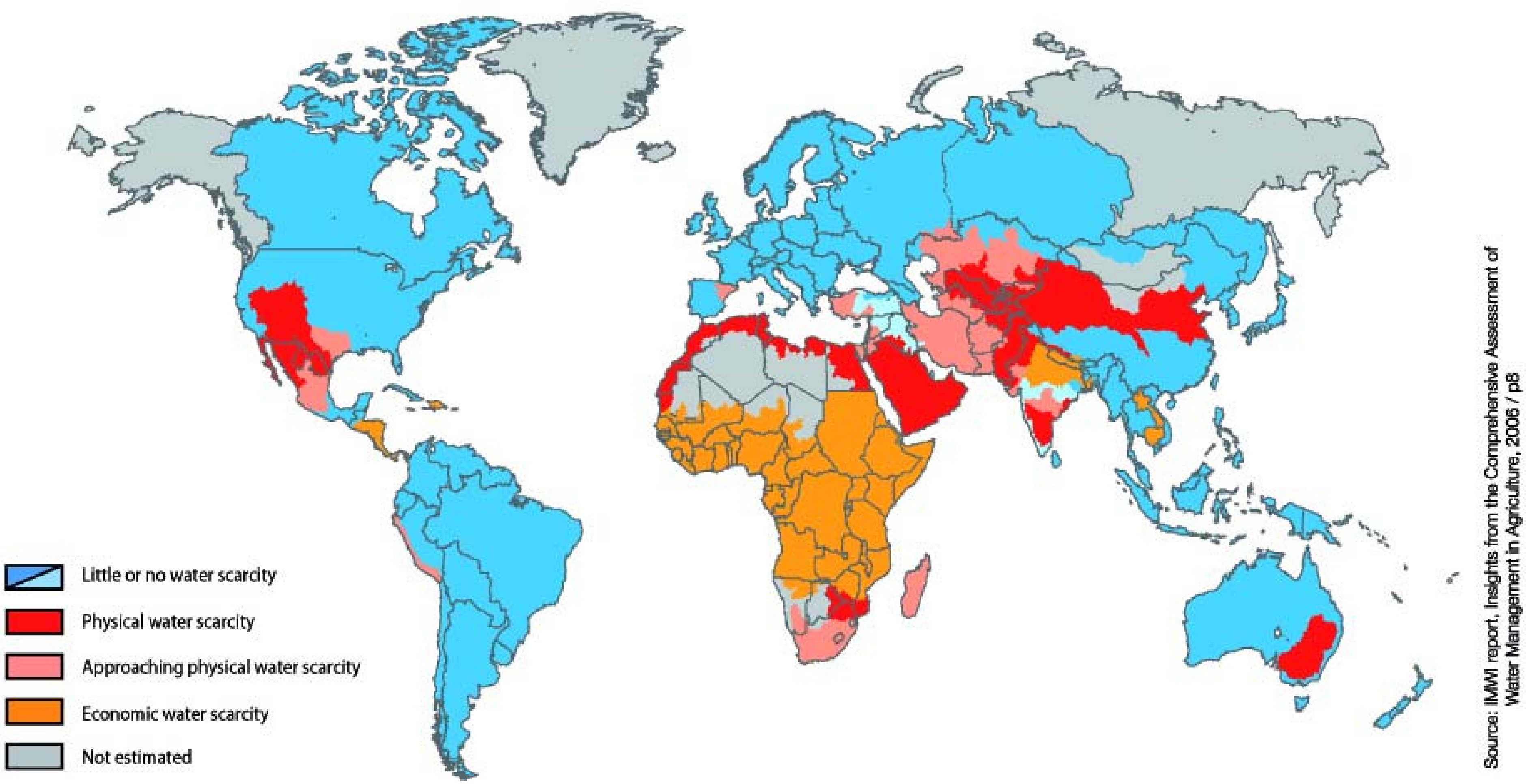


Image from Tobler, W., et al. "The Global Demography Project."
TR-95-6. Santa Barbara, CA: National Center for Geographic Information Analysis, 1995.
Image is in the public domain.

Areas of physical and economic water scarcity



UNEP/GRID-Arendal. "Areas of Physical and Economic Water Scarcity."
UNEP/GRID-Arendal Map and Graphics Library. UNEP/GRID-Arendal, 2008. Accessed September 25, 2009.

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Per capita water consumption (m^3/y)

Worldwide average	800
Nigeria	50
China	300
Mexico	800
Italy	1000
USA	2000
World desalting capacity	2

Source: *Science*, v. 319, 25 Jan 2008

laist.com

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Cleaning a sidewalk in Long Beach, CA

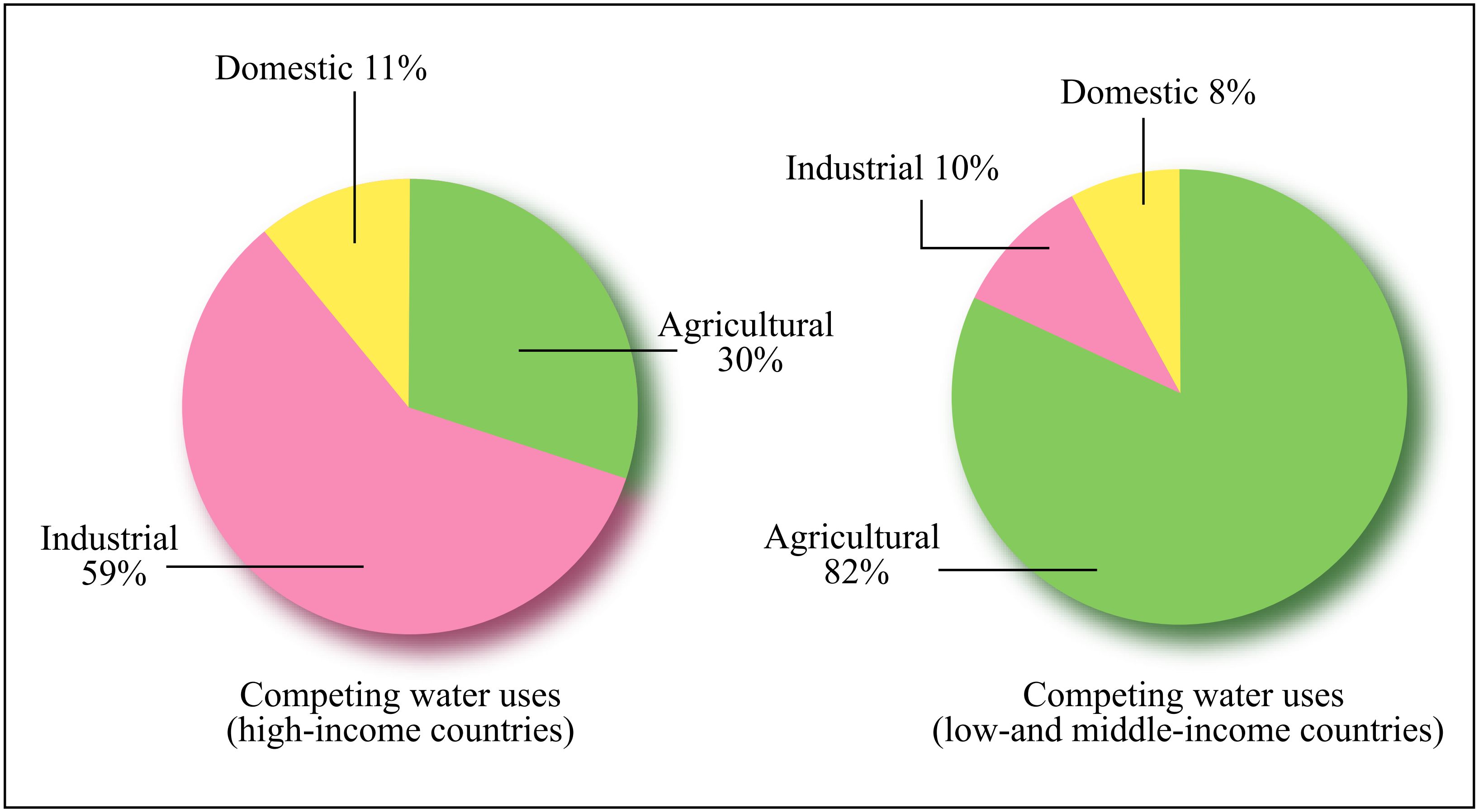
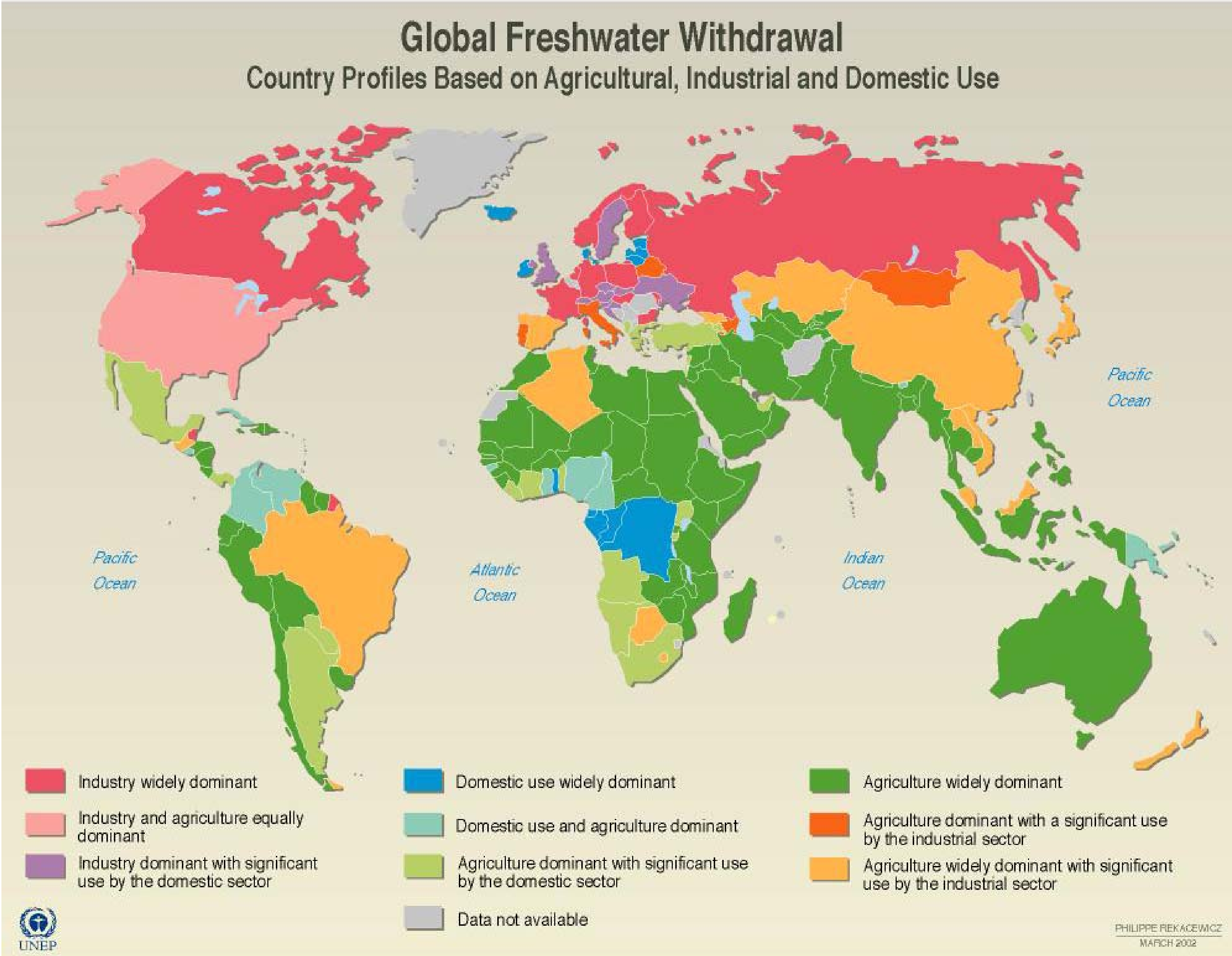
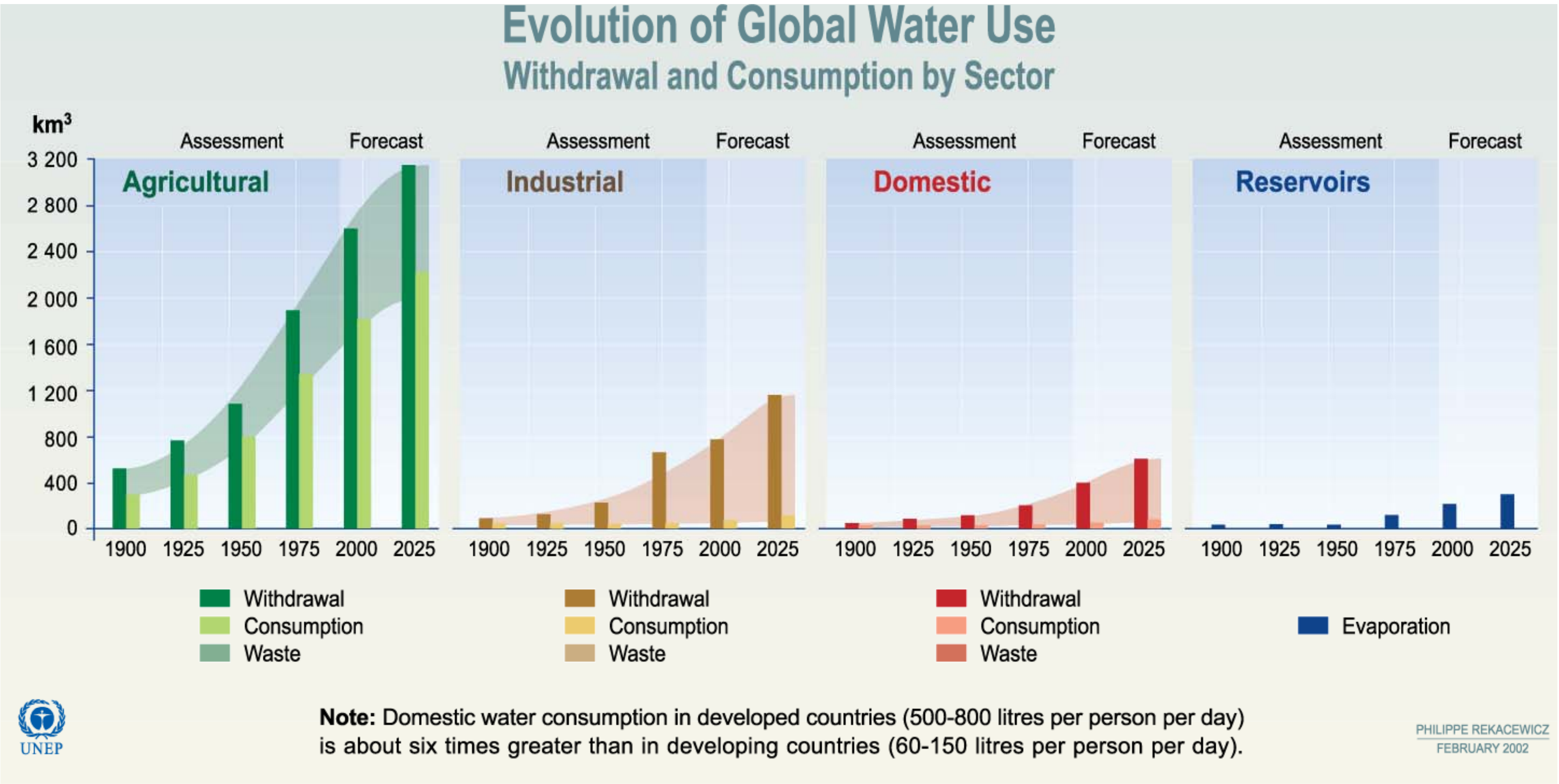


Figure by MIT OpenCourseWare.



Source: Based on data fromTable FW1 in *World Resources 2000-2001, People and Ecosystems: The Fraying Web of Life*, World Resources Institute (WRI), Washington DC, 2000.

Image by Philippe Rekacewicz for UNEP/GRID-Arendal. "Global Freshwater Withdrawal."
UNEP/GRID-Arendal Maps and Graphics Library. UNEP/GRID-Arendal, 2002. Accessed September 25, 2009.



Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational,Scientific and Cultural Organisation (UNESCO, Paris), 1999.

Author's definition of "waste" is not clear; however, it is common for municipal water distribution systems to lose 20 to 40% of water by leakage.

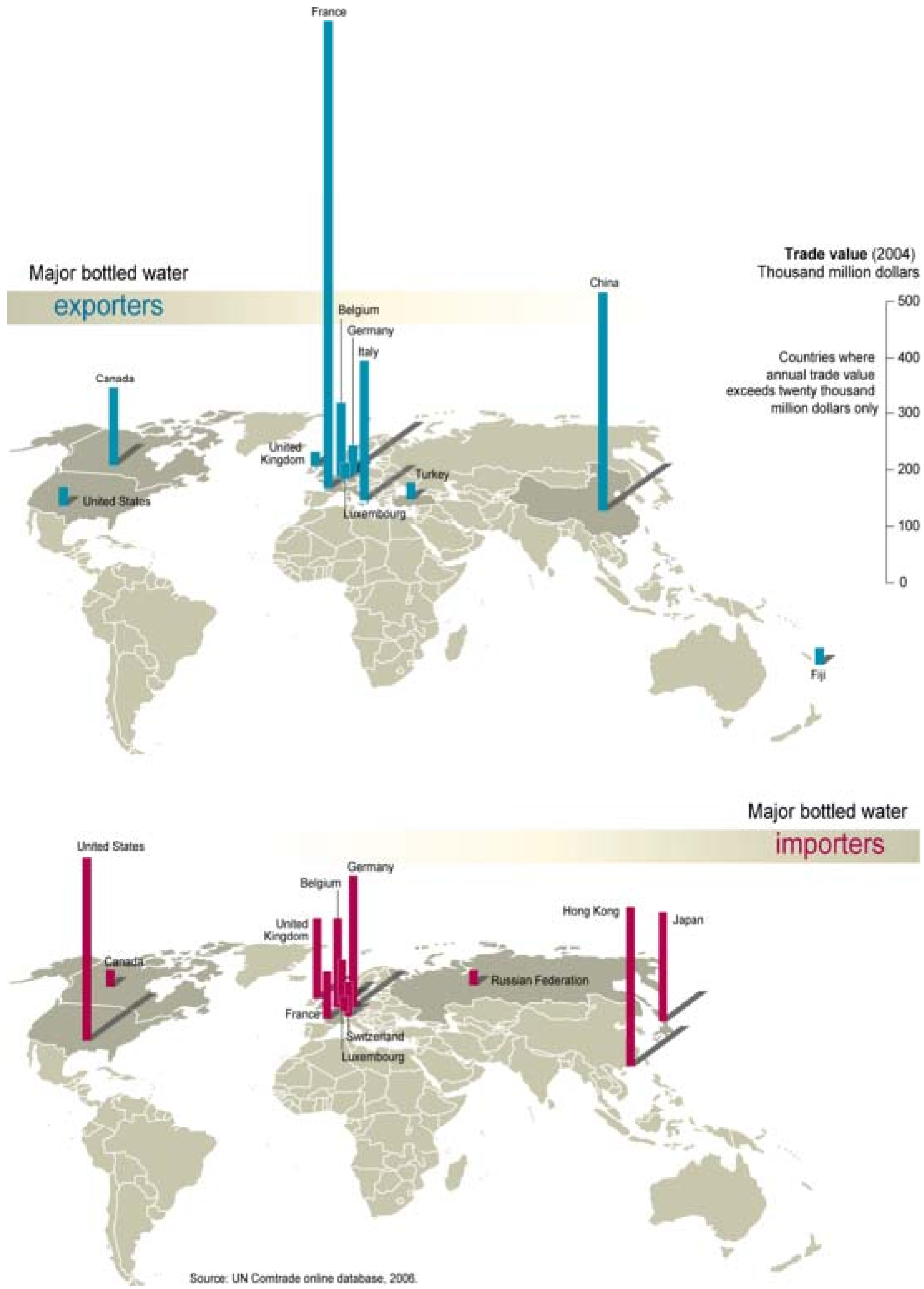
Image by Philippe Rekacewicz for UNEP/GRID-Arendal. "Trends and Forecasts in Water Use, by Sector." *UNEP/GRID-Arendal Maps and Graphics Library*. UNEP/GRID-Arendal, 2002. Accessed September 25, 2009.

Product	Unit	Equivalent water in cubic meters
Bovine (cattle)	Head	4,000
Sheep and goats	Head	500
Meat (bovine fresh)	Kilogram	15
Meat (sheep fresh)	Kilogram	10
Meat (poultry, fresh)	Kilogram	6
Cereals	Kilogram	1.5
Citrus fruit	Kilogram	1
Palm oil	Kilogram	2
Pulses, roots and tubers	Kilogram	1

Water requirement equivalent of main food production.

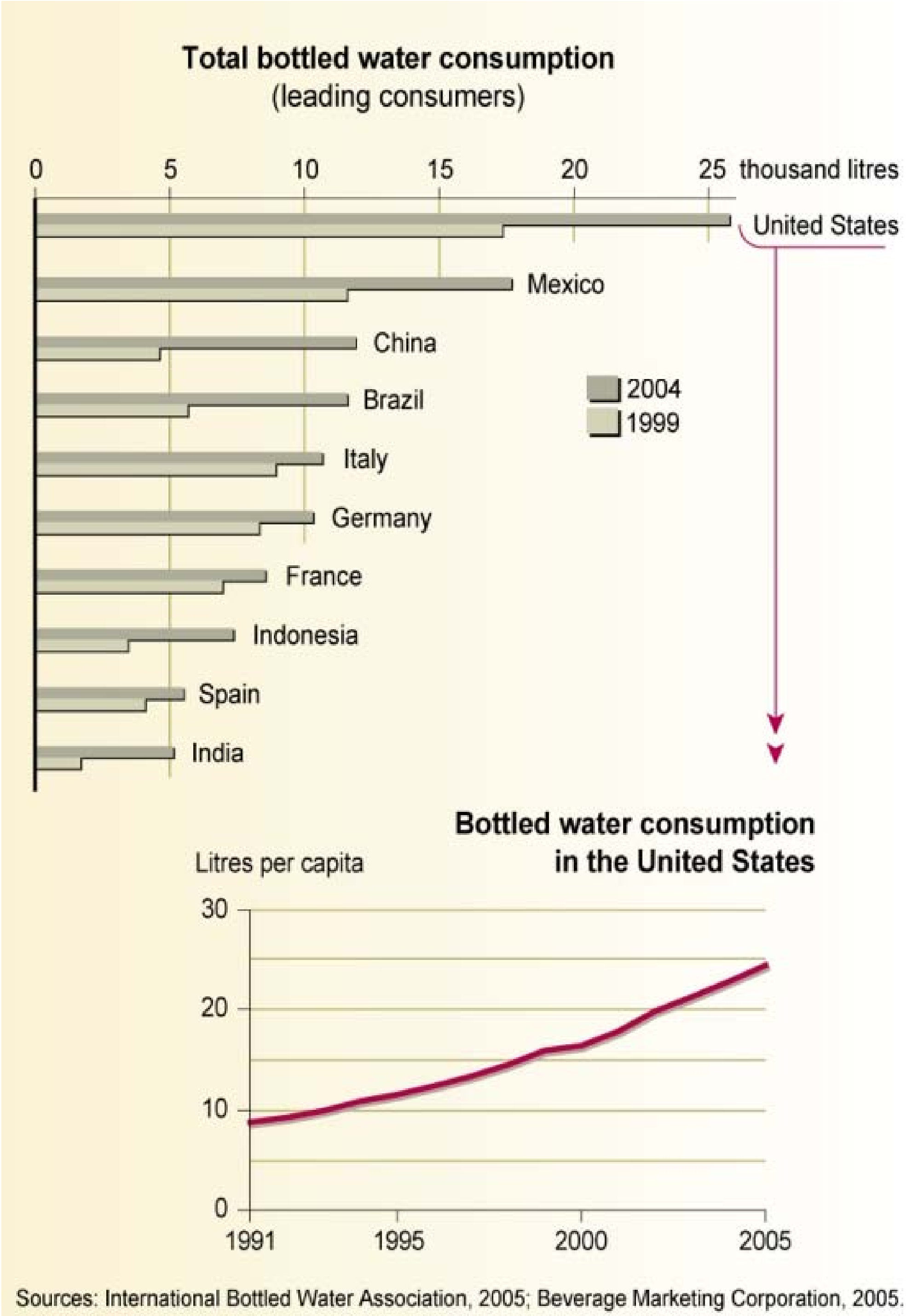
Figure by MIT OpenCourseWare.

Bottled water exportation…



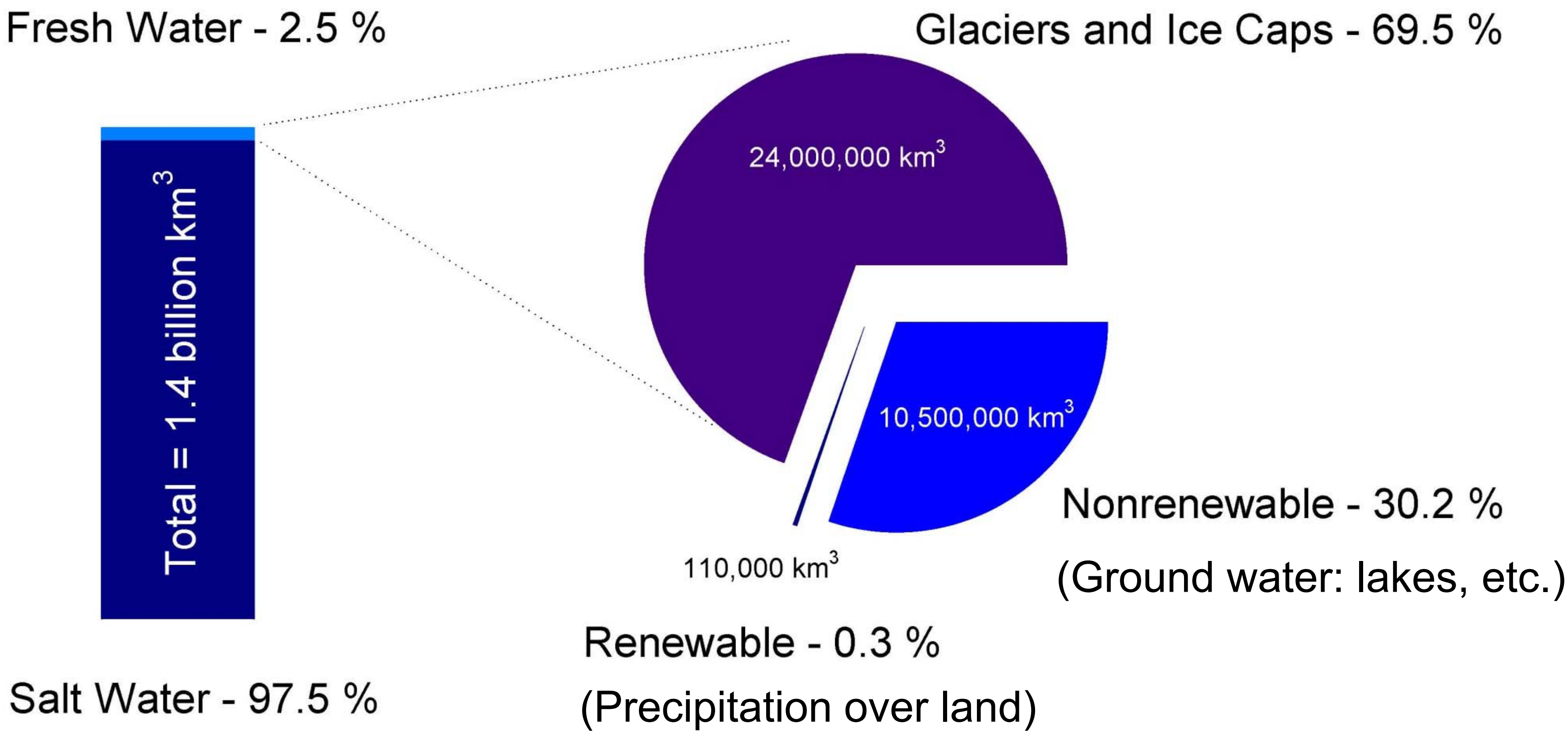
…and importation

Image by Emmanuelle Bournay. "Major Bottled Water Exporters and Importers."
UNEP/GRID-Arendal Maps and Graphics Library. UNEP/GRID-Arendal, 2006. Accessed September 25, 2009.



Many countries that consume large amounts of bottled water have excellent tap water…

Image by Emmanuelle Bournay. "Total Bottled Water Consumption." *UNEP/GRID-Arendal Maps and Graphics Library*. UNEP/GRID-Arendal, 2006. Accessed September 25, 2009.



Approximately 23% of renewable water is appropriated for human uses, including agriculture. Accessible annual run-off is about 12,500 km^3/y, of which about 54% is acquired for human use.

Source: Miller, 2003.

Water flows (km^3/y)

Precipitation on land

120,000

- Evaporation on land 70,000
- River runoff and groundwater recharge 50,000

Available river flow and recharge

12,000

- Withdrawal for human use
  - Agriculture 3,500
  - Industry 1,000
  - Domestic 500

Source: *Science*, v. 319, 25 Jan 2008

World desalting capacity = 13 km^3/y

WATER SUPPLY ALTERNATIVES

Water source	Energy requirement kWh/m^3 (kWh/kgallon)	Availability and constraints
Surface water or underground aquifer	0.1–1.5 (0.4–6)	• Quantity is limited
Desalination of brackish water	0.4–0.8 (1.5–3)	• Localized and limited availability
Desalination of seawater	3–4 (11–15)	• Available at coastal locations only • Environmental constraints
Advanced wastewater reclamation	0.8–1 (3–4)	• Available at centers of use • Public perception problem

Figures from Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Source: Sommariva,2007

Water Quality Characteristics

Ref: Reynolds & Richards

Biological Characteristics

microorganisms

Physical Characteristics

taste, odor, color,…

Chemical Characteristics

natural or manmade

Images from Wikimedia Commons, http://commons.wikimedia.org

Biological

- Bacteria
- Viruses
- Protozoa
- Coliform bacteria *(indicate human waste)*
- Helminths
- Fungi, algae

Physical

- Total solids *(dissolved and suspended)*
- Turbidity
- Color *(apparent and true)*
- Taste & odor *(organic compounds in surface water; dissolved gases in ground water)*
- Temperature

Chemical

- pH
- Anions & cations *(dissolved solids)*
- Alkalinity *(HCO_3^-, CO_3^{2+}, OH^- system)*
- Hardness *(Ca^{2+}, Mg^{2+})*
- Dissolved gases *(O_2, CO_2, H_2S, NH_3, N_2, CH_4…)*
- Priority pollutants *(organic and inorganic)*

Microbial contamination is the #1 concern for water

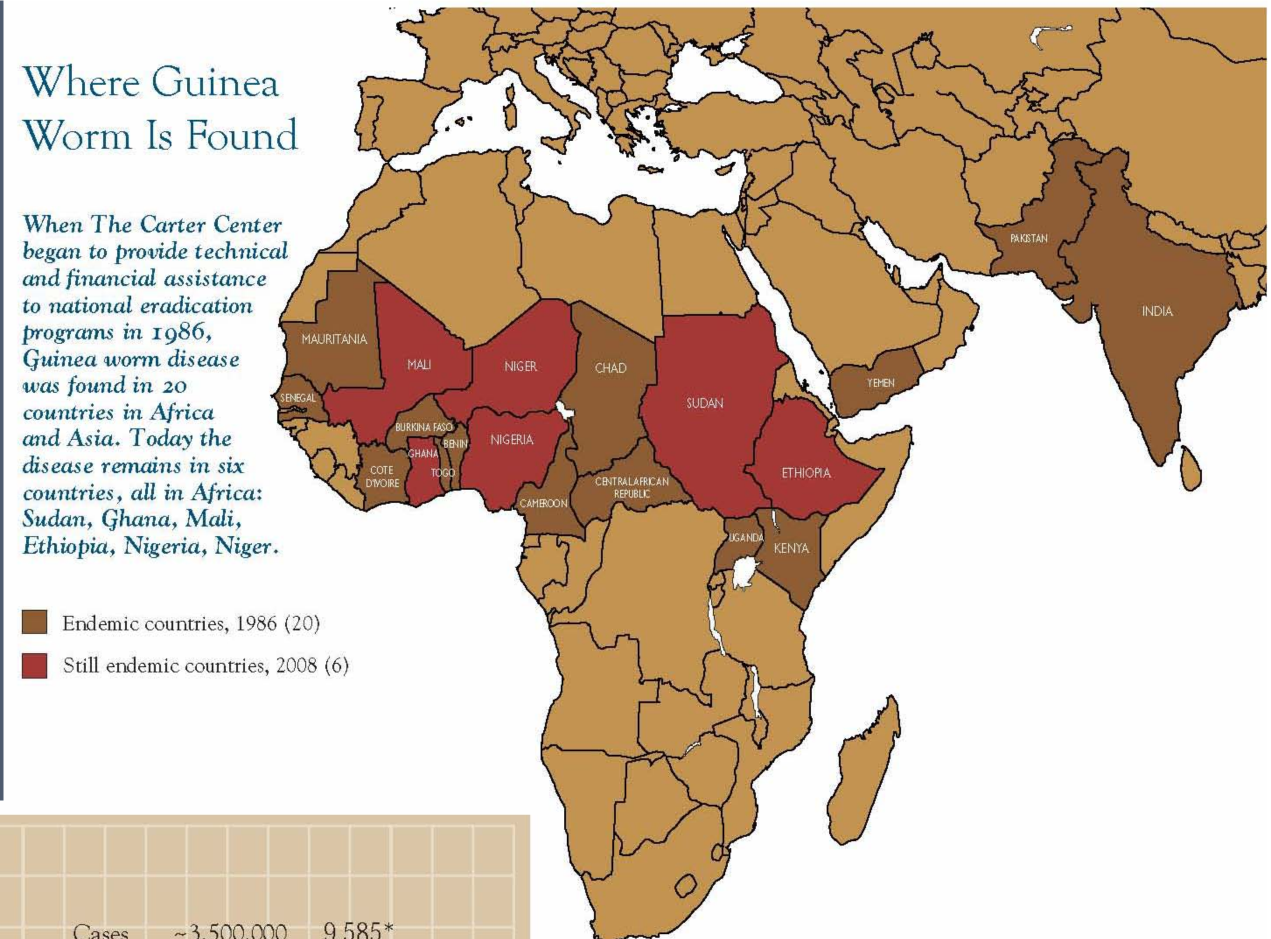
- Protozoans
  - Amoeba, cryptosporidium, giardia, algae,…
- Bacteria
  - Salmonella, typhus, cholera, shigella, …
- Viruses
  - Polio, hepatitis A, meningitis, encephalitis,…
- Helminths
  - Guinea worm, hookworm, roundworm,…

- Principal transmission is by human waste
- Principal purification technique is chlorination, especially for bacteria.

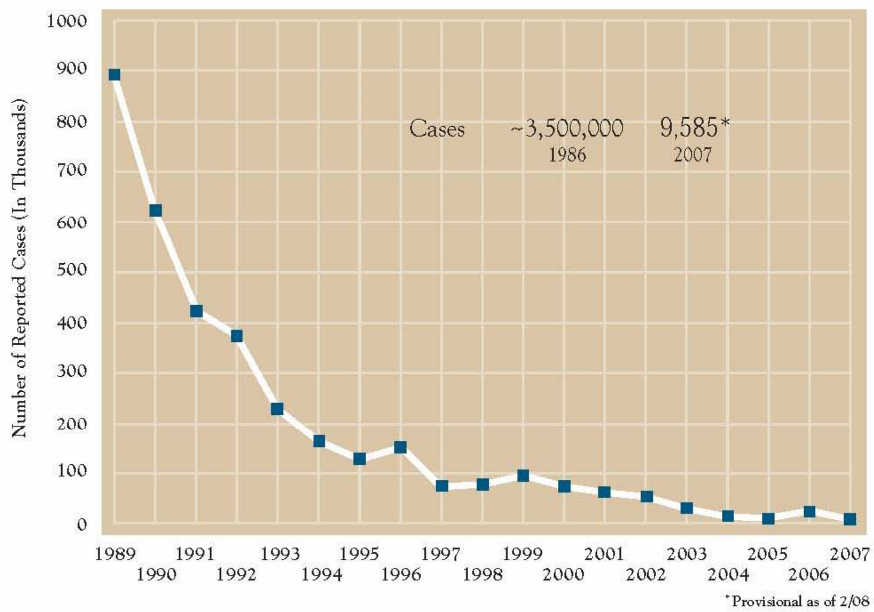
Ref: Faust and Aly, 1998.

Some water borne diseases can be eradicated…

…3,500,000 cases of Guinea worm in 1986….



Number of Reported Cases of Guinea Worm Disease by Year, 1989–2007



…<5000 cases in 2008…

…80% in Sudan.

Physical characteristics

- Suspended solids include silt, clay, algae, colloids, bacteria…remove by settling, filtration, or flocculation
- Turbidity interferes with passage of light, usually as the result of colloidal material
- Color is due to dissolved (true color) or colloidal (apparent color) material…iron, manganese, clay,…
- Taste/odor …typically treated by aeration (to release dissolved gas from ground water) or activated carbon (to remove organics from surface water)

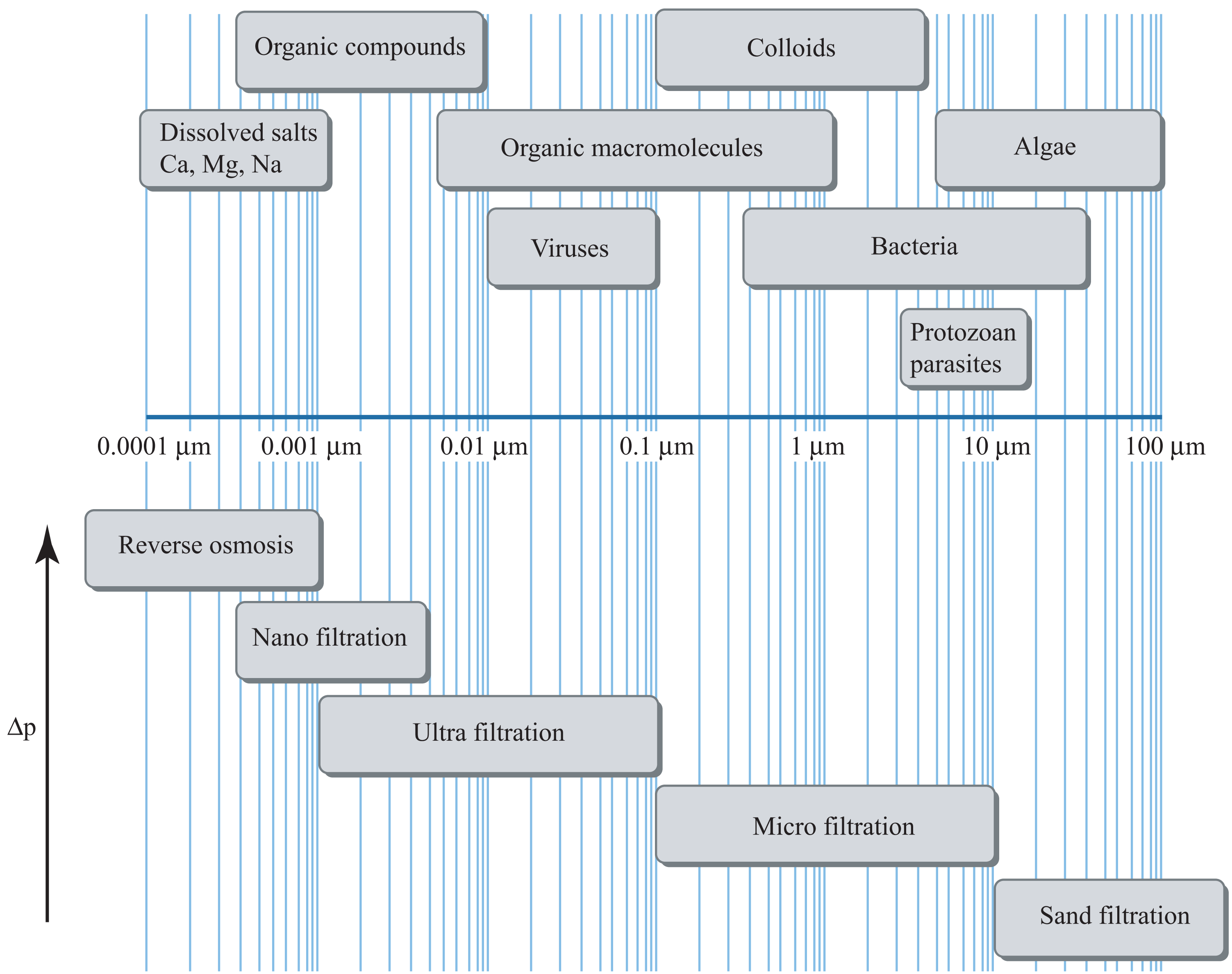
EPA Primary Standards for ~130 chemicals

- Toxic metals – Arsenic, lead, mercury, cadmium, chromium,…
- Organic compounds – insecticides, herbicides, PCBs, petrochemicals, PAH, benzene, halogenated hydrocarbons,…very long list
- Nitrate or nitrite – fertilizer byproduct
- Fluorine – damages teeth and bones at high concentrations
- Radionuclides – mainly natural alpha emitters…

- *Secondary standards* for taste, odor, appearance: Cl^-, SO_4^{2-}, pH, color, odor, iron, manganese, copper, zinc, foaming agents…

Ref: WHO, 2006.

Source: Twort et al.



Comparison of treatment methods with particle size.

Figure by MIT OpenCourseWare.

Why not drink seawater?

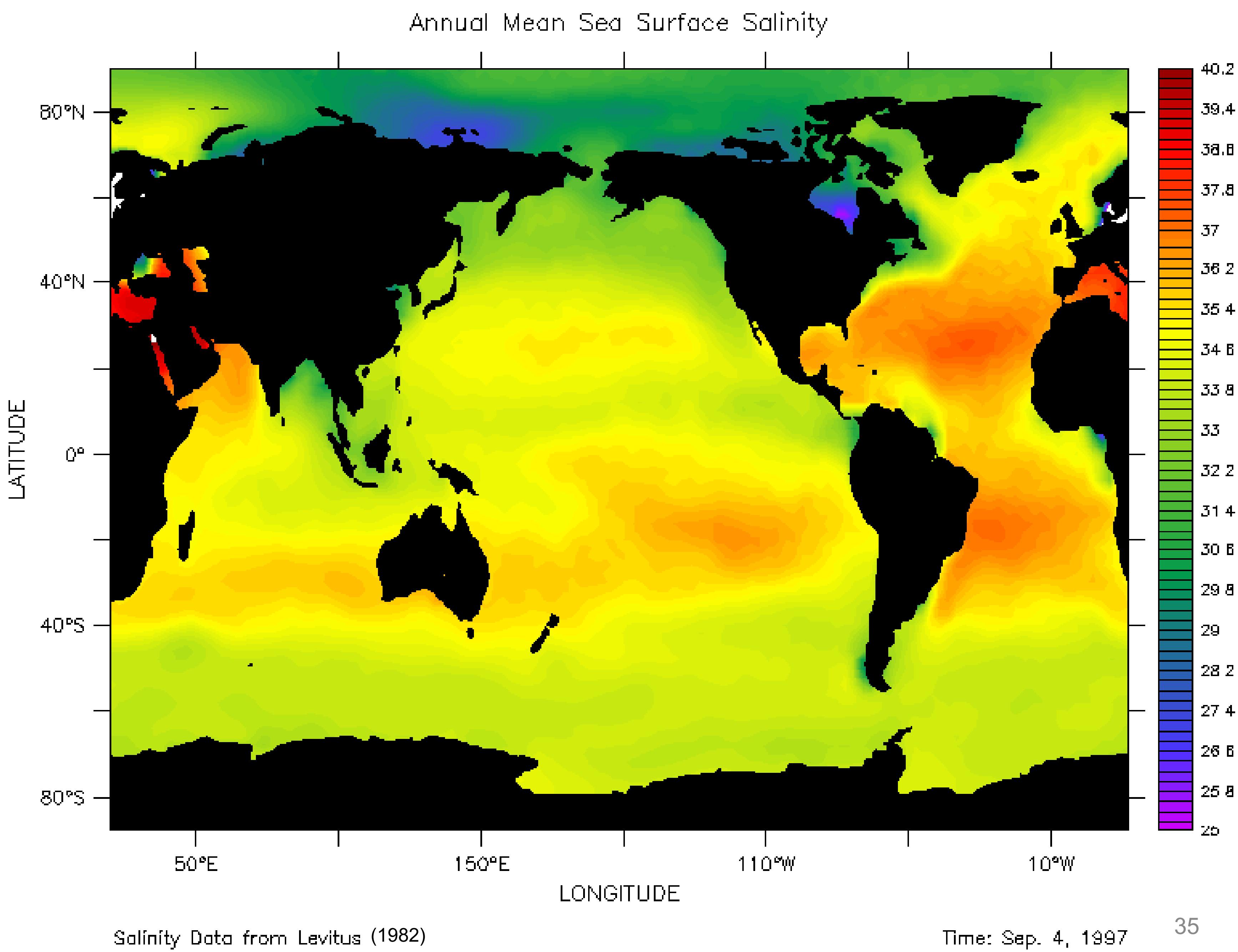
- Seawater is usually about 3.5% by weight dissolved salts (35000 ppm)
- Human blood has the [osmotic] equivalent of about 0.9% salinity (~9000 ppm)

- Ingesting too much salt leads to excretion of water and dehydration. Seawater contains about 3x more dissolved salts than human blood. You can’t drink it. It also tastes bad.

Characterization of Water Salinity

	Minimum Salinity, TDS [ppm or mg/kg]	Maximum Salinity, TDS [ppm or mg/kg]
Seawater	15,000	50,000
Brackish water	1,500	15,000
River water (brackish)	500	1,500
Pure water	0	500

After Fritzmann, 2007



Courtesy of Robert H. Stewart. Used with permission.

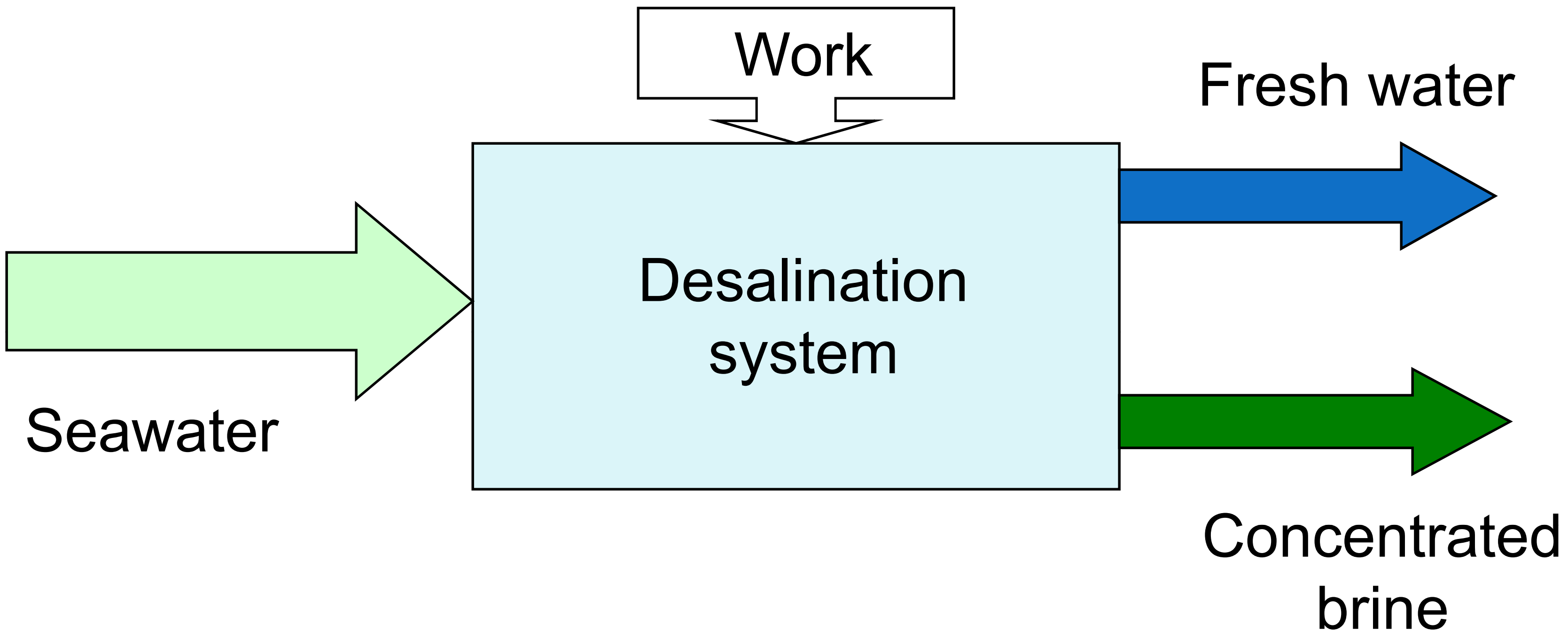
Substance (amounts in mg/kg)	**Standard Seawater**	**Cambridge City Water**	**Massachusetts Water Resources Authority**	**Poland Springs Bottled Water**	**Maximum Allowable**
Sodium, Na^+	10781	79	30	2.6-5.6	aesthetics: 200
Magnesium, Mg^{2+}	1284	5	0.8	0.7-1.9	-
Calcium, Ca^{2+}	412	25	4.5	3.5-9.5	-
Potassium, K^+	399	nr[1]	0.9	0.74-0.88	-
Strontium, Sr^+	13	nr	nr	nr	-
Chloride, Cl^-	19353	140	21	1.5-6.6	250
Sulfate, SO_4^{2-}	2712	27	8	0.87-5.9	250
Bicarbonate, HCO_3^-	126	nr	nr	13-28	-
Bromide, Br^-	67	nr	0.016	not detected	-
Boric Acid, $B(OH)_3$	26	nr	nr	nr	-
Fluoride, Fl^-	1.3	1	1	0.0-0.27	2-4
Water	965000	-	-	-	-
Total dissolved solids	35200	320	110	33-57	500
Nitrate, NO_3		0.46	0.11	0.12-0.42	10
Retail Cost, US$/$m^3$	free?	1.05	1.18	~300 to 3000	-

[1] nr = not reported.

Substance (amounts in mg/kg)	Standard Seawater	High Salinity Brackish Water	Low Salinity Brackish Water	Massachusetts Water Resources Authority
Sodium, Na^+	10781	1837	90	30
Magnesium, Mg^{2+}	1284	130	11.7	0.8
Calcium, Ca^{2+}	412	105	96	4.5
Potassium, K^+	399	85	6.5	0.9
Strontium, Sr^+	13	nr	nr	nr
Chloride, Cl^-	19353	2970	191	21
Sulfate, SO_4^{2-}	2712	479	159	8
Bicarbonate, HCO_3^-	126	250	72.6	nr
Bromide, Br^-	67	nr	nr	0.016
Boric Acid, $B(OH)_3$	26	nr	nr	nr
Fluoride, Fl^-	1.3	1.4	0.2	1
SiO_2	2	17	24	3.3
Nitrate, NO_3	nr	5.0	nr	0.11
Total dissolved solids	35200	5881	647	110

Brackish compositions are representative;
from M. Wilf, 2007

Seawater purification



Ideally, this requires 2.5 to 7 kJ per kg fresh water produced.

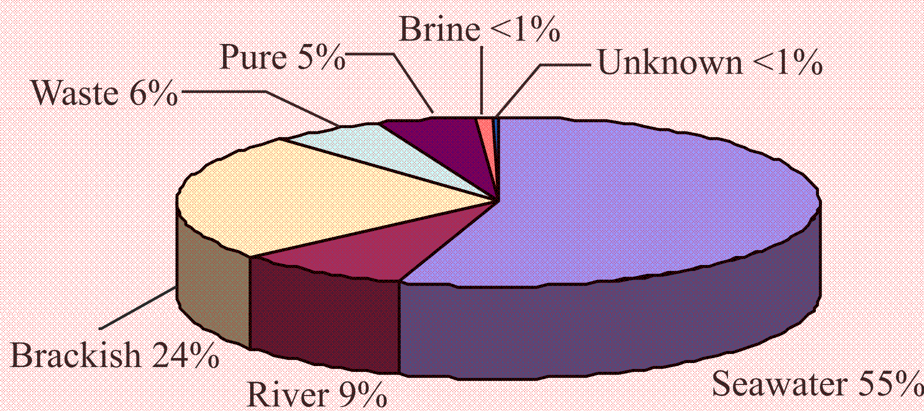
Practically, it takes an order of magnitude more energy.

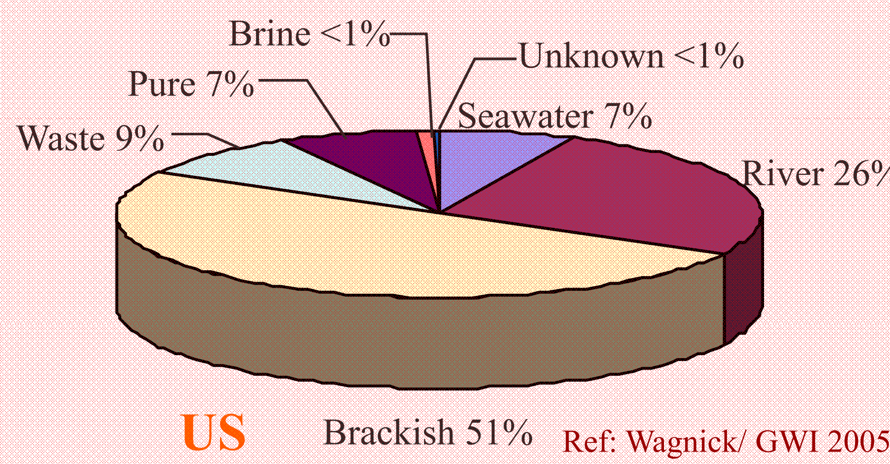
Principal desalination techniques

- Membrane techniques
  - Reverse osmosis (SWRO or BWRO)
  - Electrodialysis (ED)
  - Capacitative deionization (CDI)
  - Nanofiltration (NF)
- Distillation techniques
  - Multistage flash evaporation (MSF)
  - Multieffect distillation (MED or MEE)
  - Vapor compression distillation
  - Solar thermal distillation (concentrating or not)
- Related methods
  - Deionization
  - Water softening

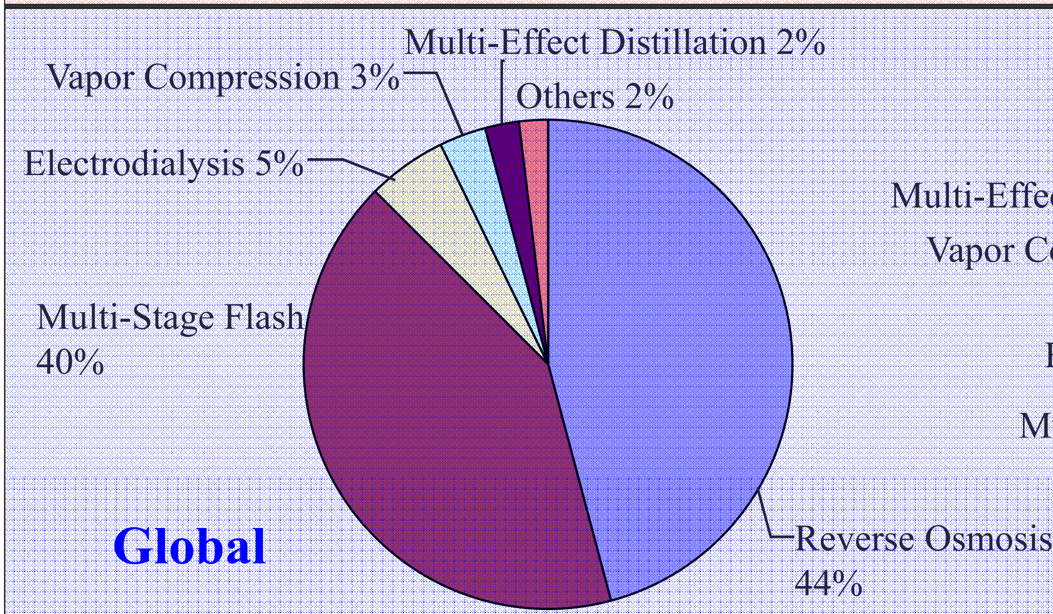
Installed desalination capacity

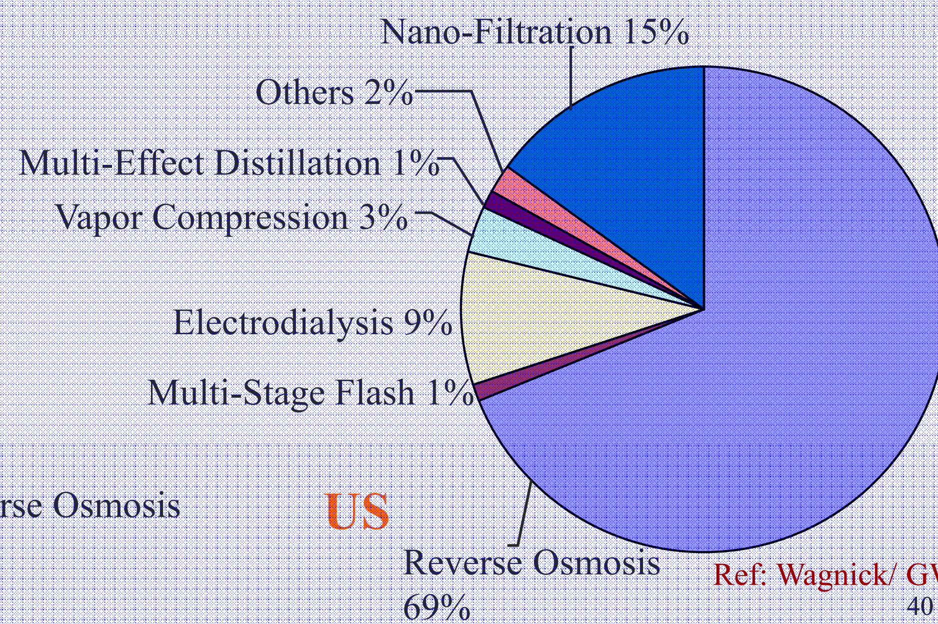
S O U R C E





Ref: Wagnick/ GWI 2005





P R O C E S S

Ref: Wagnick/ GWI 2005

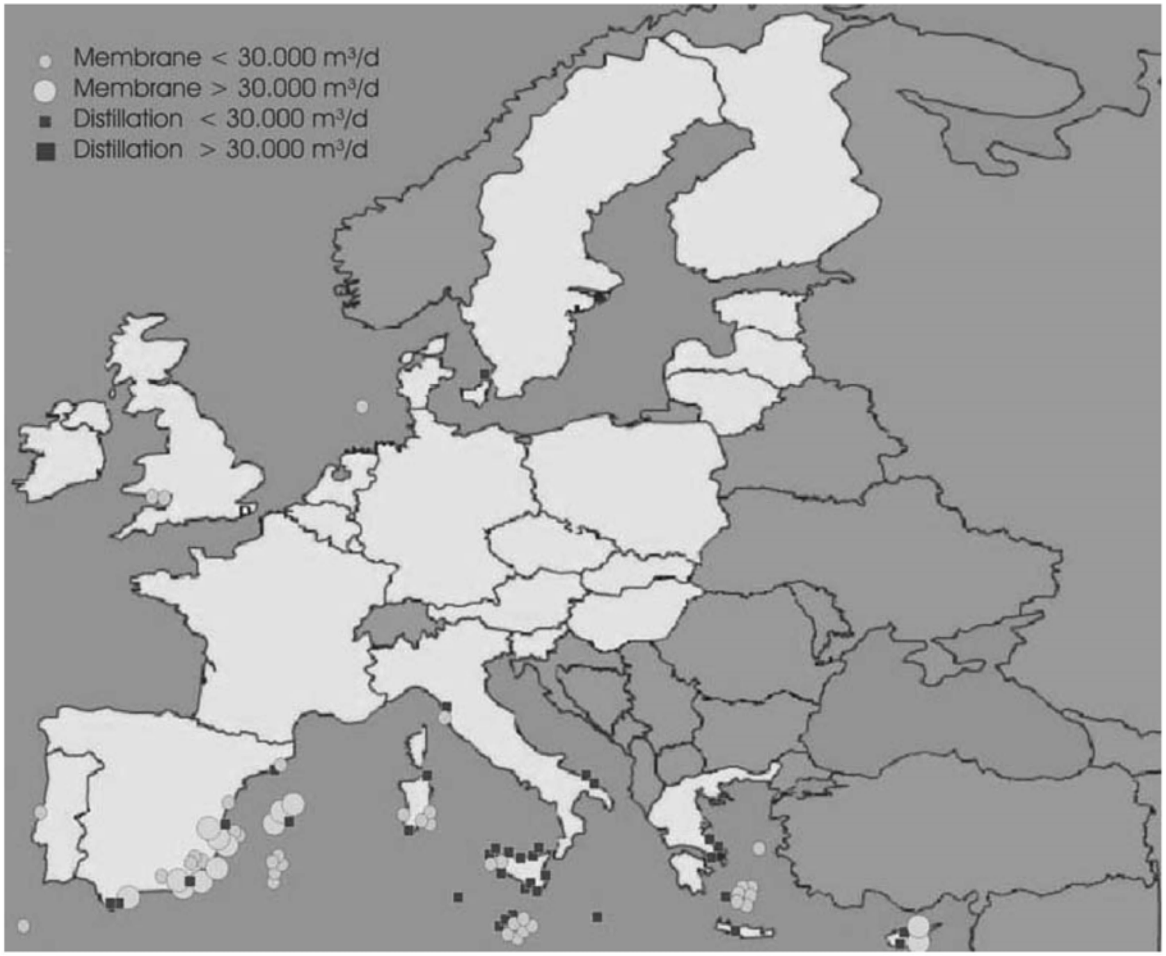


Fig. 5. Seawater desalination plants constructed from 1985 until today. (Only plants with a capacity of at least 700 m³/d were considered). Modified from [2].

Source: Fritzmann et al., *Desalination*, 2007

1) Multi Stage Flash - MSF

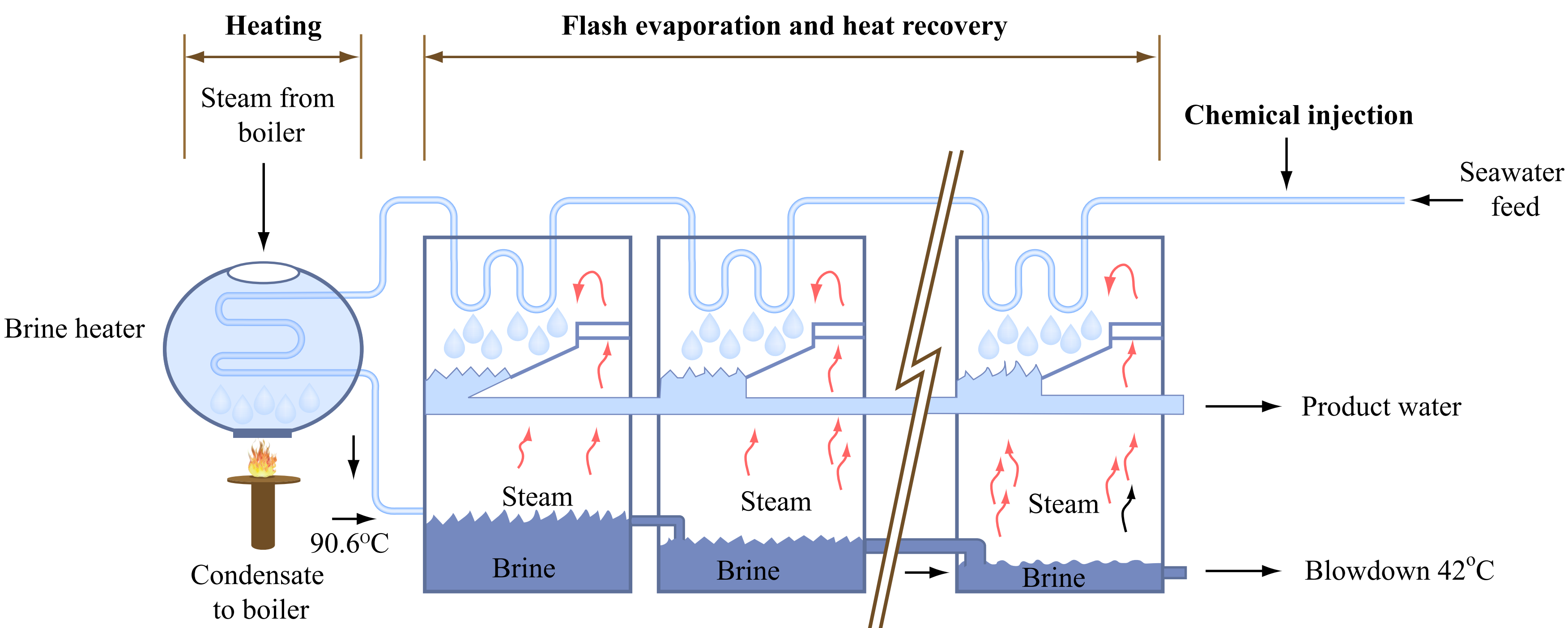
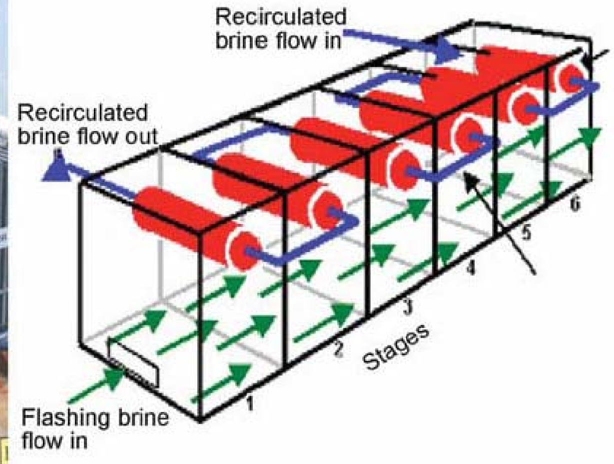


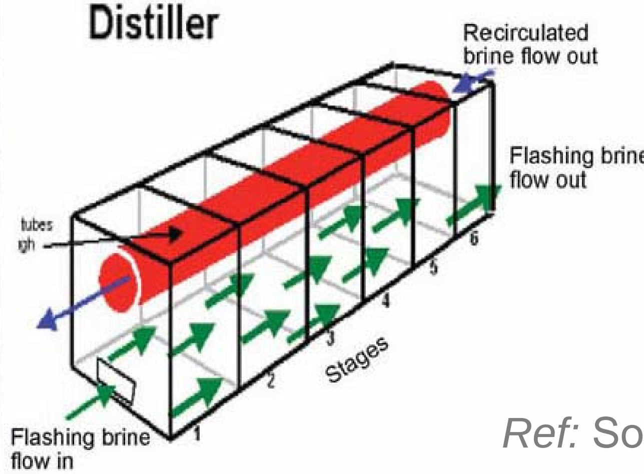
Figure by MIT OpenCourseWare.

Multi stage flash

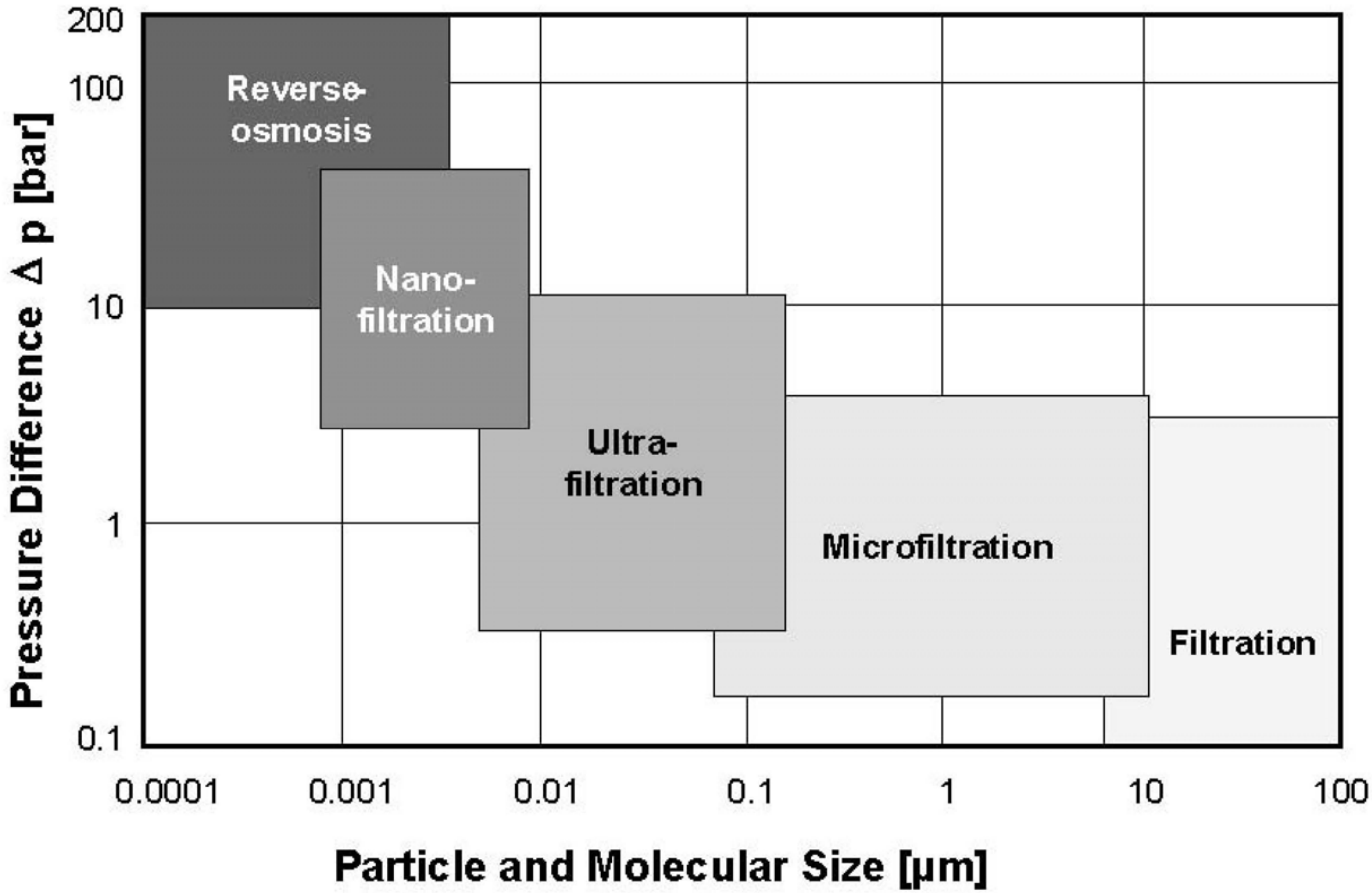
Cross Tube



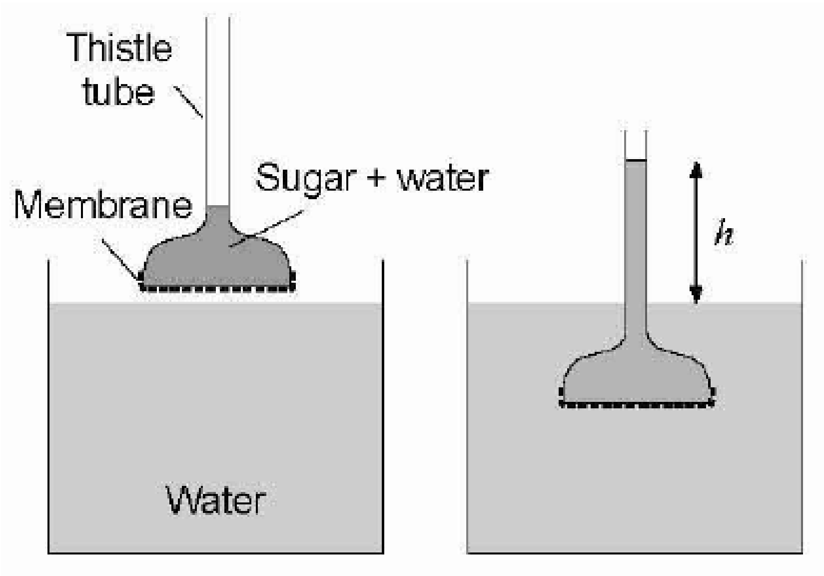
Long Tube Distiller



Ref: Sommariva, 2007



Source: Fritzmann et al., 2007



Courtesy of Dennis Freeman, Martha Gray, and Alexander Aranyosi.
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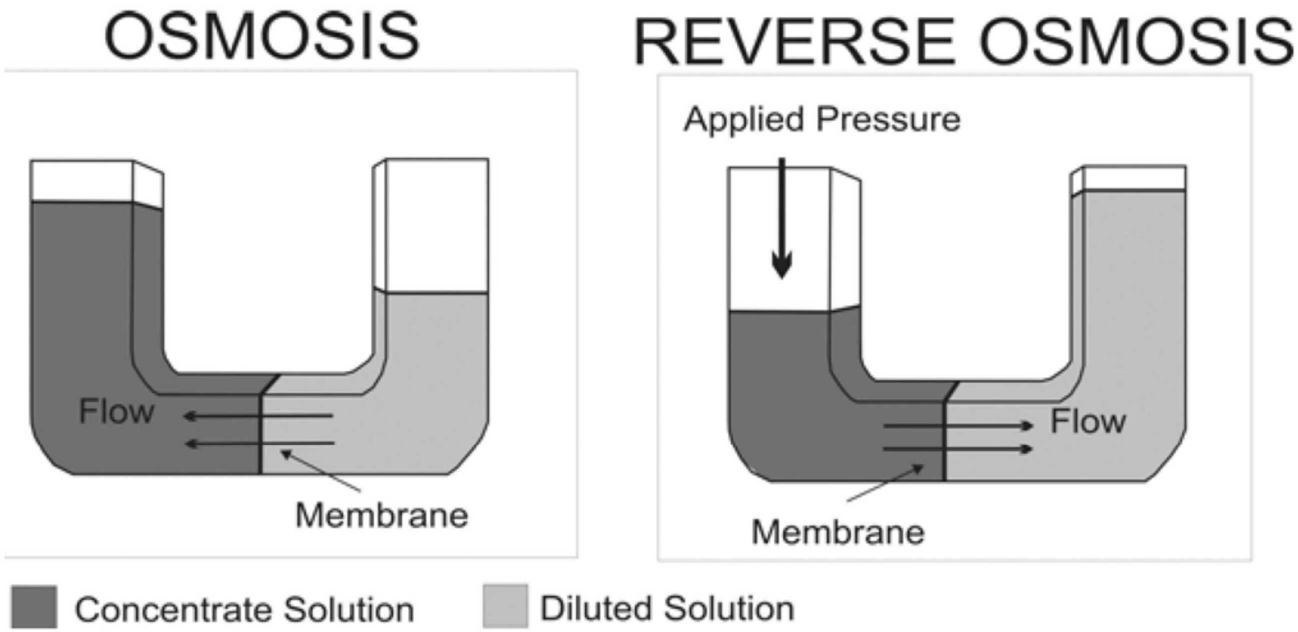
Osmosis. to achieve equilibrium, water will diffuse through a semi-permeable membrane into a solution. This occurs until sufficient hydrostatic pressure develops to offset the *osmotic pressure*

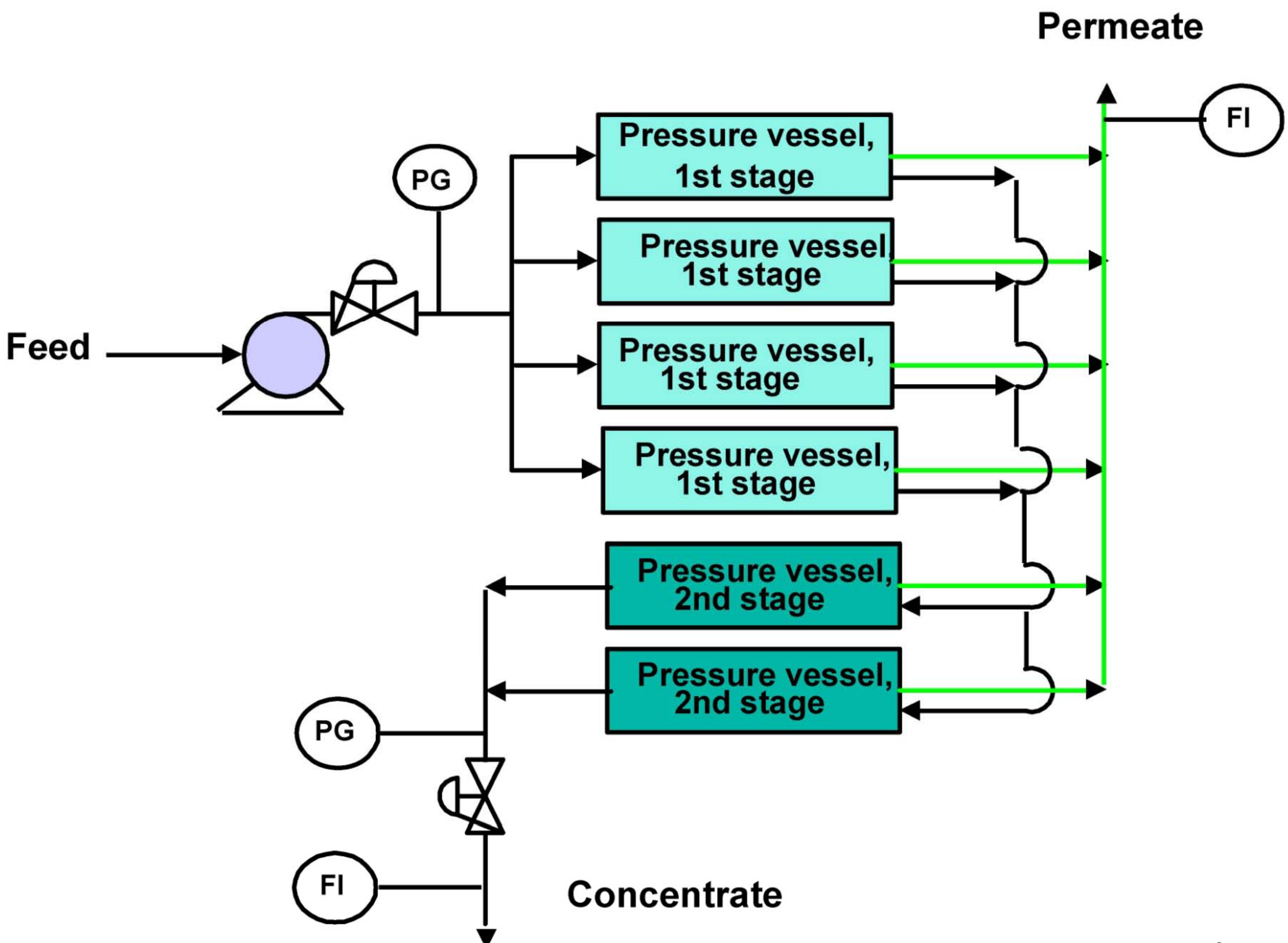
Sources:
http://encarta.msn.com (left)
http://library.tedankara.k12.tr/



If pressure is applied to the solution, the direction of osmotic flow can be reversed. In this way solvent can be driven through the membrane, purifying it.

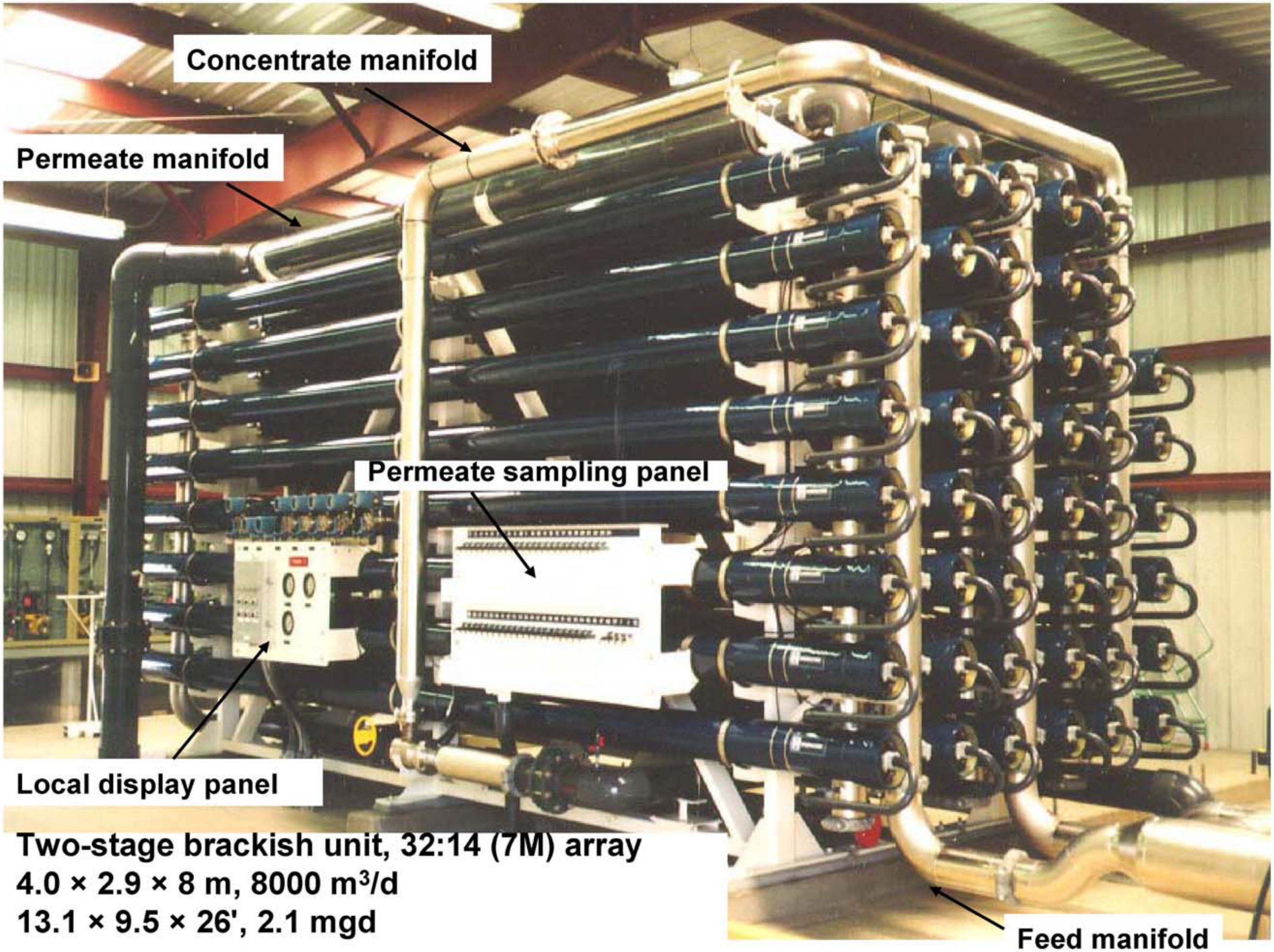
Source: Fritzmann et al., 2007

Two stage RO system



Source: Sommariva,2007

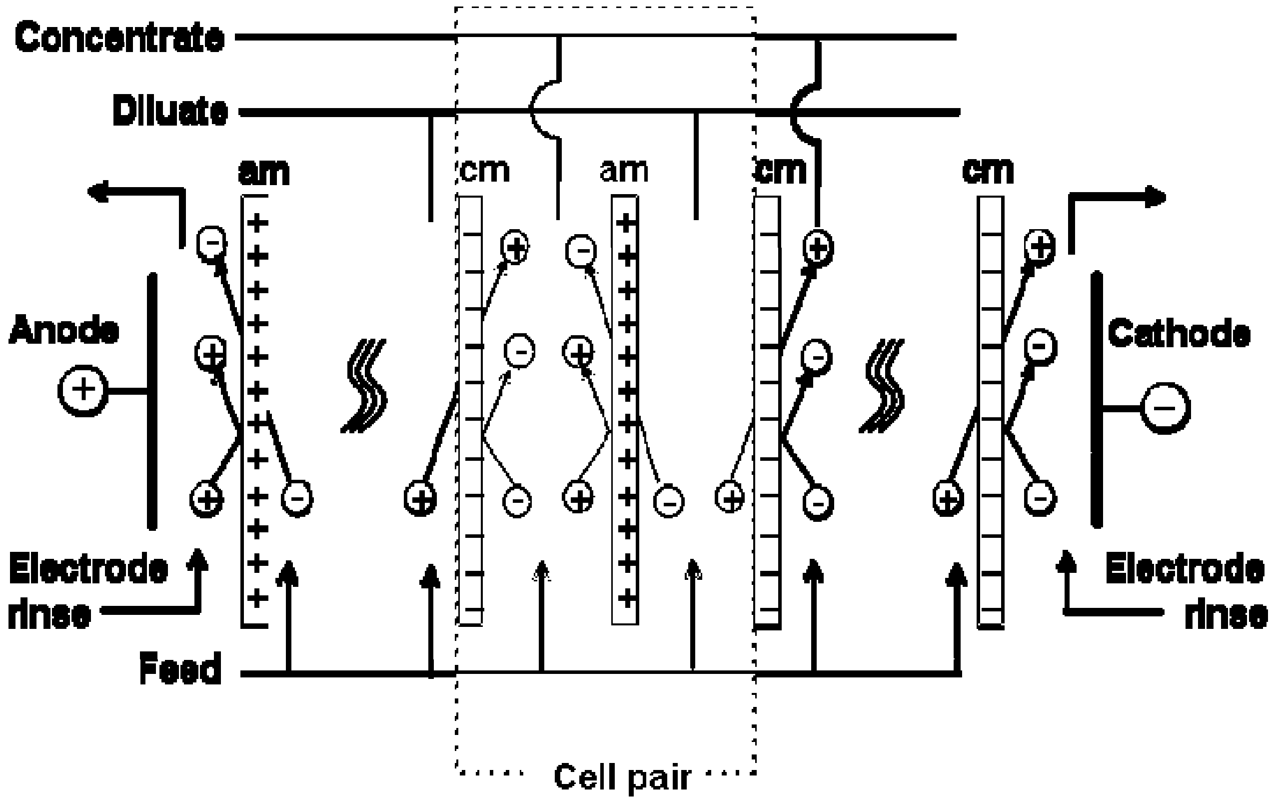
Figures from Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.



First stage has 32 pressure vessels; second stage has 14 *(Wilf & Balaban ,2007)*

CONVENTIONAL ELECTRODIALYSIS

The process principle



Courtesy of Heiner Strathmann. Used with permission.

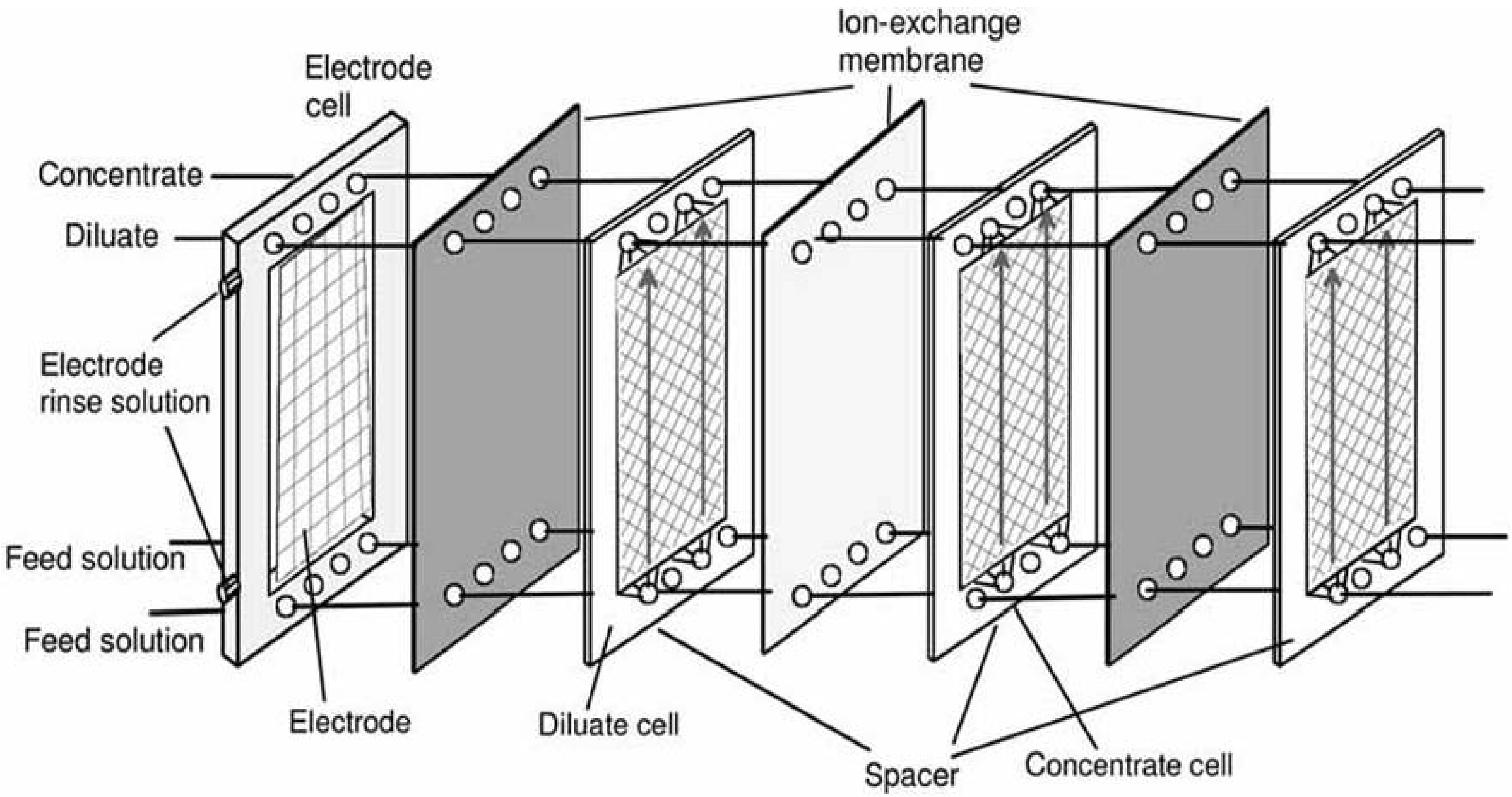
ions are removed from a feed solution and concentrated in alternating cells

a cation and an anion-exchange membrane, and a diluate and concentrate cell form a cell pair

Strathmann, 2007

CONVENTIONAL ELECTRODIALYSIS

The electrodialysis stack



Courtesy of Heiner Strathmann. Used with permission.

an electrodialysis stack is composed of 100 to 400 cell pairs between electrode compartments

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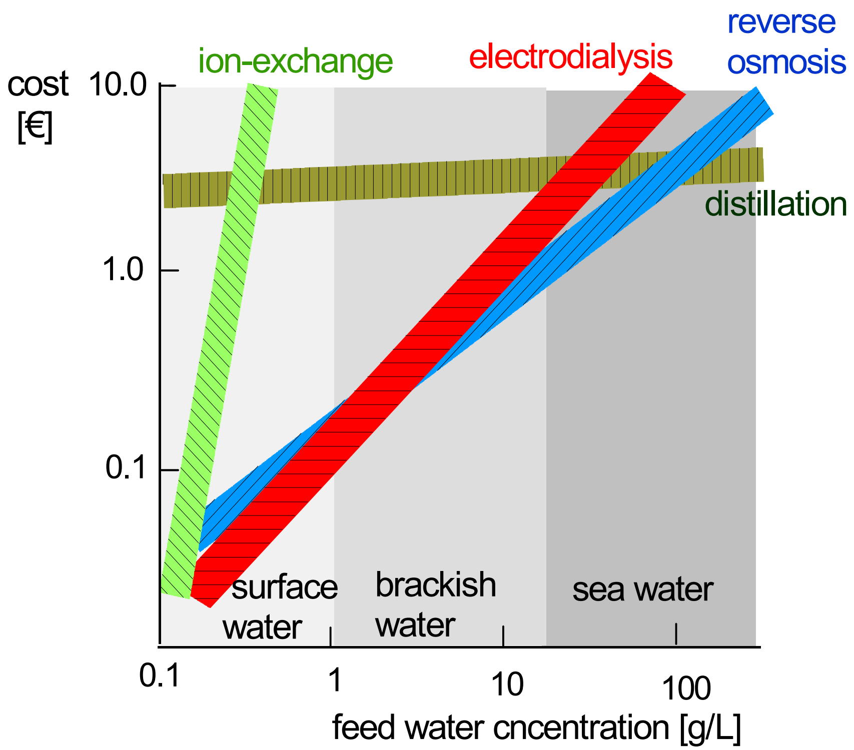
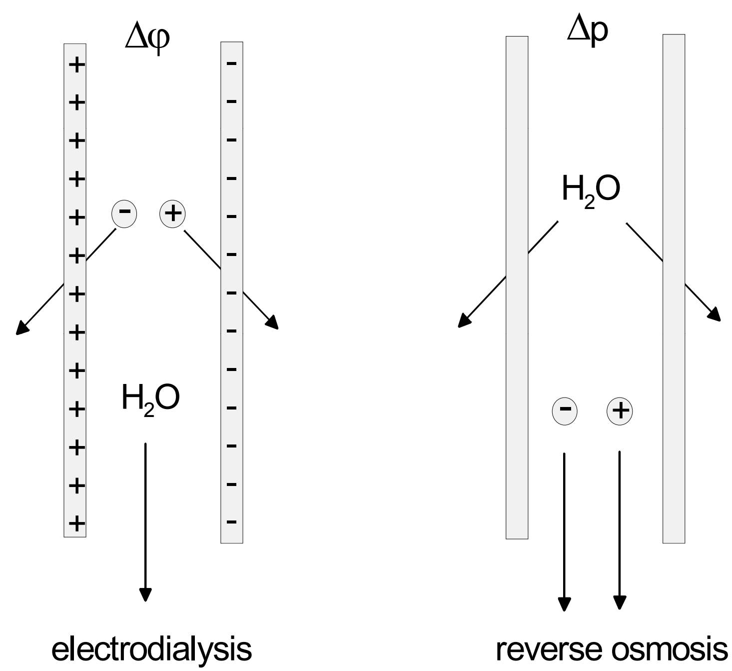
CONVENTIONAL ELECTRODIALYSIS

Water desalination costs



costs estimated for a required product concentration of < 0.2 g/L (200 ppm)

Process principles of electrodialysis and reverse osmosis



irreversible energy loss proportional to ion transport (E_{irr} = z_i F ΔC_i U V)

irreversible energy loss proportional to water transport (E_{irr} = Δp V_{water})

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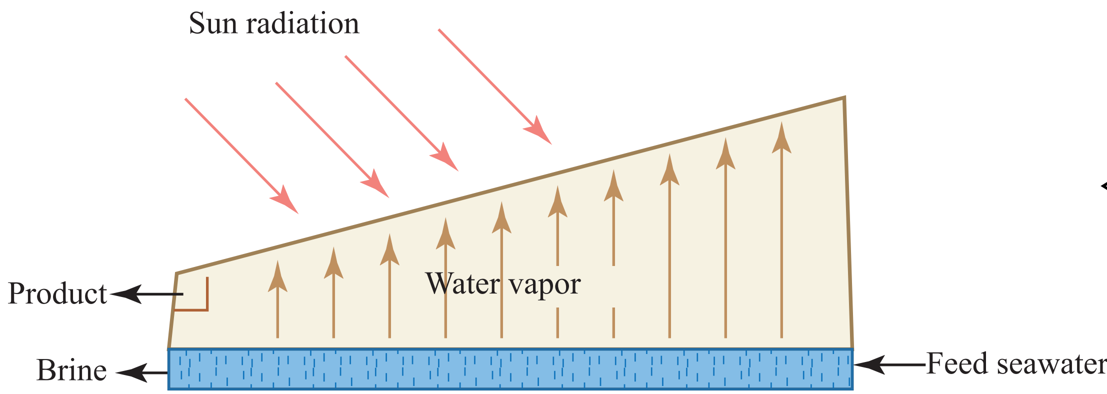
Solar Distillation

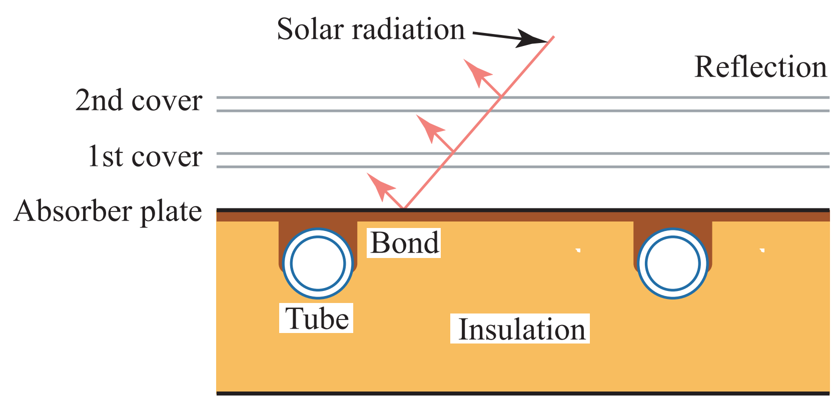


Schematic of simple solar still.

Figure by MIT OpenCourseWare.

Optimally bad?

~ 1 L/m^2-day



Sheet-and-tube solar collector.

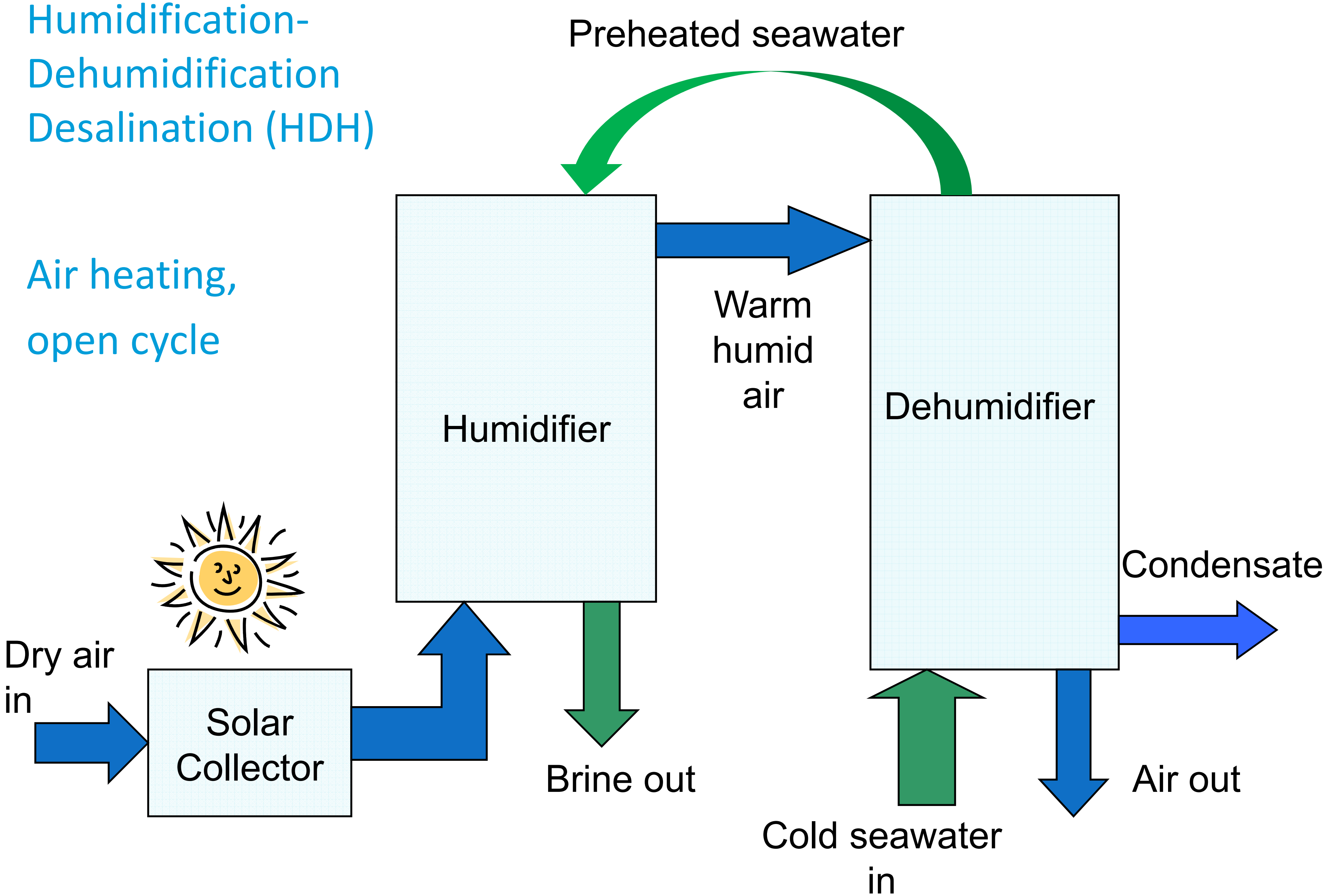
Figure by MIT OpenCourseWare.

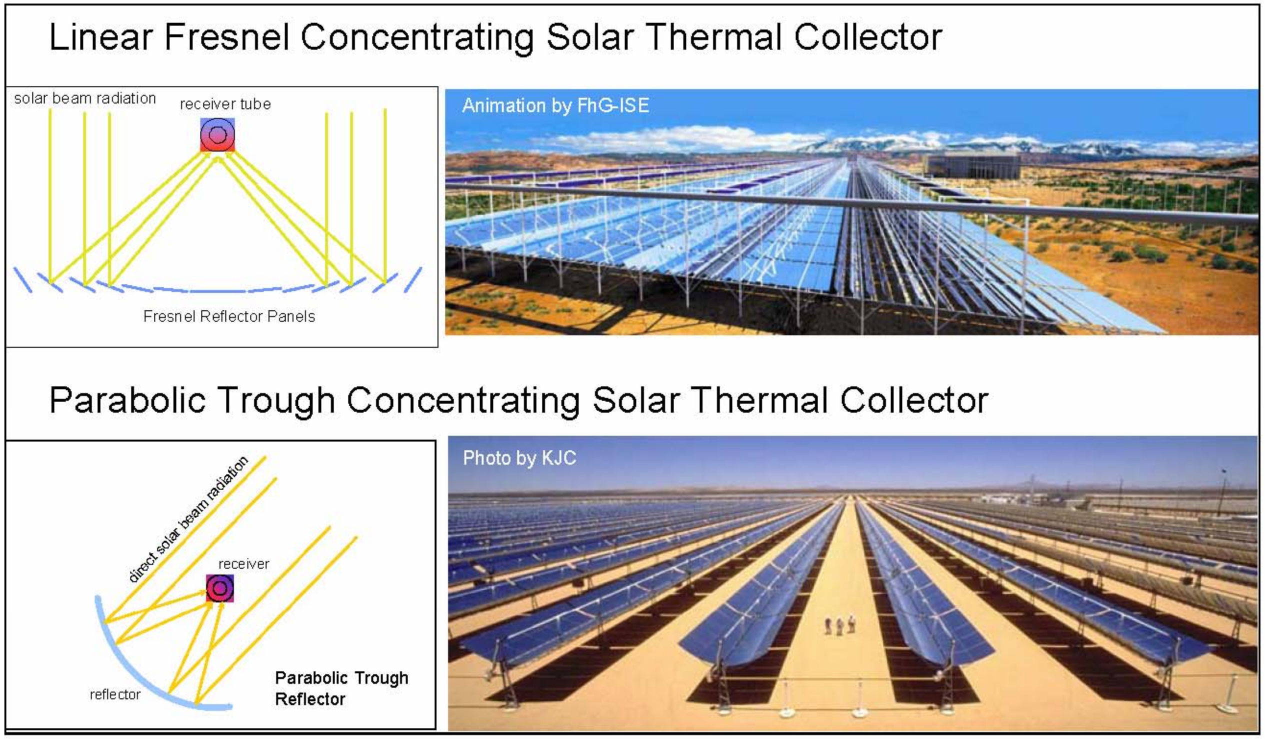
..obvious improvements…
…multiple glazing to control IR and convective loss…

Refs: Ettouney & Rizzuti, 2006; Duffie & Beckman, 2006

Humidification-Dehumidification Desalination (HDH)

Air heating, open cycle

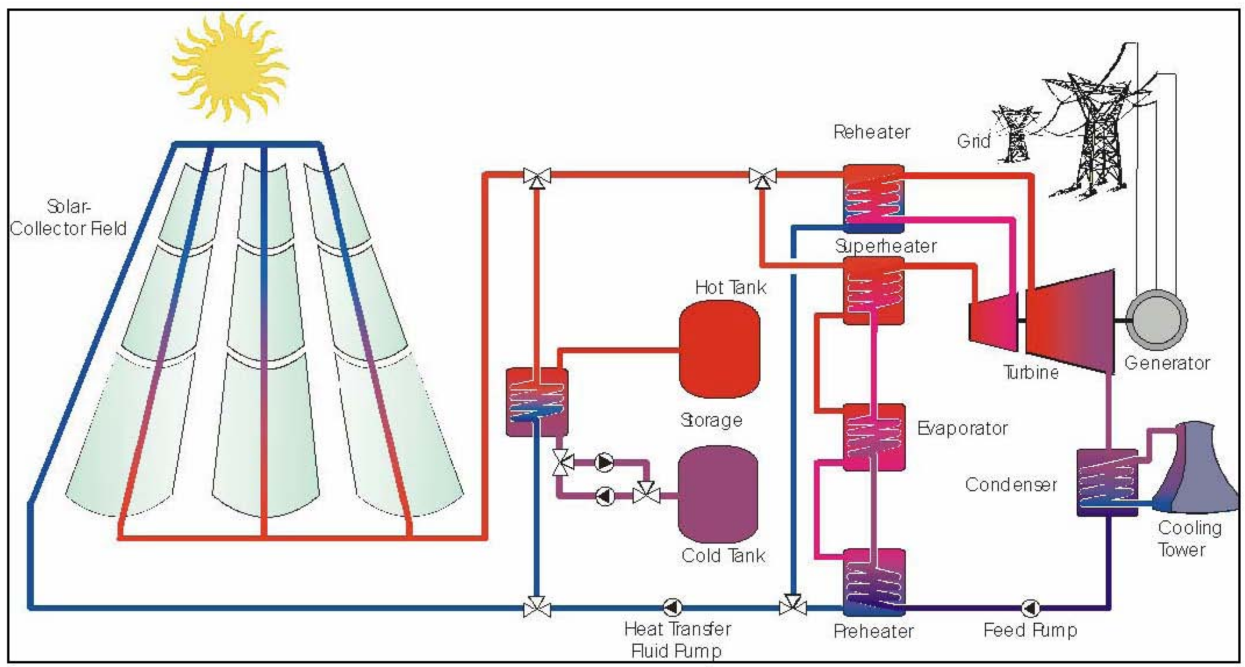




Concepts from concentrating solar power can be applied to solar distillation…generate electricity, then make water from waste heat or electricity

…theoretical performance can be ~100X better than solar still

Ref: Trieb et al., Nov. 2007



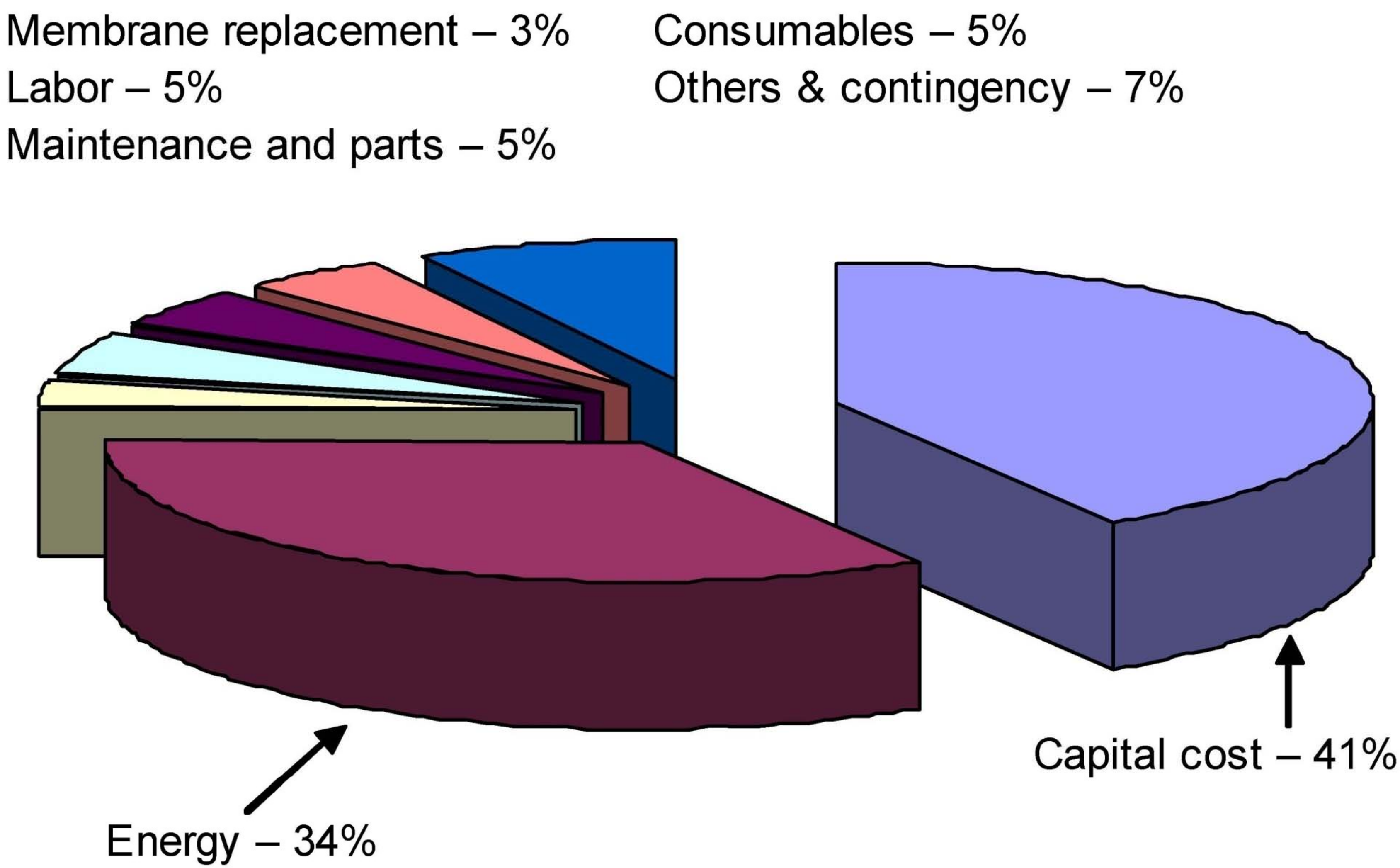
Courtesy of Franz Trieb and DLR. See www.dlr.de/tt/aqua-csp. Used with permission.

Major concerns in desalination systems

- Cost: hardware, site development
- Cost: energy consumption
- Cost: maintenance
  - Scaling, from precipitation of salts (has a *controlling* influence on design of thermal systems)
  - Fouling, from bacteria and other deposits
  - Degradation of membranes
  - Corrosion of hardware
- Disposal of brine efflux, environmental impact

- Reliability, distribution,…

Total water cost distribution in SWRO



Figures from Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Source: Sommariva,2007

Prices for consumers in office spaces occupying 4180 m^2 of city space and using 10,000 m^3/y

Country	$/M^3
Germany	$1.91
Denmark	$1.64
Belgium	$1.54
Netherlands	$1.25
France	$1.23
United Kingdom	$1.18
Italy	$0.76
Finland	$0.69
Ireland	$0.63
Sweden	$0.58
Spain	$0.57
U.S.A.	$0.51
Australia	$0.50
South Africa	$0.47
Canada	$0.40

Figure by MIT OpenCourseWare.

Some notes on 2.500 this semester

- Term project on purifying village well water in Haiti (will be introduced in March)
- Visit Koch Membrane Systems in Wilmington on Tuesday, March 10
- Visit GE Ionics in Watertown on Friday, March 13
- Final project presentations on Tuesday May 12

- GRADING
  - Approximately: homework (55%), term project (35%), class participation (10%)

- *Listeners must register as listeners*

Readings to accompany this lecture, all on Course Website

- Michael Specter, *The Last Drop*, The New Yorker, 23 October 2006, pp. 60-71.
- *Water for People, Water for Life*, UNESCO, 2003 (skim)
- Section on Water Quality from Reynolds & Richards, *Unit Operations…*,1995
- EPA Primary Drinking Water Standards
- Peruse the other general articles on water if you are interested…

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2. UNESCO Photobank, http://photobank.unesco.org/exec/index.htm
3. J.P. Holdren, "Science and Technology for Sustainable Well-Being," *Science*, 319 (25 Jan 2008) 424-434.
4. United Nations Environment Program (UNEP), Maps and Graphics Library. http://maps.grida.no/
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7. Water quality results obtained from web sites of the Massachusetts Water Resources Authority, the Cambridge City Water Department, and the Poland Spring Water Company.
8. T.D. Reynolds and P.A. Richards, *Unit Operations and Processes in Environmental Engineering*, 2nd ed. Boston: PWS Publishing Co., 1995.
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10. M. Wilf, *The Guidebook to Membrane Desalination Technology.* L'Aquila Italy: Balaban Desalination Publications, 2007.
11. C. Fritzmann, J. Lowenberg, T. Wintgens, T. Melin, "State-of-the-art reverse osmosis desalination, *Desalination*, 216 (2007) 1-76.
12. M. Wilf and M. Balaban, *Membrane Desalination and Membrane Water Filtration*, European Desalination Society intensive course notes, L'Aquila, Italy, February 2007.
13. S.D. Faust and O.M. Aly, *Chemistry of Water Treatment*, 2nd ed. Boca Raton: Lewis Publishers/CRC, 1998.

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15. Seawater Salinity Graphic from Texas A&M University Physical Oceanographic Course Web site. http://oceanworld.tamu.edu/resources/ocng_textbook/chapter06/chapter06_03.htm
16. M. Al-Ghamdi, *Saline Water Conversion Corporation: Challenge, Achievement, and Future Prospective.* Lecture notes, April 2006.
17. C. Sommariva, Short Course Notes on Reverse Osmosis Desalination, 2007.
18. H. Strathmann, *Electromembrane processes: State-of-the-art processes and recent developments*, *lecture notes,* 2007.
19. Dr. Franz Trieb et al., *Concentrating Solar Power for Seawater Desalination*, German Aerospace Center (DLR), Institute of Technical Thermodynamics, Nov. 2007.