2.500 Desalination and Water Purification
Spring 2009

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Spring 2009

Summary

Haiti

Ghana

Photos by Amy Smith. Used with permission.

Context

Safe water supply … is not universal

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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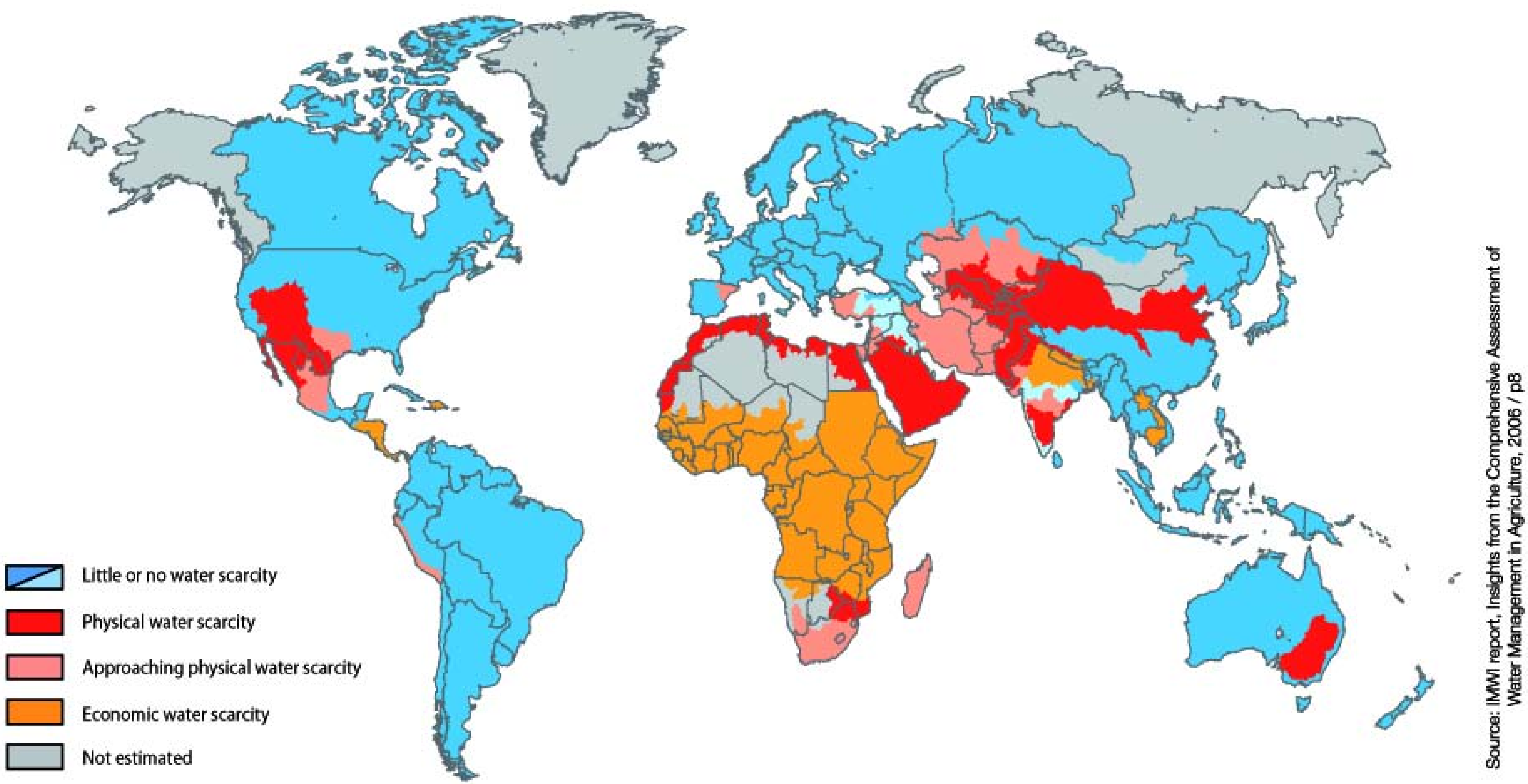
http://www.flickr.com/photos/andrewheavens/100063338/
http://jimbicentral.typepad.com/photos/uncategorized/2007/09/18/water_scarcity.jpg

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.

MITMECHE

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

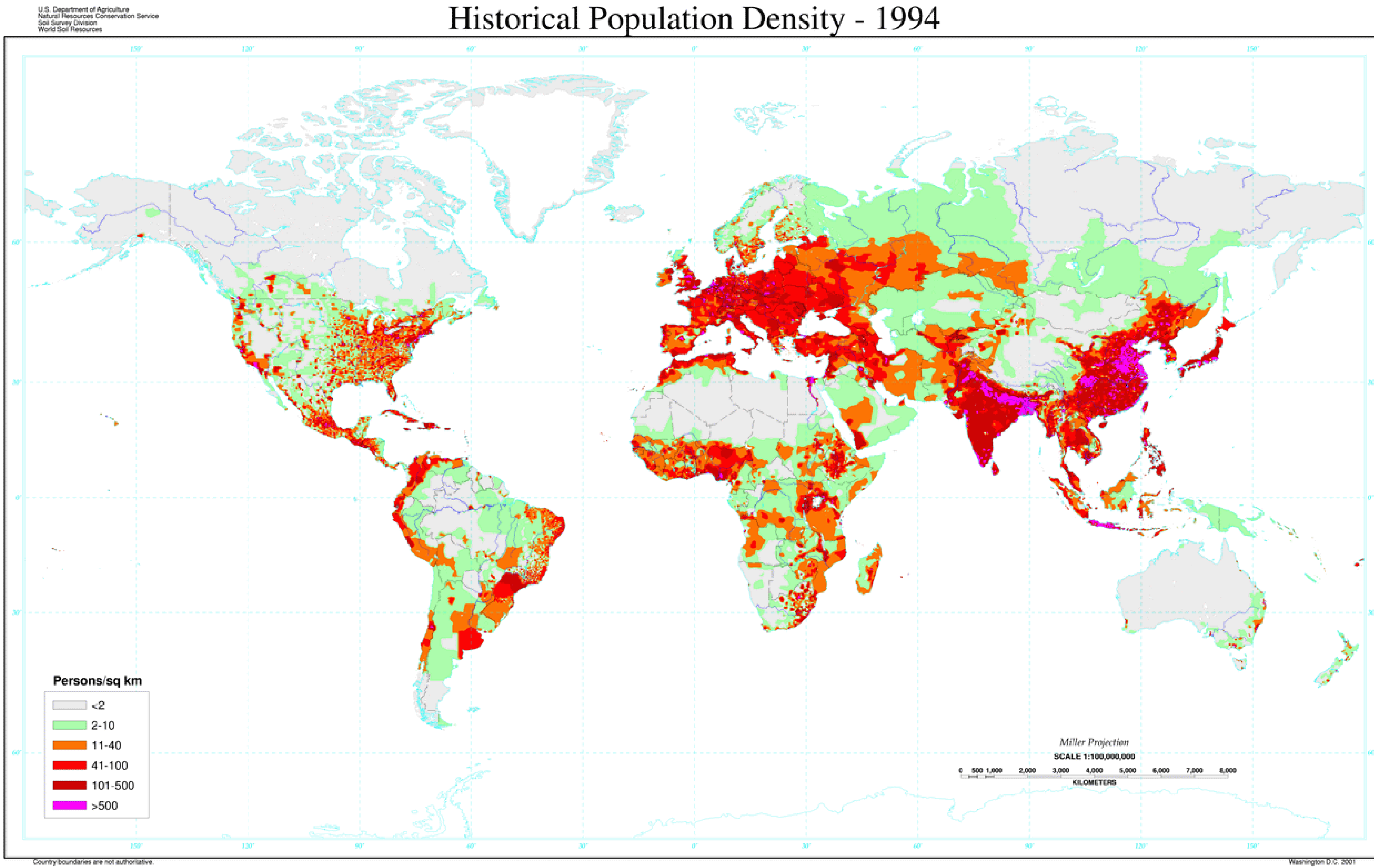

Image from Tobler, W., et al. "The Global Demography Project." TR-95-6. Santa Barbara, CA: National Center for Geographic Information Analysis, 1995. Image is in the public domain.

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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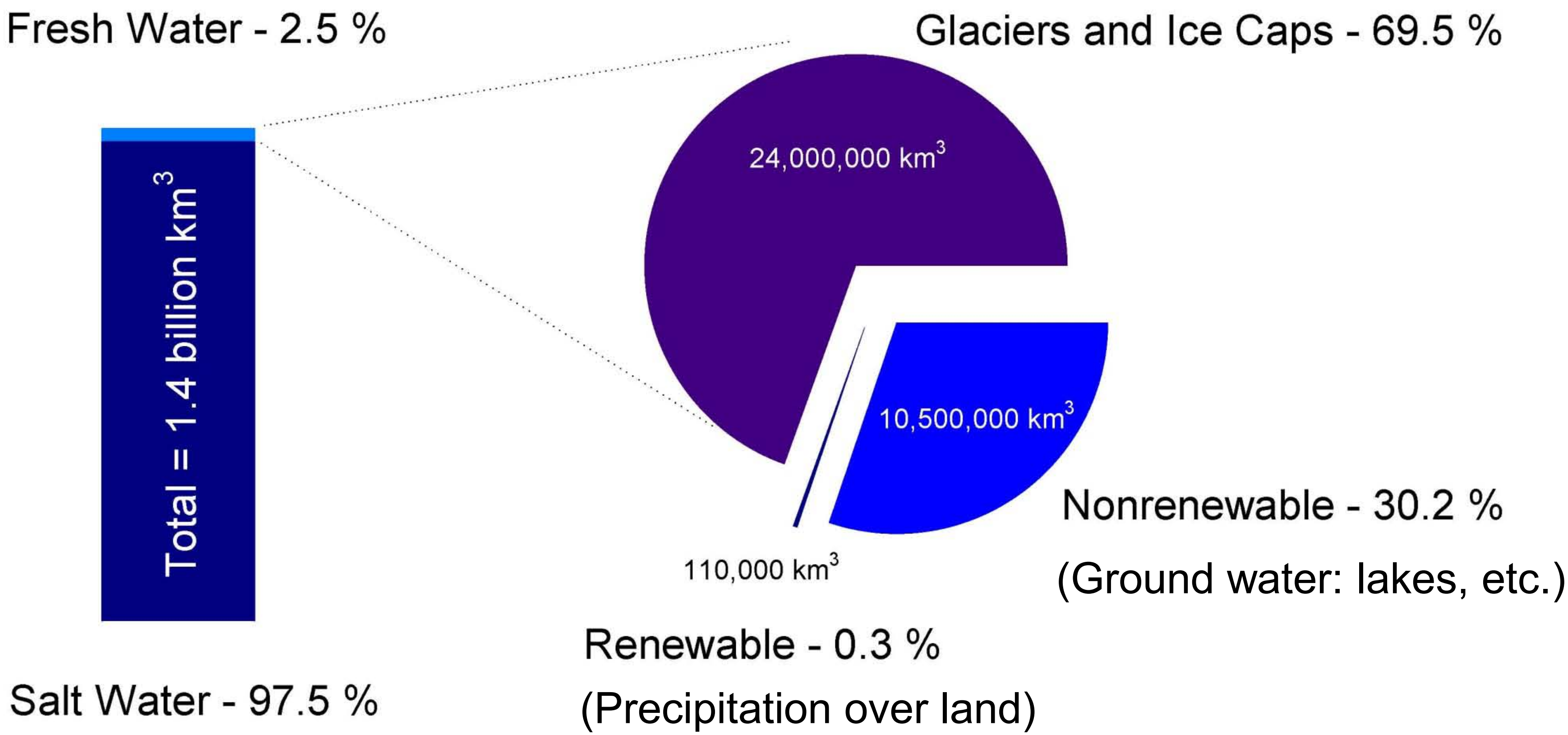
Cleaning a sidewalk in Long Beach, CA

July - September, 1989 August 12, 2003

Images from NASA Earth Observatory.

Aral Sea – water diverted for agriculture

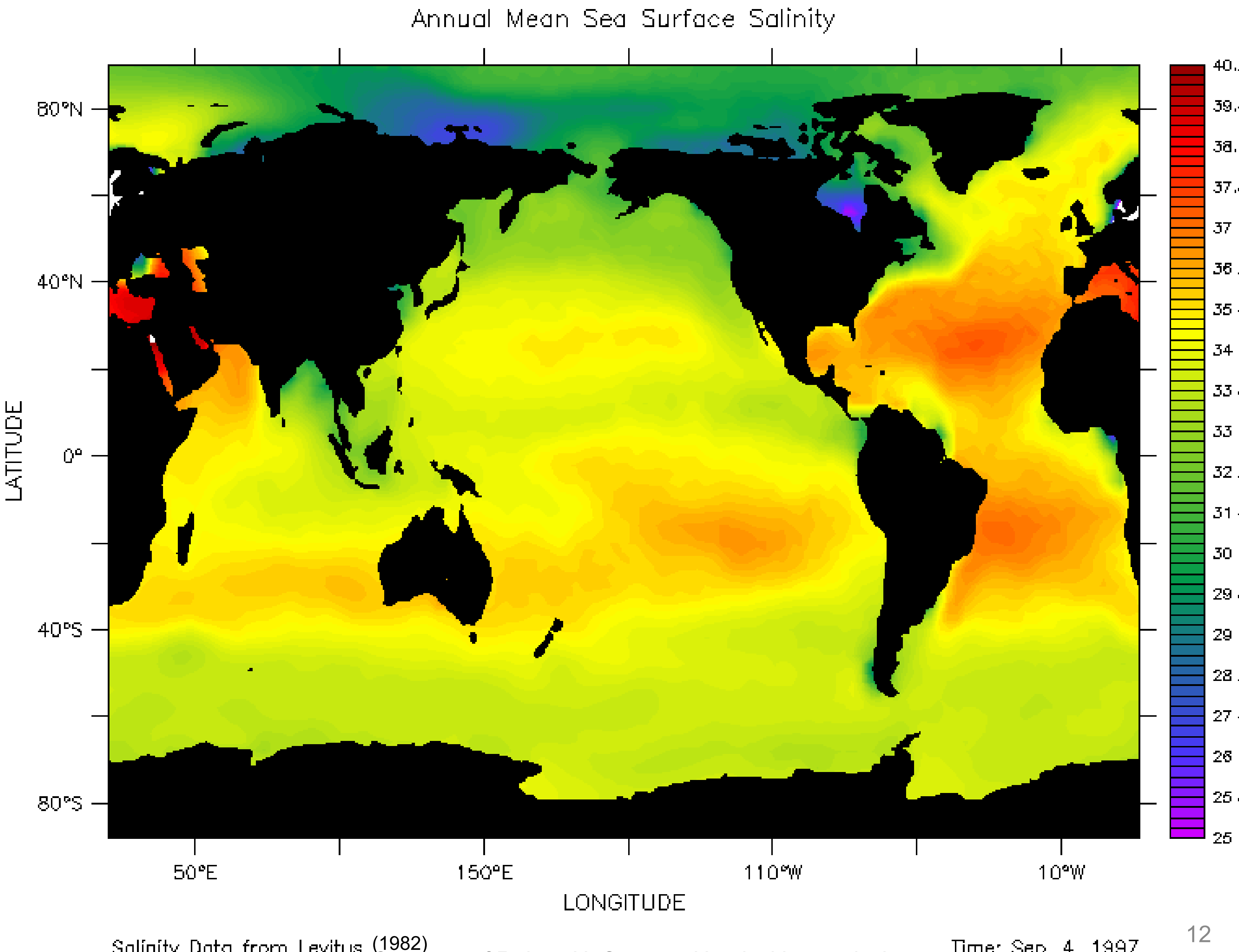
Source: infranetlab.org



Courtesy of Sandia National Labs. Used with permission.

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.



Courtesy of Robert H. Stewart. Used with permission.

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 Quality

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.

Disinfection of water

- Chlorination
  - Highly effective for bacteria, and effective for viruses
  - Not effective for protozoa
  - Inexpensive, very common
- Ozonation
  - Highly effective
- Ultraviolet radiation
  - Effective for low turbidity
- Boiling
  - Complete sterilization possible

Ref: Twort et al.

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.

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.

Concepts from Physical Chemistry

- Gibbs energy
- Chemical activity
- Colligative properties (especially osmosis)
- Electrolyte behavior
- Osmotic coefficient
- Ion transport
- Colloidal Stability

$$G = H - TS$$

Measures of concentration

- Mass fraction (% by mass, ppm,…), w_i
- Mole fraction (% of total moles), x_i
- Total dissolved solids is a mass fraction
- Molality (mol solute/kg solvent), m_i

Dissolution of salts

$$A_{\nu+}B_{\nu-} \longrightarrow \nu_+ A^{z+} + \nu_- B^{z-}$$

Electroneutrality: $\begin{cases} \nu_+ z_+ + \nu_- z_- = 0 \\ z_+ c_+ + z_- c_- = 0 \end{cases}$

$$\mathrm{MgCl_2} \longrightarrow \mathrm{Mg^{2+}} + 2\mathrm{Cl^-}$$

Salts that dissociate completely are called *strong electrolytes.*

$NaCl$, $MgCl_2$, $MgSO_4$, $CaSO_4$, K_2SO_4, KBr, …$CaCO_3$ are related to seawater

Partial molar Gibbs energy

$$\underline{G} = x_a \overline{G_a} + x_b \overline{G_b}$$

mixture, J/mol

$$\overline{G_i} = \underline{G}_i + RT \cdot \ln(a_i)$$

partial molar, J/mol

For pure substance in reference state

For equilibrium between two phases or solutions, the partial molar Gibbs energy of each species is the same.

Chemical Activity

$$a_{solvent} = \gamma_{solvent} x_{solvent}$$

$$a_{electrolyte} = \left(\gamma_{\pm} m_{\pm}\right)^{\nu}$$

$$\ln(a_{solvent}) = -\phi \cdot M_{solvent}\left(10^{-3}\,\mathrm{kg/g}\right) \cdot \sum m_i$$

Note that the osmotic coefficient provides a less error sensitive means of calculating the partial molar Gibbs energy of the solvent.

Colligative Properties

- Properties that depend upon the amount of dissolved solute but not the identity of the solute
  - Vapor pressure lowering (Raoult's Law)
  - Boiling point elevation,
  - Freezing point depression
  - Osmosis
- Amount: molality (mol solutes/kg solvent)

- These properties refer to equilibrium between phases or solutions of differing composition, and all are related to partial molar Gibbs energy

Property	Ideal Solute	Real Solute
Osmotic pressure	$\Pi = RTc_{solutes}$ $(\phi = 1)$	$\Pi = \phi RT\rho_{solvent}\sum m_i$
Freezing point depression	$\delta = k_f \times \sum m_i$	$\delta = \phi \times k_f \times \sum m_i$
Boiling point elevation	$\delta = k_b \times \sum m_i$	$\delta = \phi \times k_b \times \sum m_i$
Vapor pressure lowering	$p_{vap} = p_{sat,pure}x_{solvent}$	$p_{vap} = p_{sat,pure}a_{solvent}$

Osmotic coefficient, Φ, is a function of solute, solvent, temperature, and molality

Osmotic pressure

$$\Pi = p_{solution} - p_{pure-solvent} = -\frac{RT}{\underline{V}_w}\ln\left(a_{solvent}\right)$$

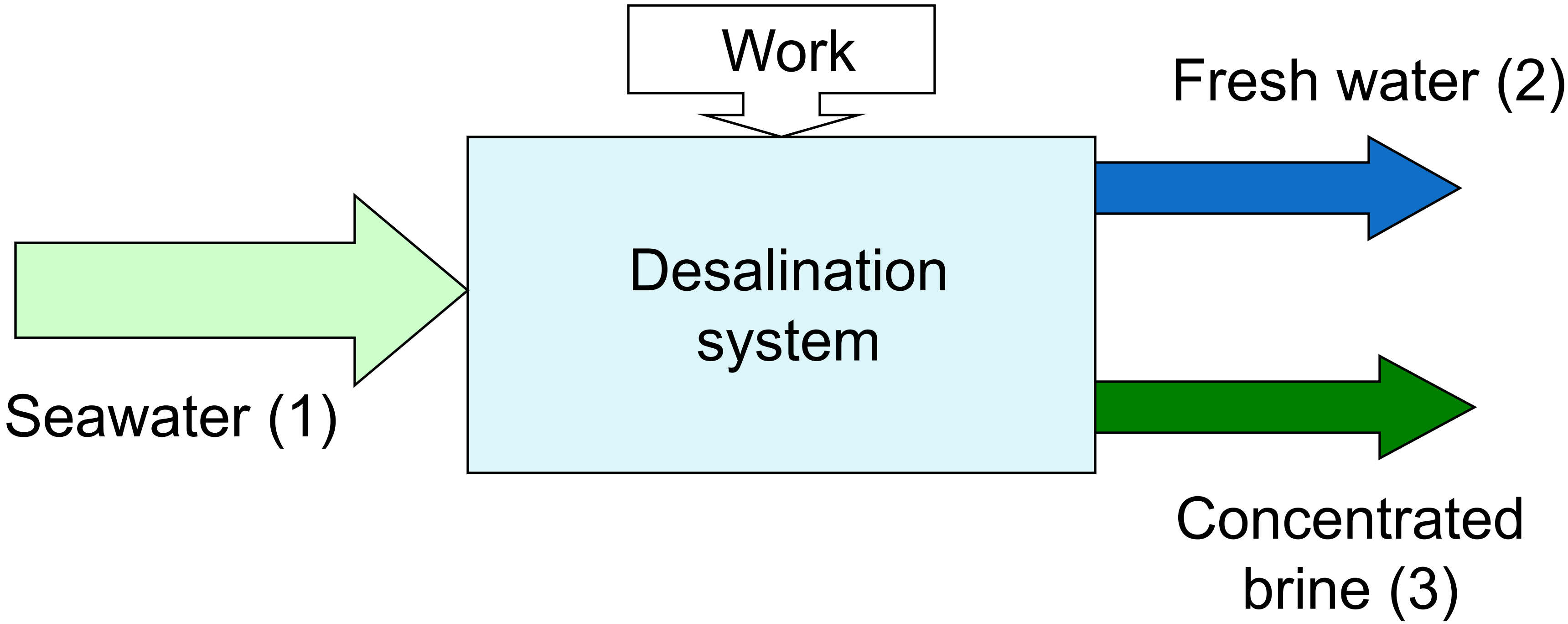
$$\Pi = \phi RT \rho_{solvent} \sum m_i$$

$$\Pi_{seawater} \approx \left(7.6\times10^{-4}\right)\left(\text{TDS in ppm}\right)$$

Comparing seawater to aqueous sodium chloride

- Seawater with 35,000 ppm TDS
  - 0.62 molal NaCl solution has the same TDS or mass fraction of dissolved salts
  - 0.55 molal NaCl solution has the same chemical activity

Seawater purification



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

Practically, it takes an order of magnitude more energy.

Work of separation

$$\dot{W} = [(\dot{N}\underline{G})_2 + (\dot{N}\underline{G})_3] - (\dot{N}\underline{G})_1 + T\dot{S}_{gen}$$

Least work of separation (consider 0.62 molal aqueous NaCl)

- 1 kg removed from "ocean": 3.05 kJ/kg-fresh
- 38% recovery of water: 3.82 kJ/kg-fresh
- Remove salt from salt water: 8.32+3.05 = 11.37 kJ/kg-fresh

Least work varies with salinity and recovery (about 15% lower for 0.55 molal NaCl; much lower for brackish water)

Scale Formation

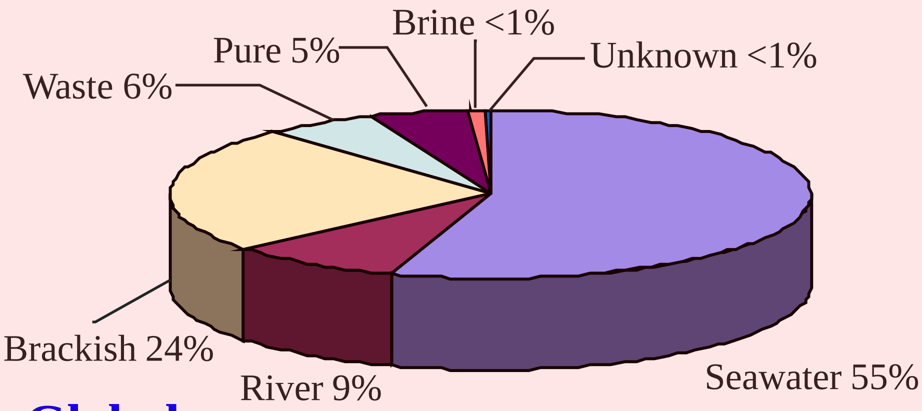
- Certain relatively insoluble salts precipitate easily when seawater is concentrated and heated
  - $CaCO_3$
  - $Mg(OH)_2$
  - $CaSO_4$
- These salts substantially impact the design of thermal desalination systems
  - Acid scale control ($T < 120°C$)
  - Polyphosphate control ($T < 85°C$)
- $CaSO_4$ has no economical control, so regimes where it precipitates are avoided (concentration factors of 2 or less for temperature below 120°C)

Principal desalination techniques

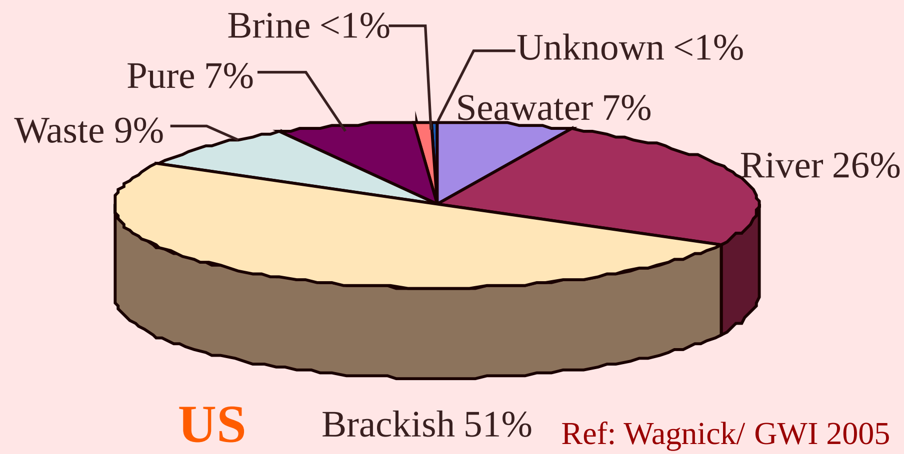
- Membrane techniques
  - Reverse osmosis (SWRO or BWRO)
  - Electrodialysis (ED)
  - Capacitative deionization (CDI)
  - Nanofiltration (NF)
- Distillation techniques
  - Multistage flash evaporation (MSF)
  - Multieffect distillation (MED or MEE)
  - Vapor compression distillation
  - Solar thermal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

Installed desalination capacity

S O U R C E

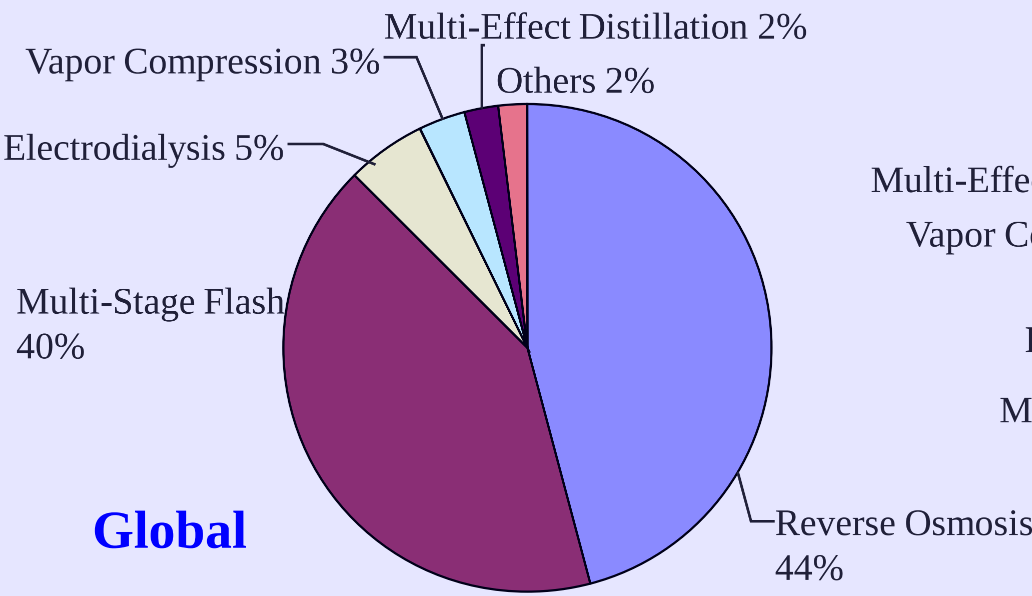


Global

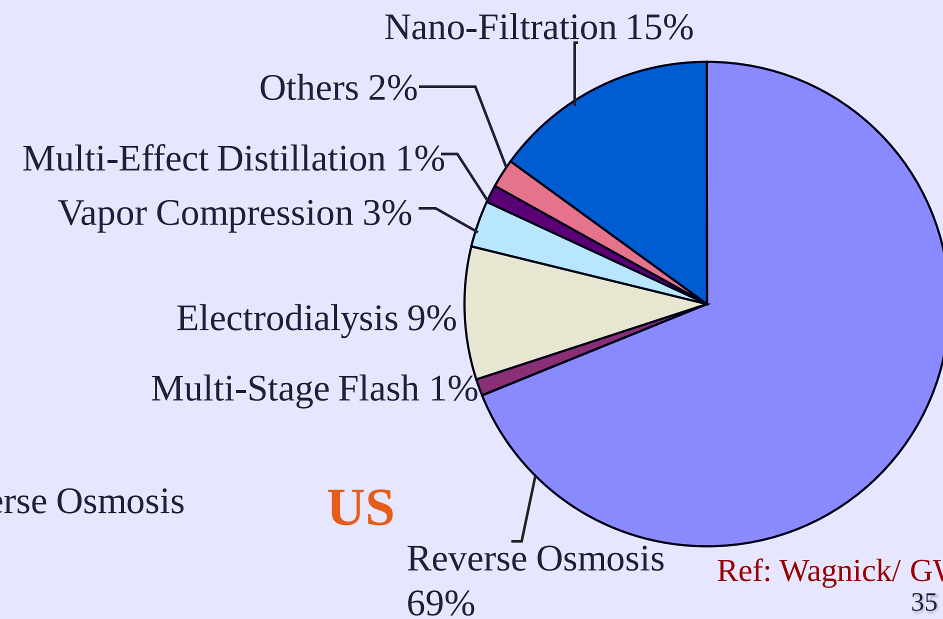


US

Ref: Wagnick/ GWI 2005



Global

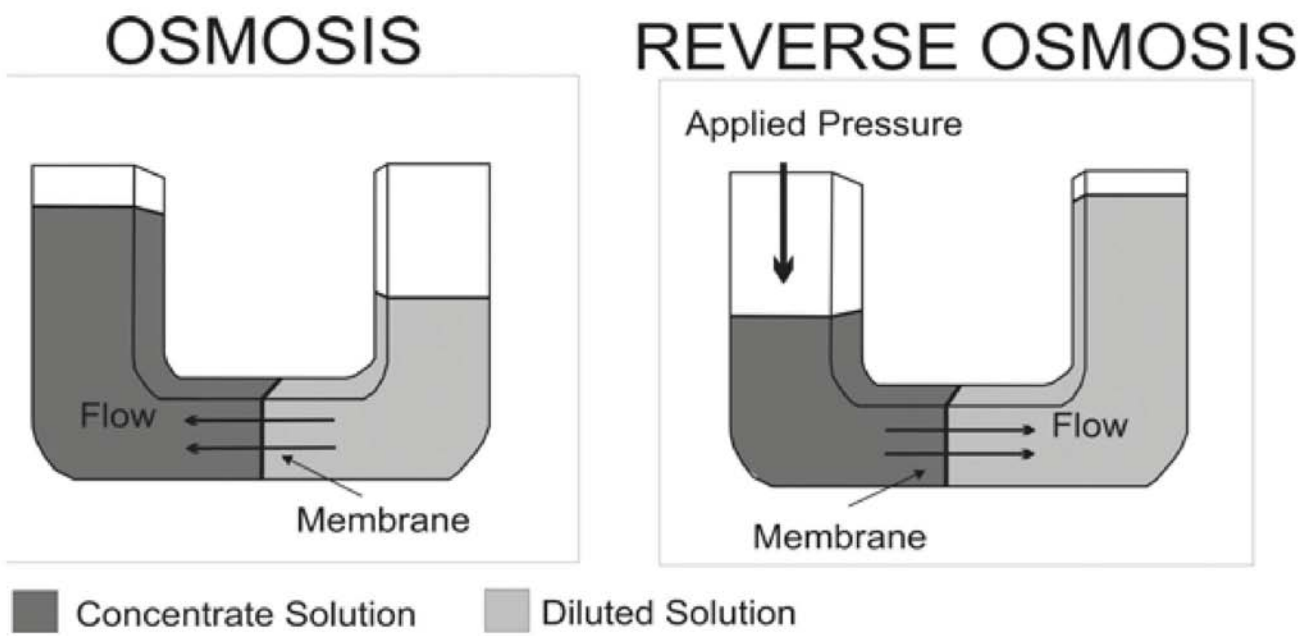


US

P R O C E S S

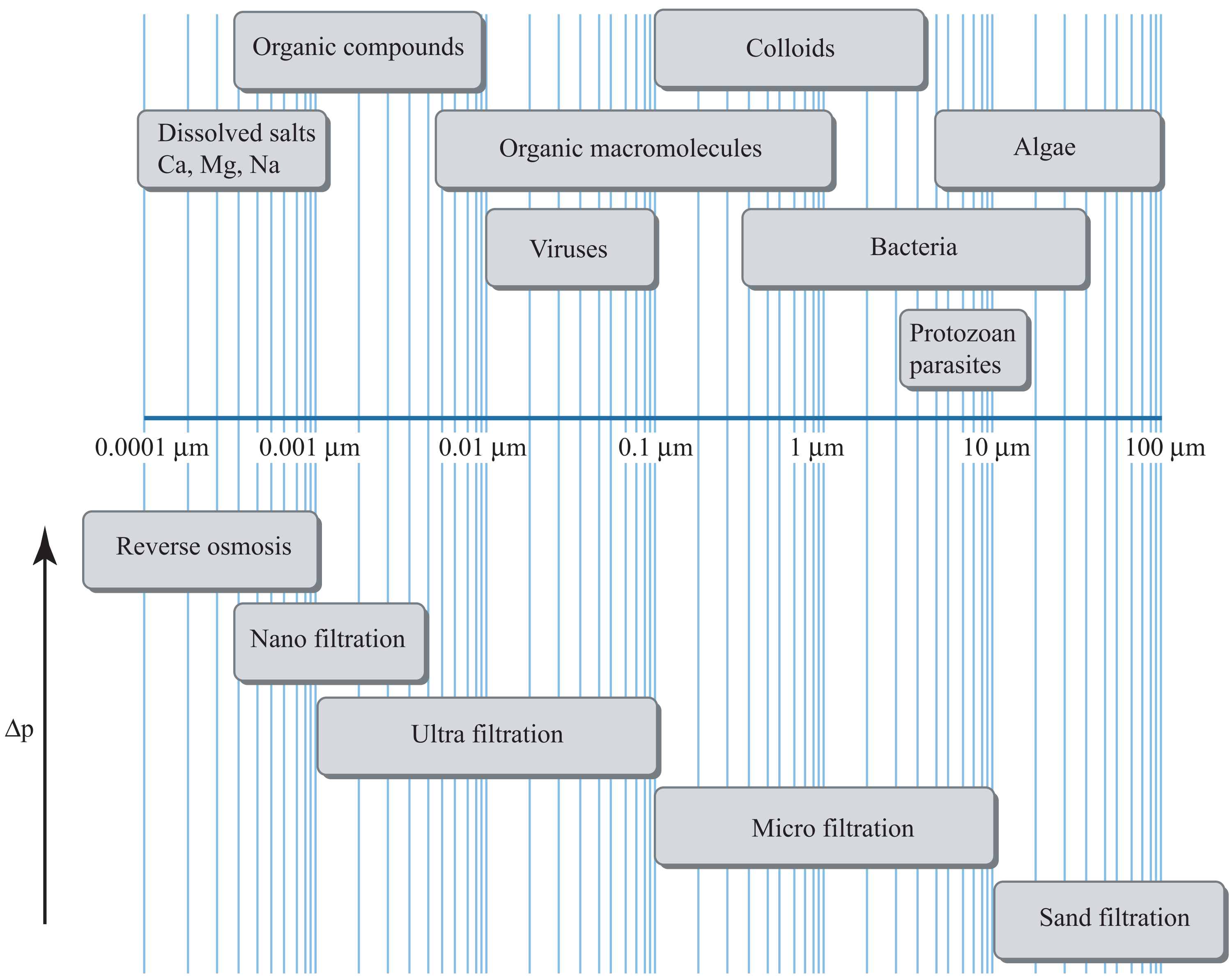
Ref: Wagnick/ GWI 2005

Reverse Osmosis



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.

Fritzmann et al., 2007



Comparison of treatment methods with particle size.

Figure by MIT OpenCourseWare.

Source: Twort et al.

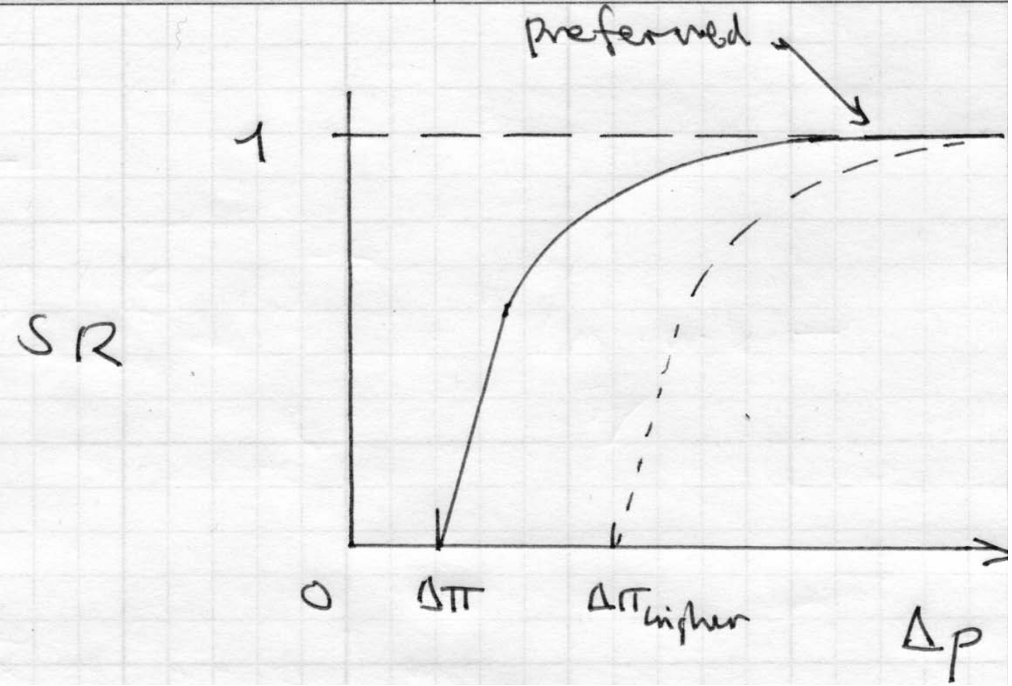
Solution-diffusion model

- Transport through membranes is controlled by the solubility of ions and water in membrane and their diffusion through the membrane.

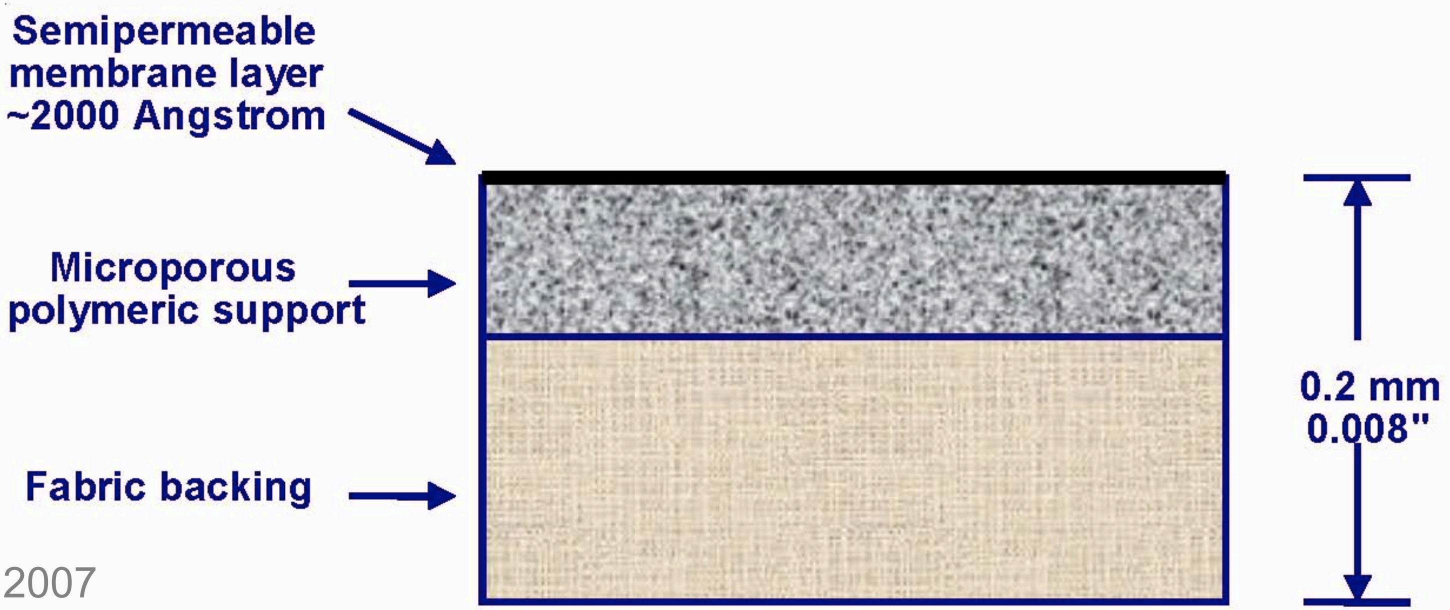
$$J_v = A(\Delta p - \Delta\Pi)$$ Volume flux, L/m^2-s

$$J_s = B(c_{s,f} - c_{s,p})$$ Salt flux, mol/m^2-s

$$SR \equiv 1 - c_{s,p}/c_{s,f} = \frac{(A/B)(\Delta p - \Delta\Pi)}{1 + (A/B)(\Delta p - \Delta\Pi)}$$ Salt rejection



Salt rejection as a function of driving pressure



Membrane structure

Ref: Wilf & Balaban,2007

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

Concentrations for crossflow RO separator

$$\frac{c_{s,r}}{c_{s,f}} = \left(1 - R_p\right)^{-SR}$$

Salt concentration of retentate

$$\overline{c_{s,p}} = \left(\frac{c_{s,f}}{R_p}\right)\left[1 - \left(1 - R_p\right)^{1-SR}\right]$$

Average salt concentration of permeate

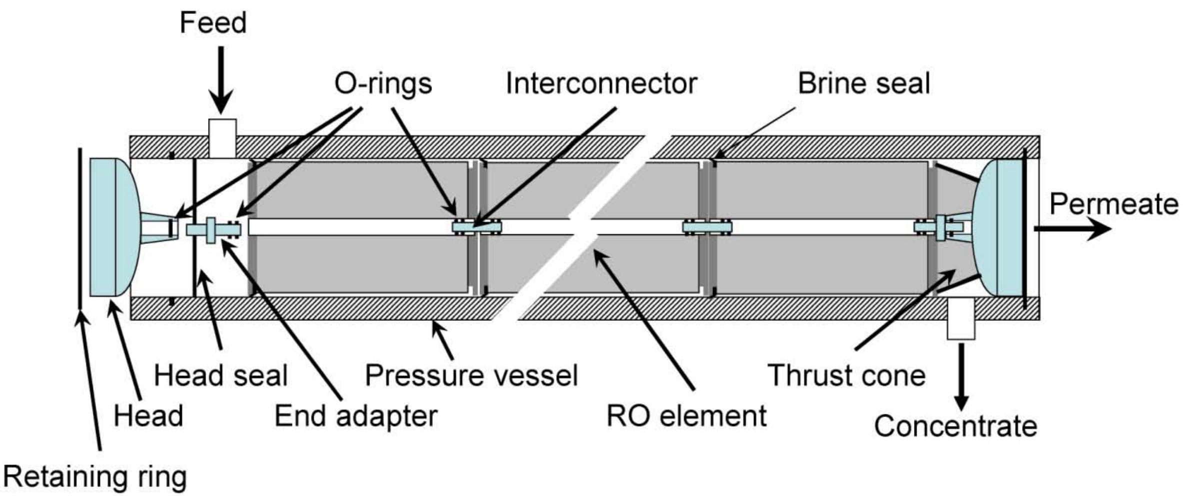
Spiral-wound element

20 cm diam by 1 m length

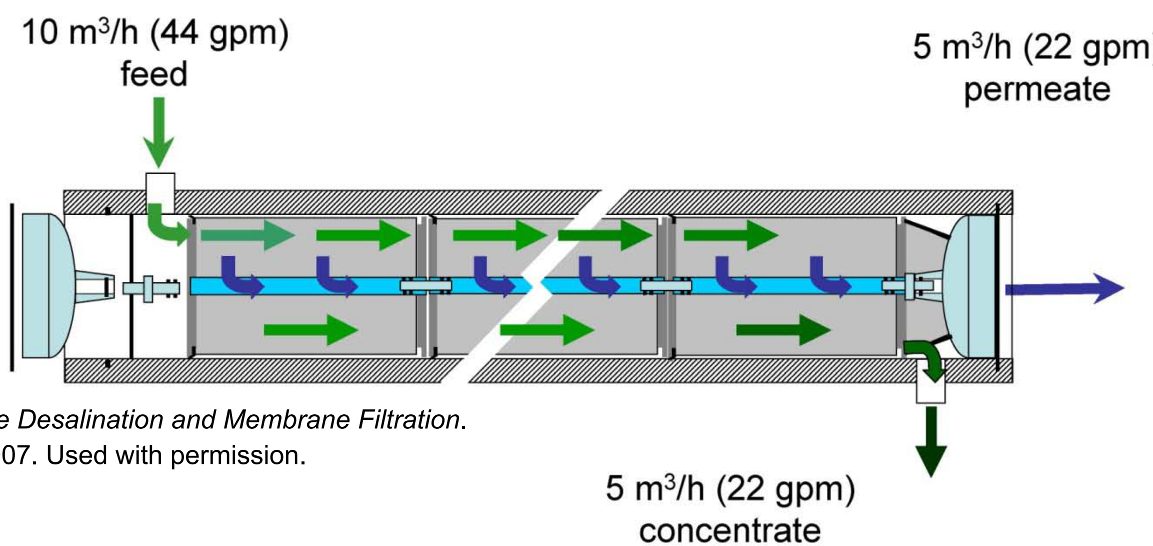
Figures from Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Ref: Wilf & Balaban,2007

Configuration of a pressure vessel assembly



Water flow in a pressure vessel assembly



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

Ref: Wilf & Balaban,2007

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

Pressure Vessels and Vertical Centrifugal Pumps

Ref: Wilf & Balaban,2007

Location	1	2	3	4	5	6	7	8	9
Flow, m^3/h (gpm)	521.3 (2294)	521.3 (2294)	184.9 (814)	184.9 (814)	104.2 (458)	336.0 (1478)	80.7 (355)	416.7 (1833)	104.2 (458)
Pressure, bar (psi)		17.1 (248)	14.2 (206)	23.2 (336)	20.8 (302)				0.5 (7)
TDS ppm	5881	5881	16313	16313	28444	139	657	240	28444

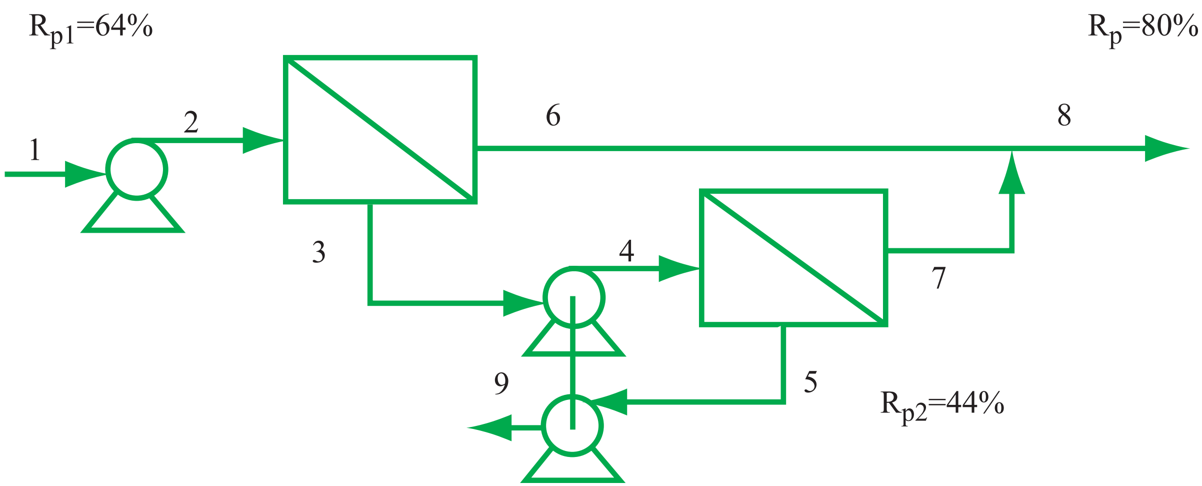


Figure by MIT OpenCourseWare.

Concentrate staging in a high-salinity brackish RO system with 80% recovery. Note turbine assisted booster pump.

from M. Wilf, 2007

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

Turbocharger applied as interstage booster pump

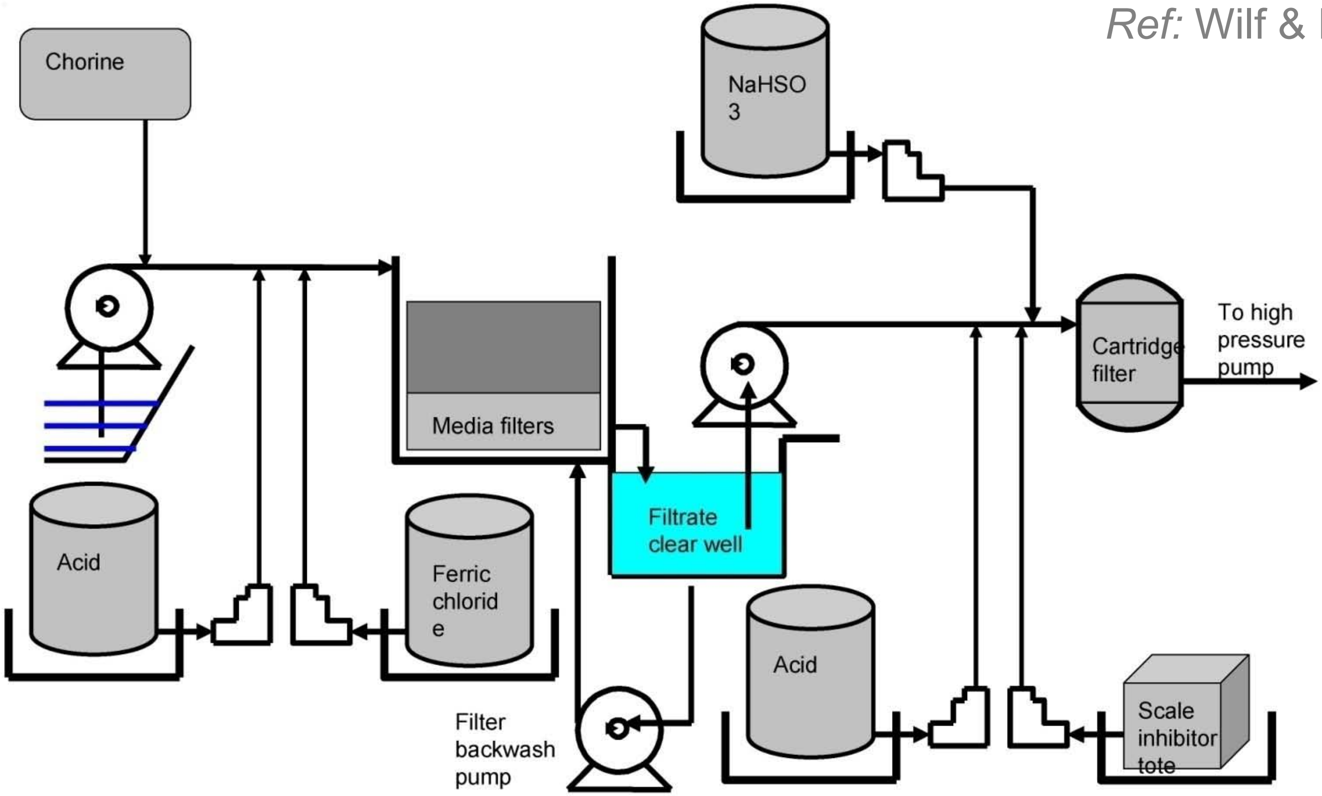
Ref: Wilf & Balaban,2007

Pumping system at Larnaca plant. (Cyprus)

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

Ref: Wilf & Balaban,2007

Ref: Wilf & Balaban,2007



Configuration of a conventional RO pretreatment system treating surface water source.

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

Seawater pretreatment.

Disinfect with chlorine

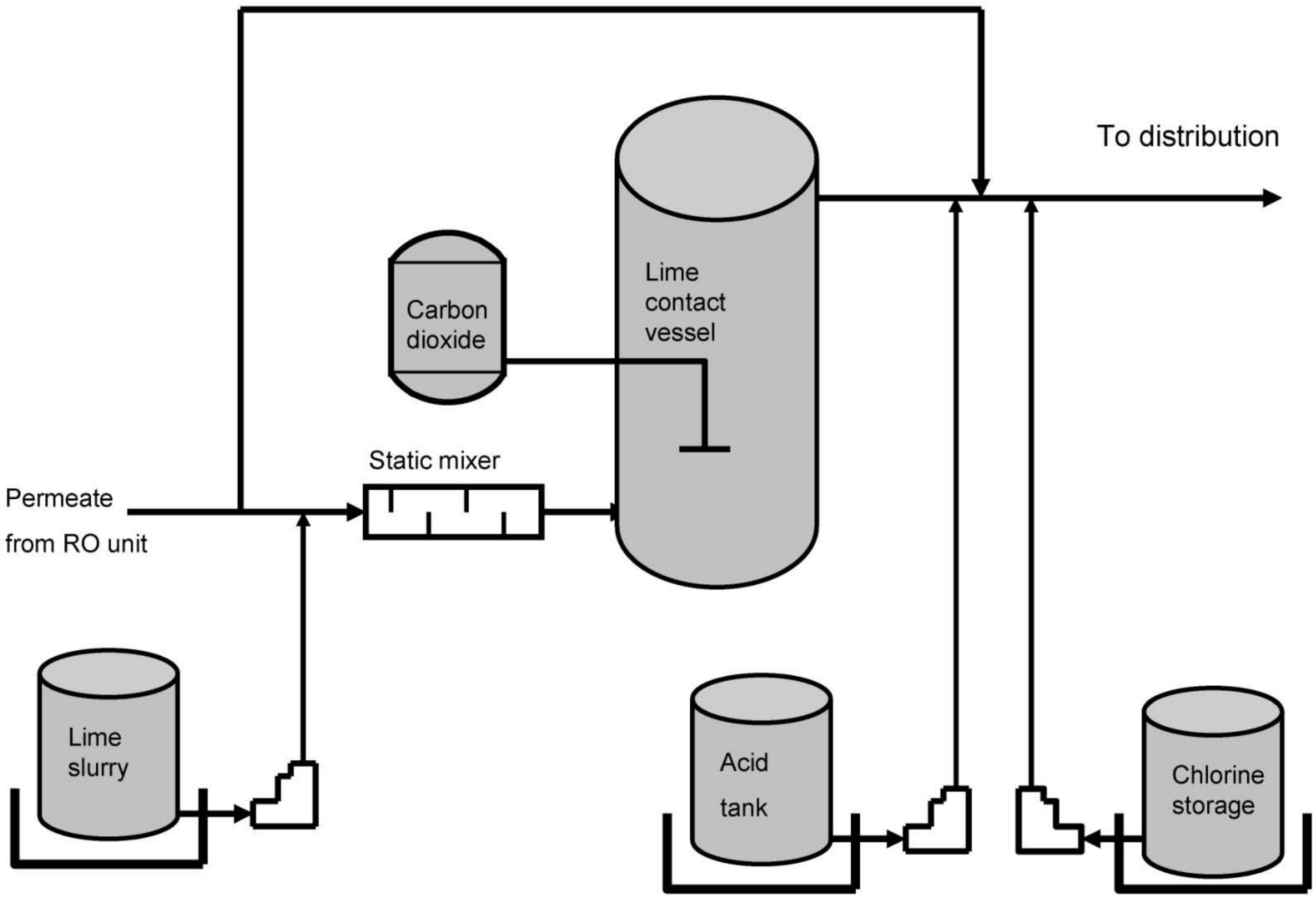
Add ferric chloride to coagulate small particulates

Filter, adjust pH to protect membranes, add scale inhibitor

dechlorination (by sodium bisulfate), cartridge filtration (5-15 μm porosity)

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

Ref: Wilf & Balaban,2007



Seawater RO Post-treatment.

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

Add alkalinity and hardness via: CO_2+Ca(OH) → $Ca(HCO_3)_2$

Disinfect with additional chlorine, control pH

Ref: Wilf & Balaban,2007

Total water cost distribution in SWRO

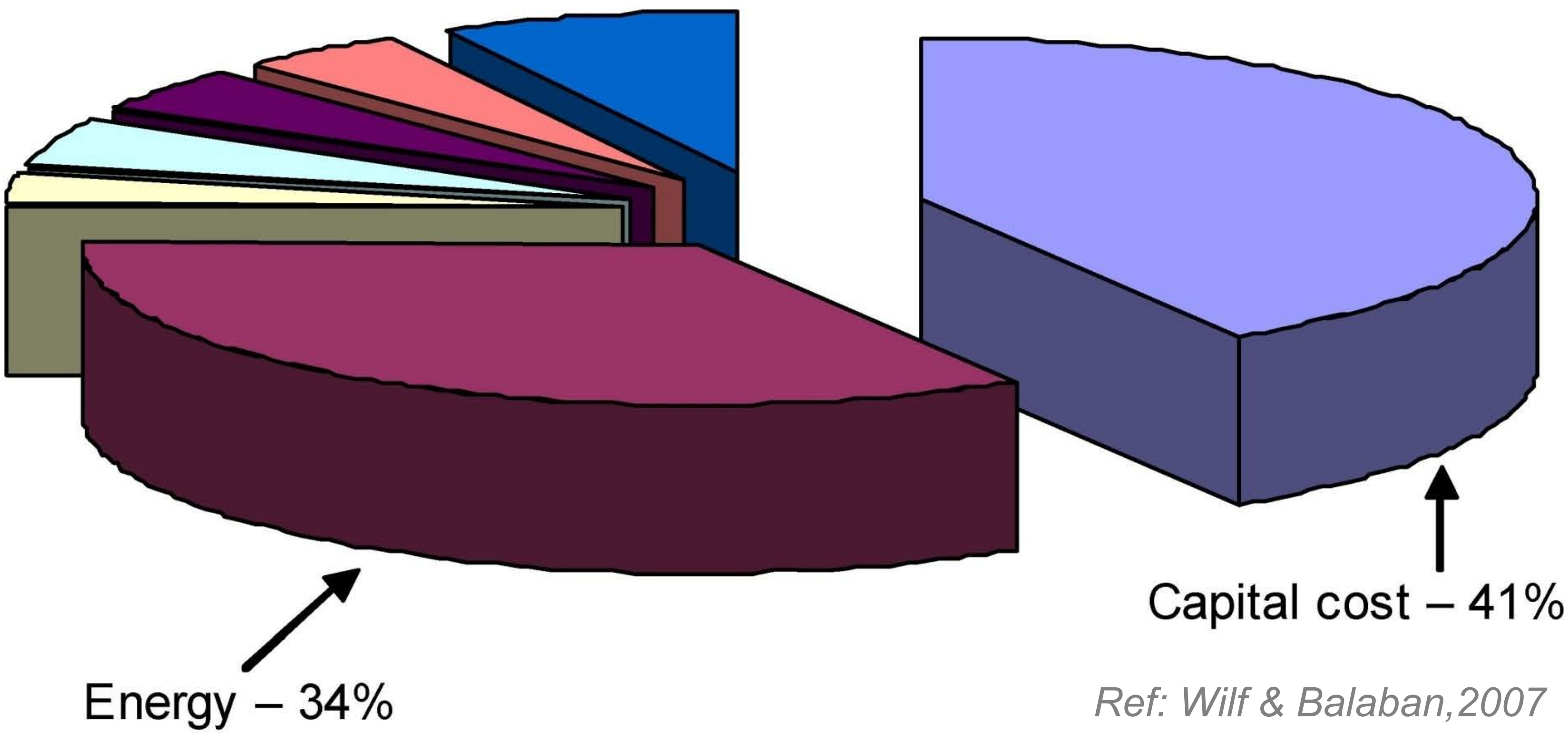
Membrane replacement – 3%

Labor – 5%

Maintenance and parts – 5%

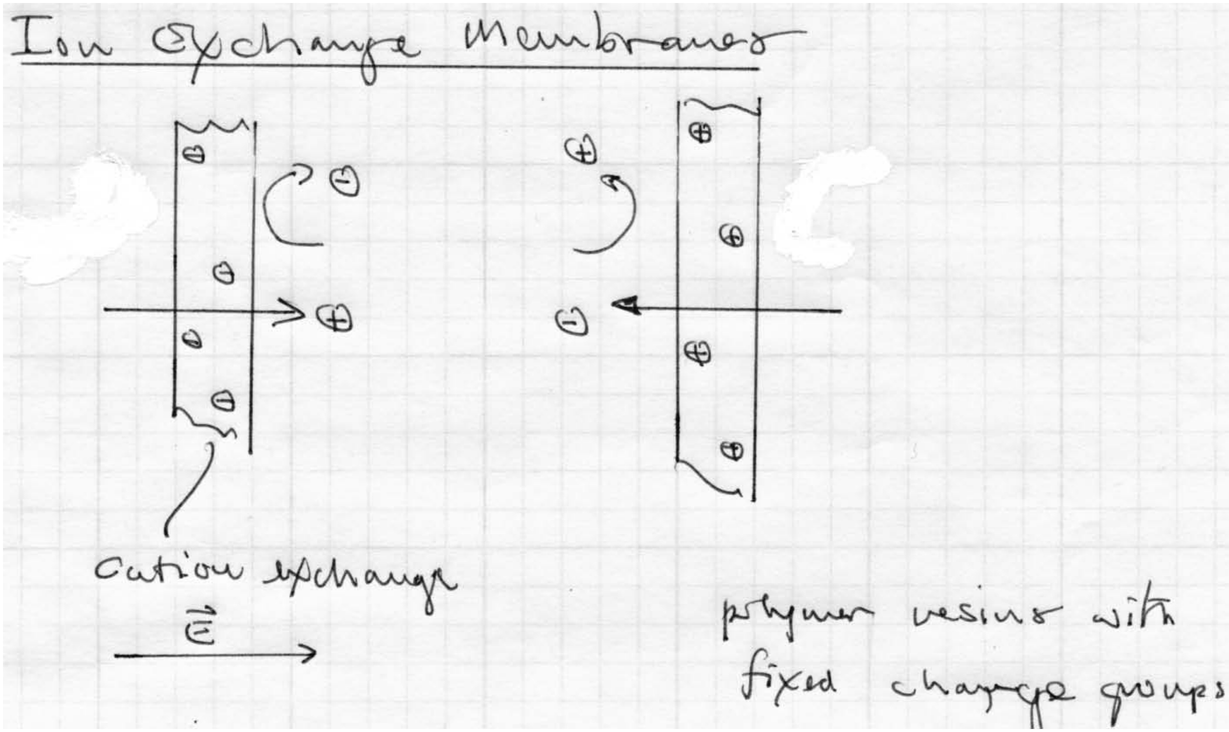
Consumables – 5%

Others & contingency – 7%



Ref: Wilf & Balaban,2007

Electrodialysis

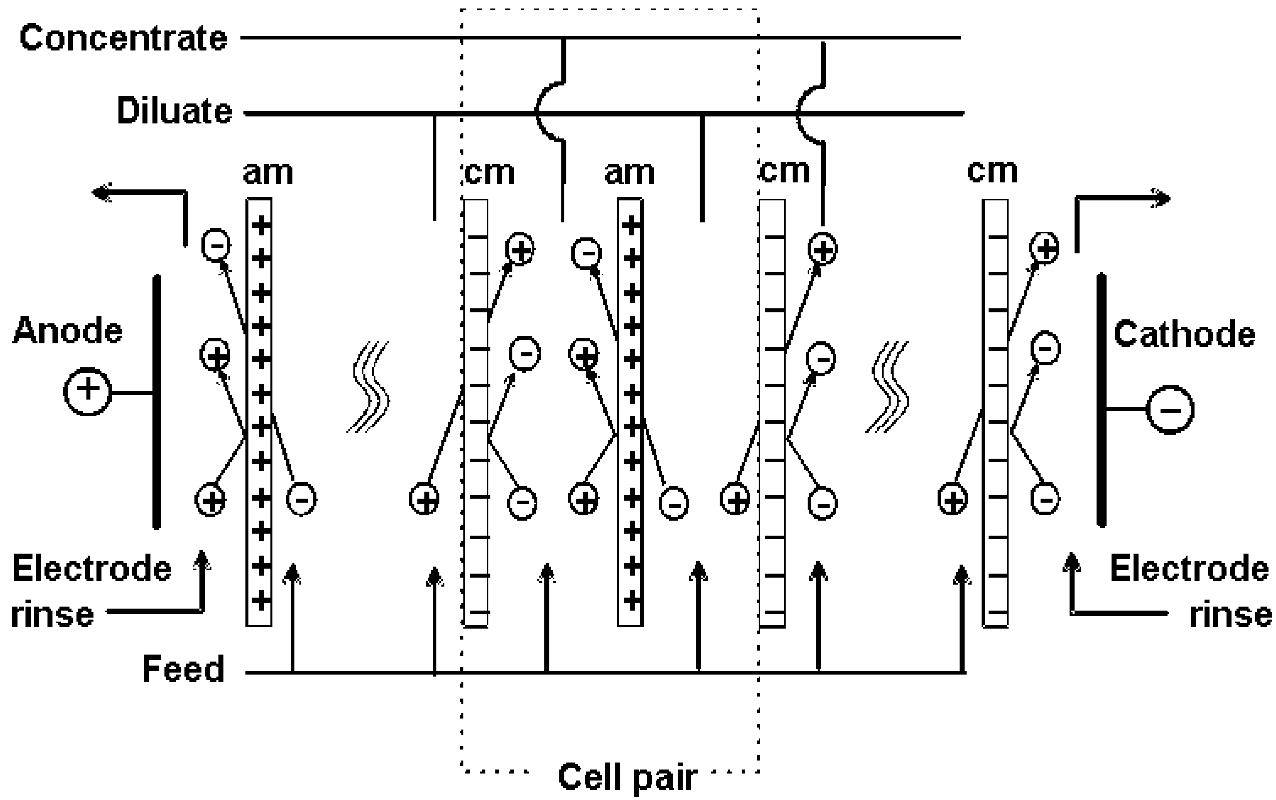


Cation exchange membranes contain fixed negative charges. *Donnan exclusion* prevents anions from passing through membrane.

Anion exchange membranes contain fixed positive charges.

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

Currents in electrodialysis systems are tied to concentrations of ions

$$I = \frac{\Delta c_d \dot{V}_d F|z|\nu}{\xi}$$

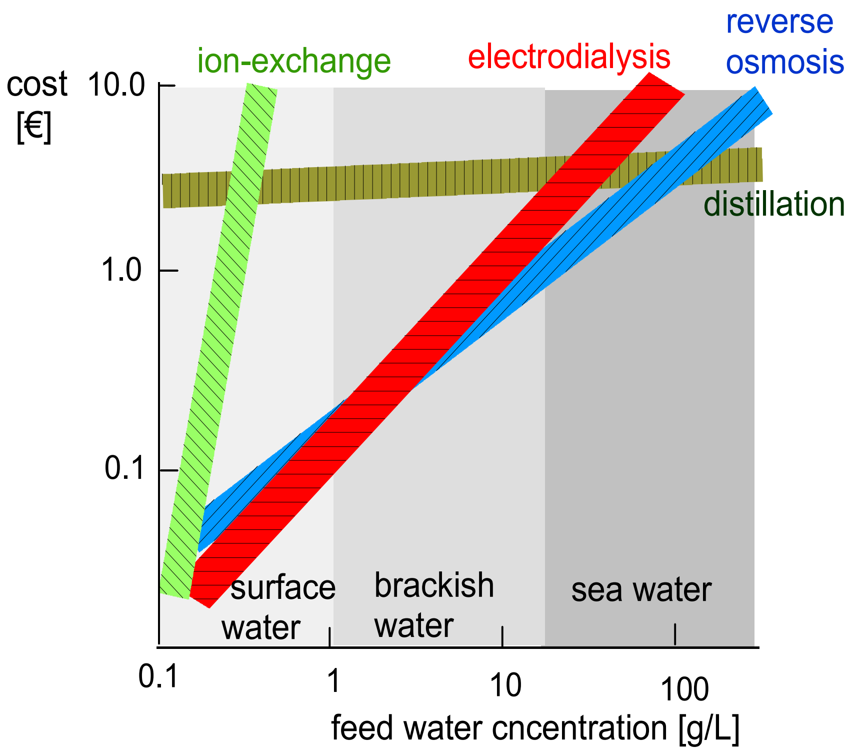
Operating current

$$i_{\lim} \cong \frac{2|z|Fc_{d,bulk}D}{\delta}$$

Limiting current density, due to concentration polarization

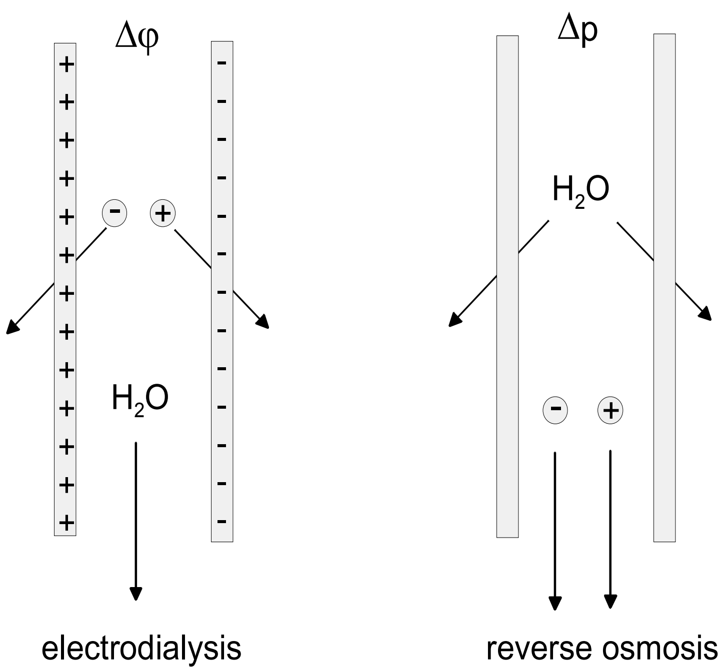
CONVENTIONAL ELECTRODIALYSIS

Water desalination costs



costs estimated for a required product concentration of < 0.2 g/L

Process principles of electrodialysis and reverse osmosis



irreversible energy loss proportional to ion transport ($E_{irr} = z_i\ F\ \Delta C_i\ U\ V$)

irreversible energy loss proportional to water transport ($E_{irr} = \Delta p\ V_{water}$)

Strathmann, 2007

Distillation methods

Least work of separation

$$\dot{W}_{least} = [(\dot{N}\underline{G})_2 + (\dot{N}\underline{G})_3] - (\dot{N}\underline{G})_1$$

Least heat of separation

$$\dot{Q}_{least} = \frac{\dot{W}_{least}}{(1 - T_c / T_h)}$$

Energy consumption in distillation

- For single stage distillation or single stage flashing: $q\left(\mathrm{kJ/kg}\right)\approx h_{fg}$

- This is far larger than the theoretical least heat of distillation (about 12 kJ/kg-fresh). The reason is both irreversibility and wasted available work (due to hot discharge).

- Performance ratio:

$$R=\frac{h_{fg}}{q}$$

Key steps to improving distillation energy efficiency

- Regeneration:
  - use hot brine or distillate to preheat feed
- Multiple effects:
  - latent heat released by condensing vapor from stage *n* drives vaporization in stage *n+1* as lower pressure (MED)
  - hot brine is flashed in successively lower pressure stages (MSF)
- Can achieve performance ratios $R \sim 10$ with these methods

1) Multi Stage Flash - MSF

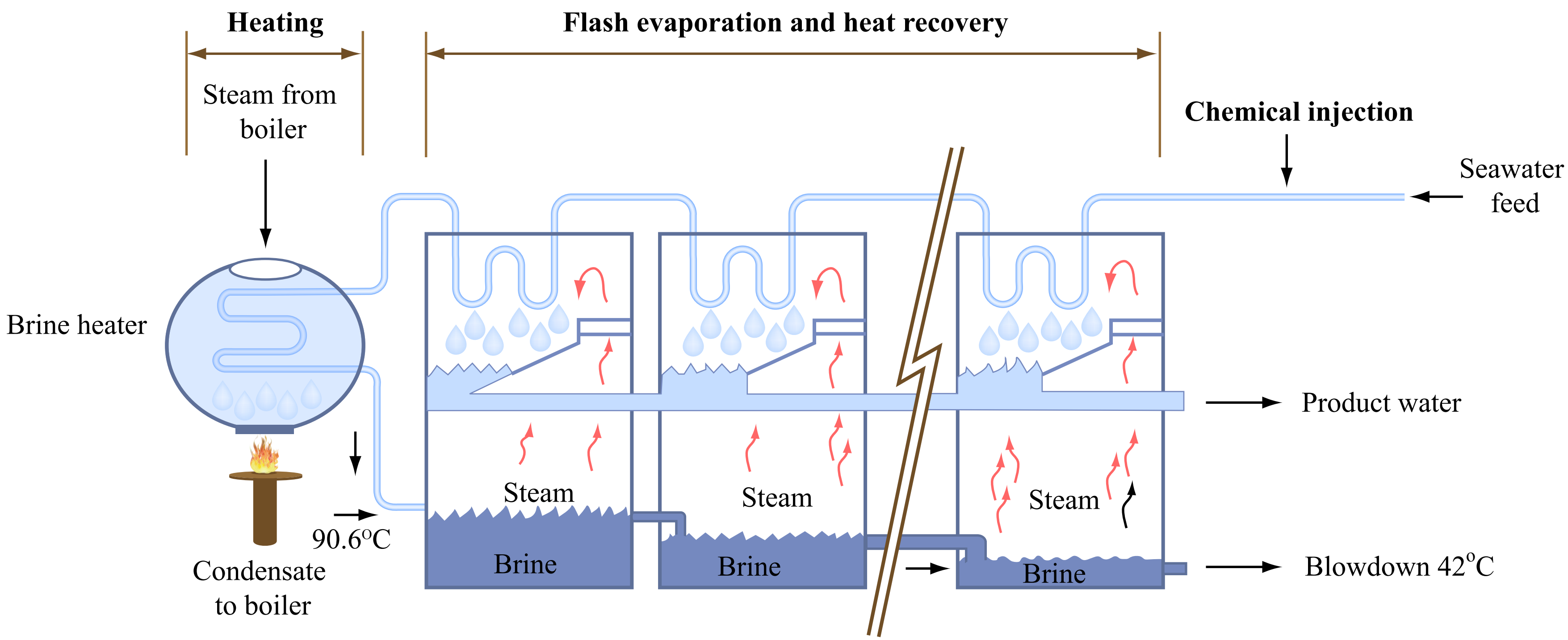
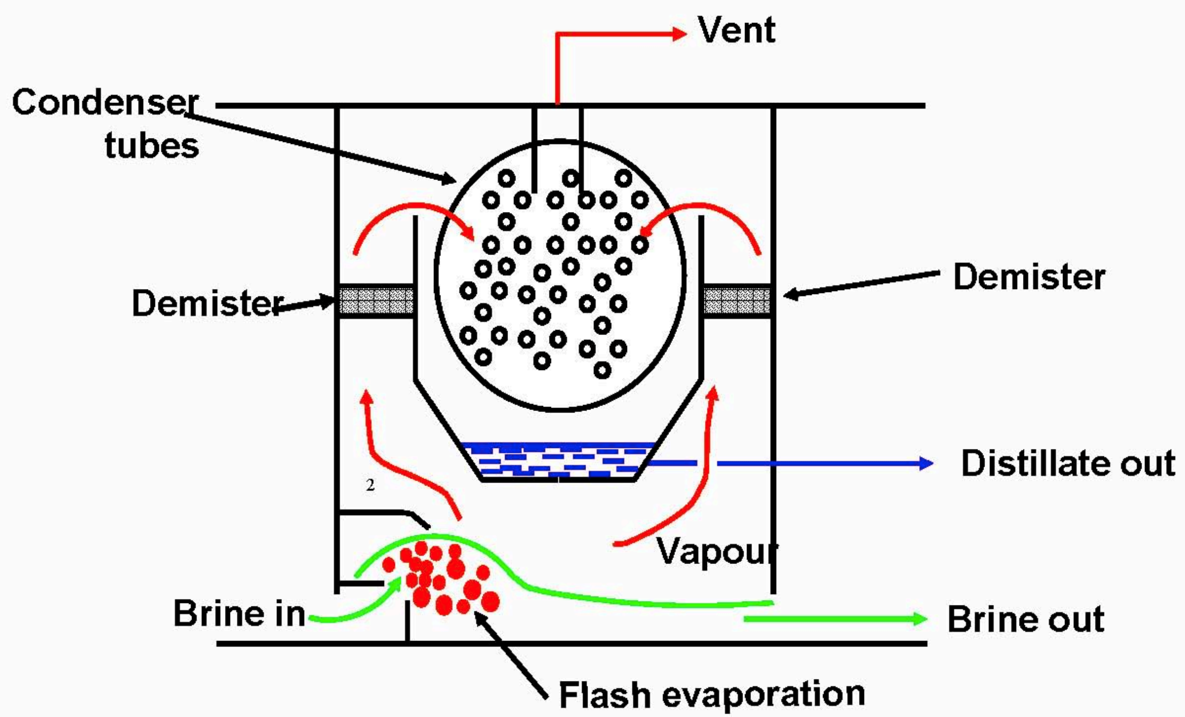
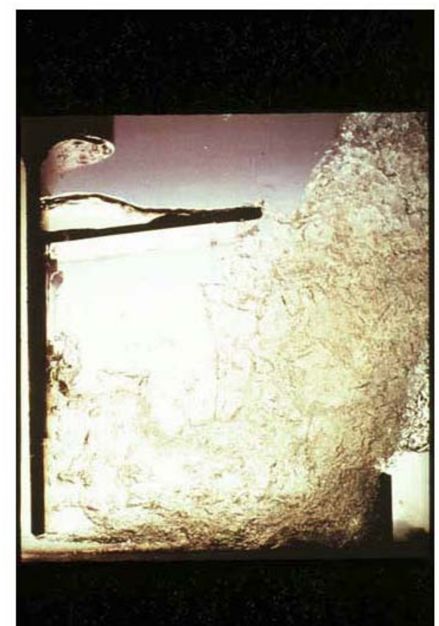


Figure by MIT OpenCourseWare.

Typical stage arrangement of a large MSF plant

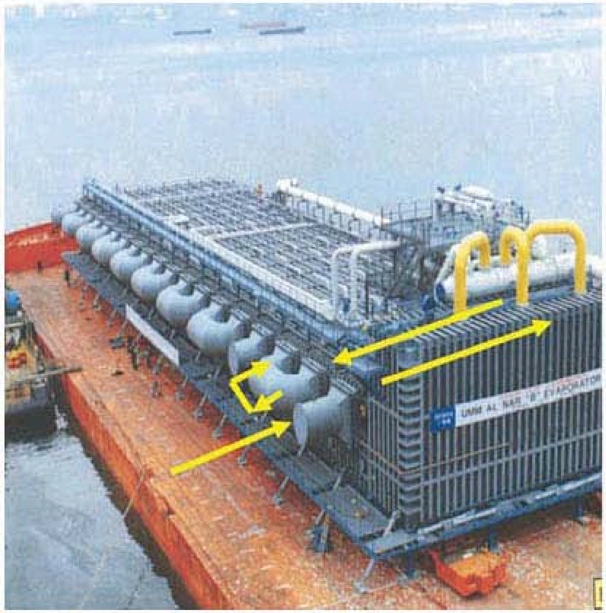




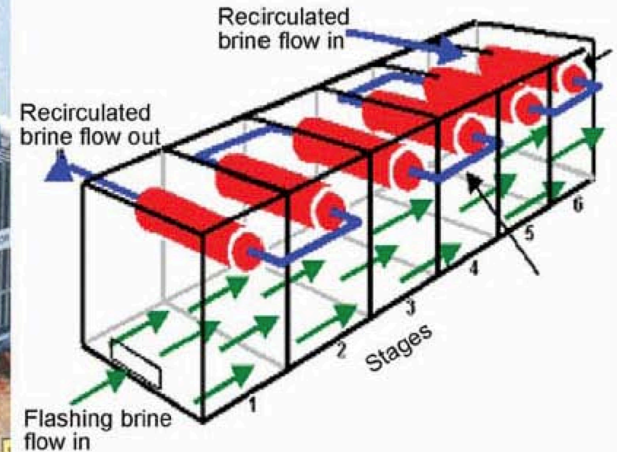
Ref: Sommariva, 2007

Courtesy of Corrado Sommariva. Used with permission.

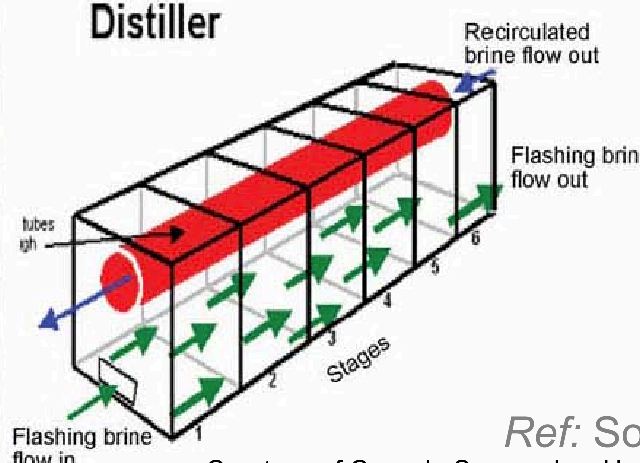
Multi stage flash



Cross Tube

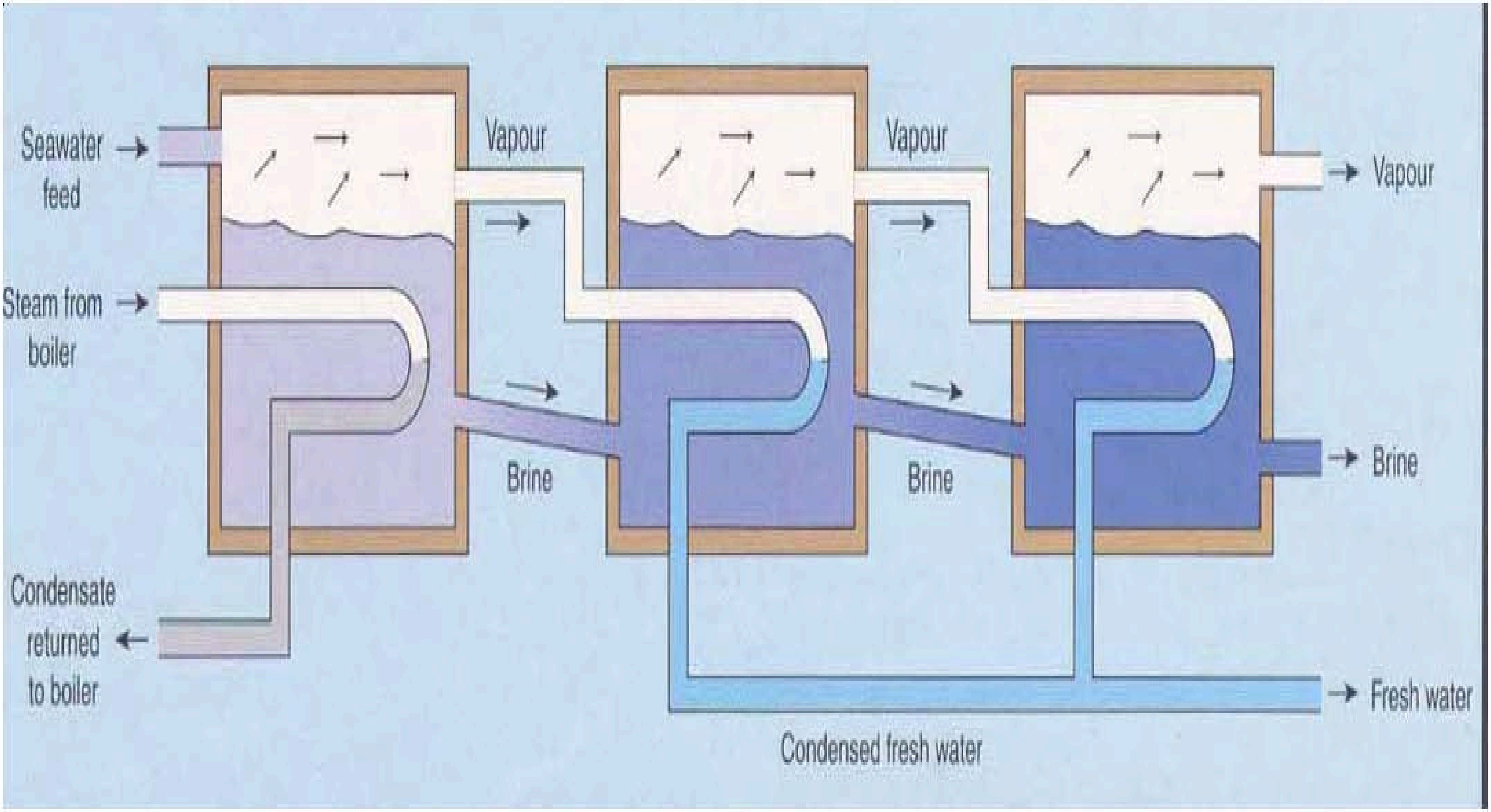


Long Tube Distiller



Ref: Sommariva, 2007

Multieffect distillation concept



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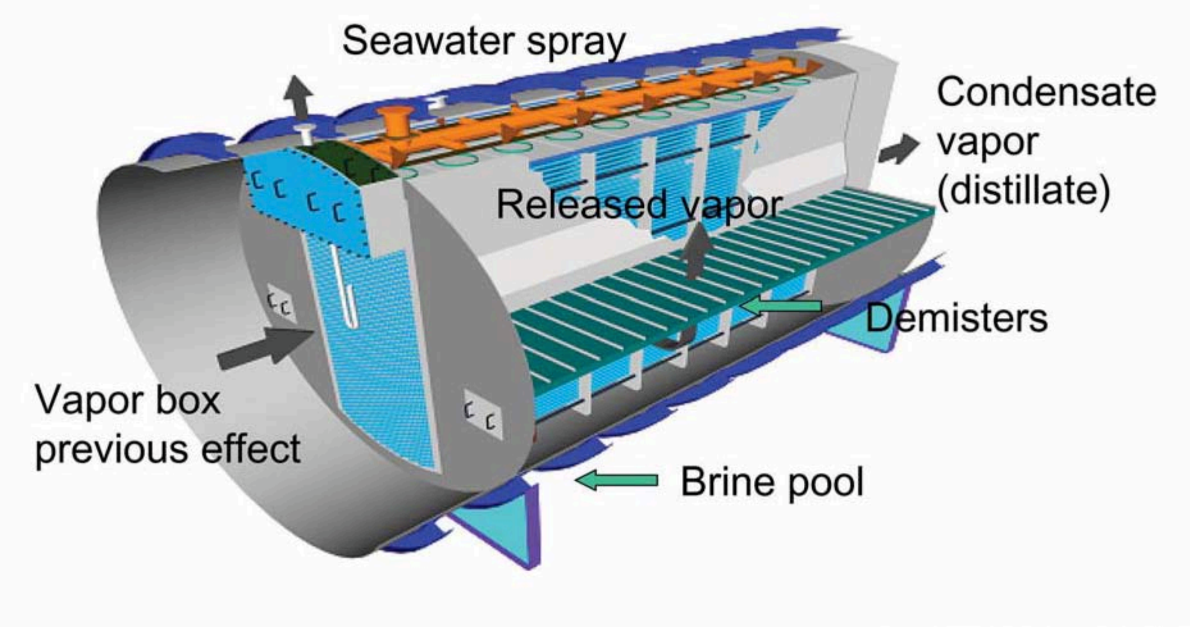
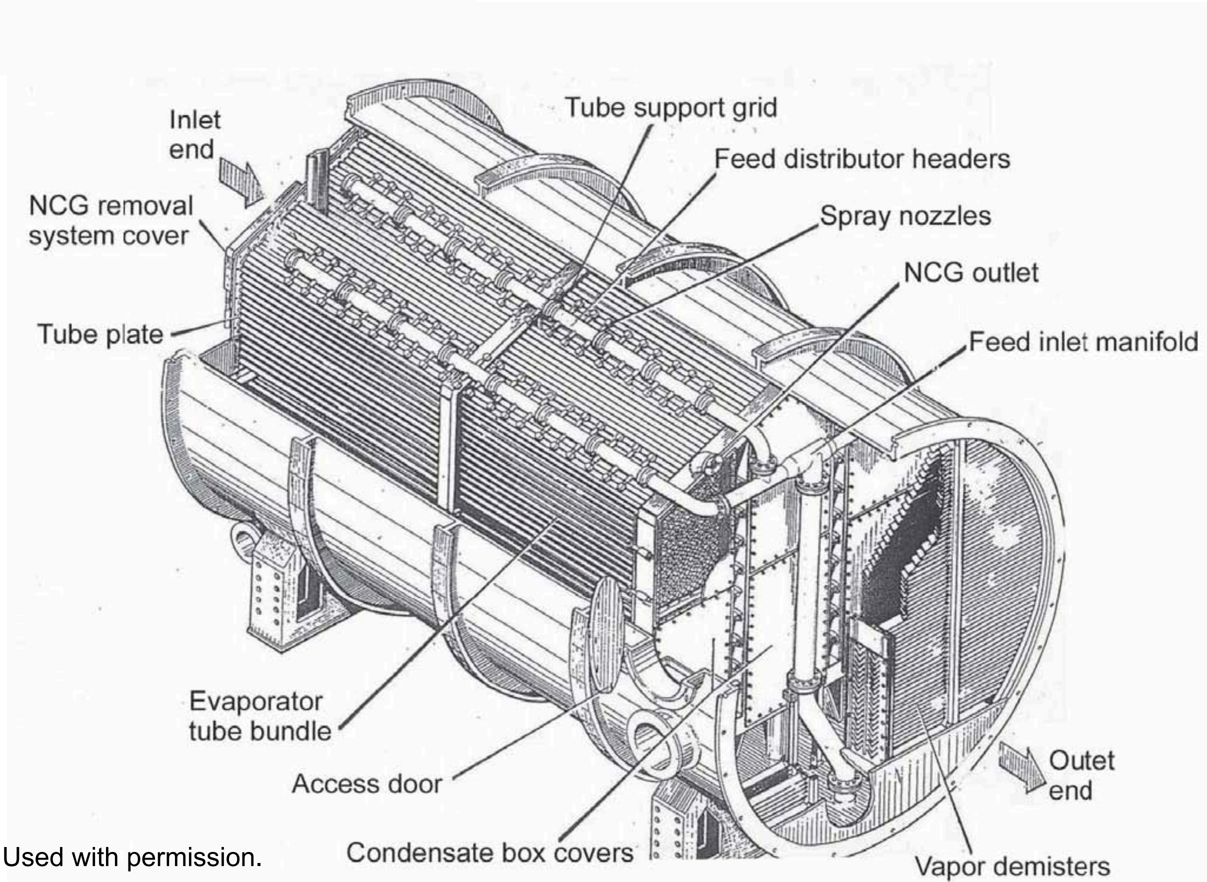
Ref: Sommariva, 2007



MED: horizontal tube evaporators



Ref: Sommariva, 2007

Combined power production and MSF distillation – substantially lowers cost of energy for distillation

Courtesy of Corrado Sommariva. Used with permission.

Ref: Sommariva, 2007

Solar Desalination

World Insolation (kWh/m^2-day)

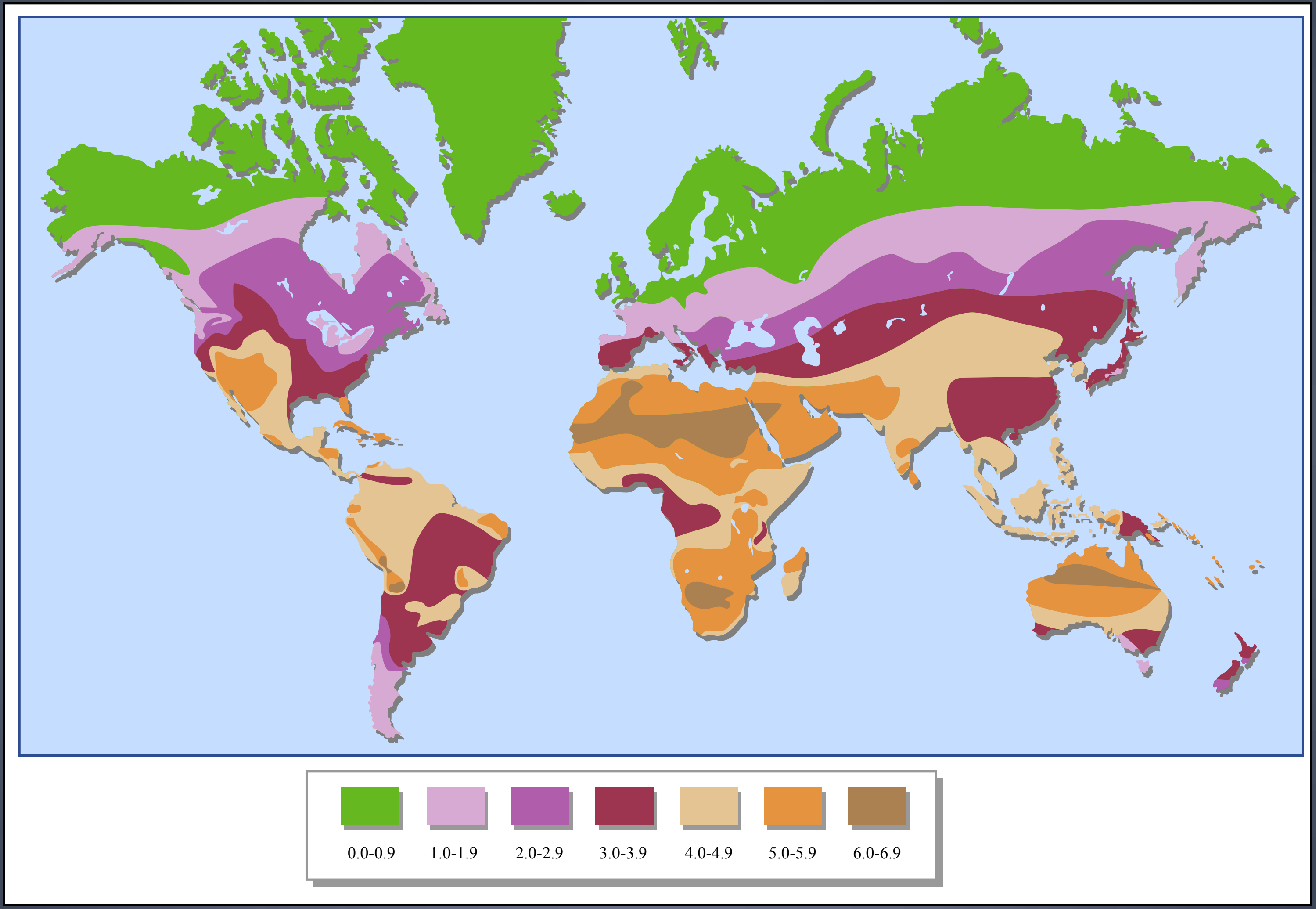
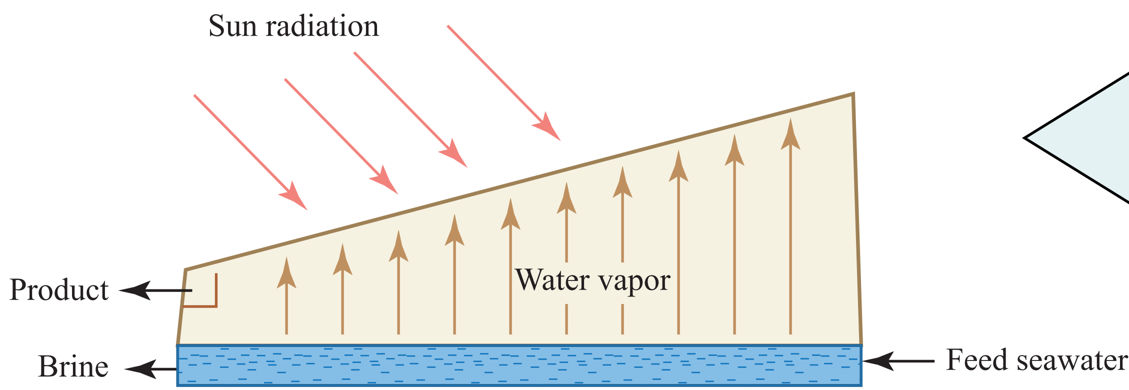


Figure by MIT OpenCourseWare.

Solar Distillation

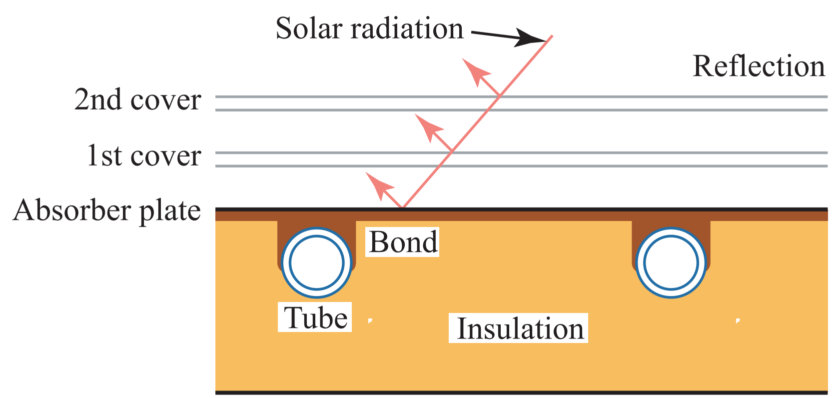


Schematic of simple solar still.

Figure by MIT OpenCourseWare.

Optimally bad?

~ 1 L/m^2-day



Sheet-and-tube solar collector.

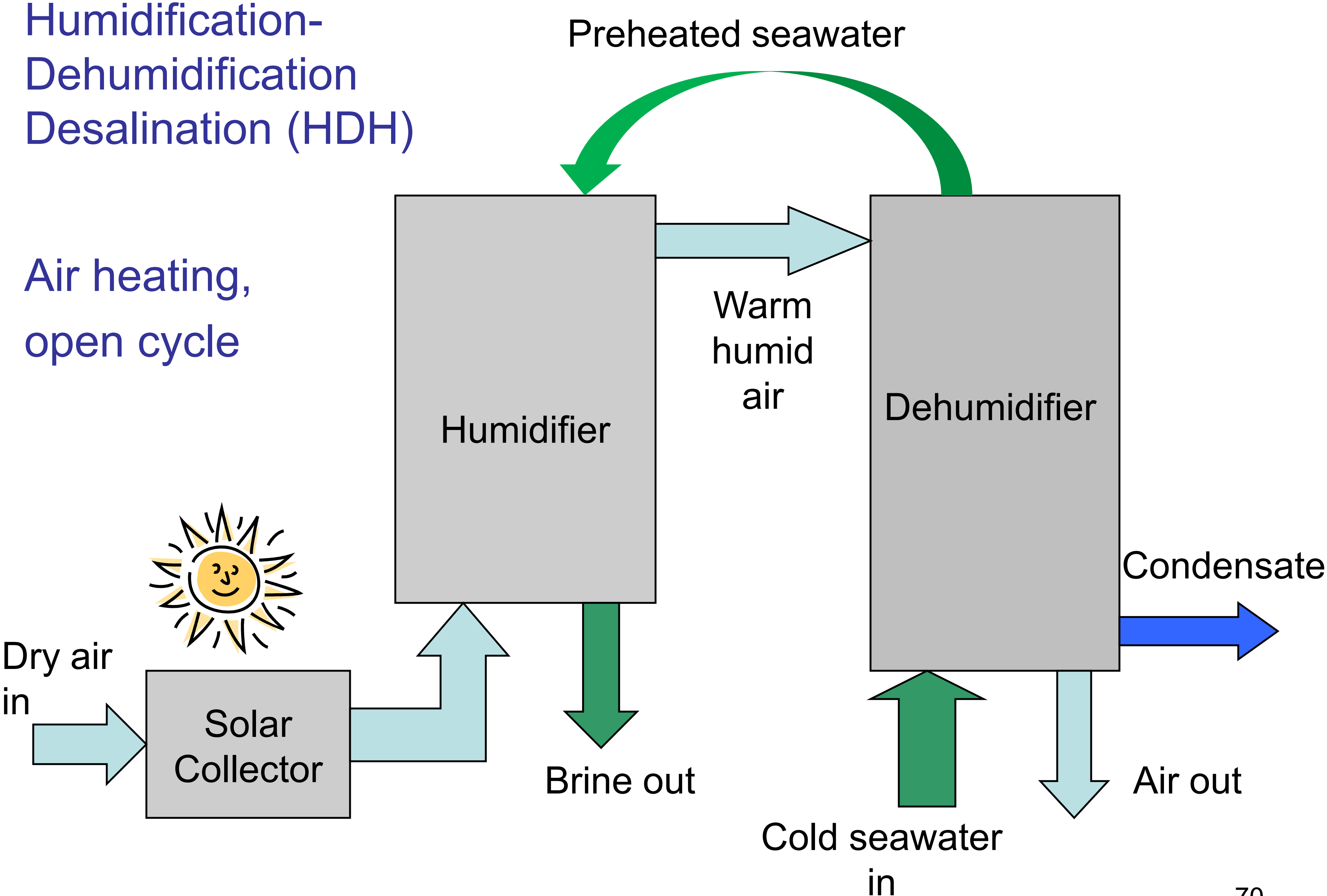
Figure by MIT OpenCourseWare.

..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



Ref: Fath et al., *Desalination*, 2008

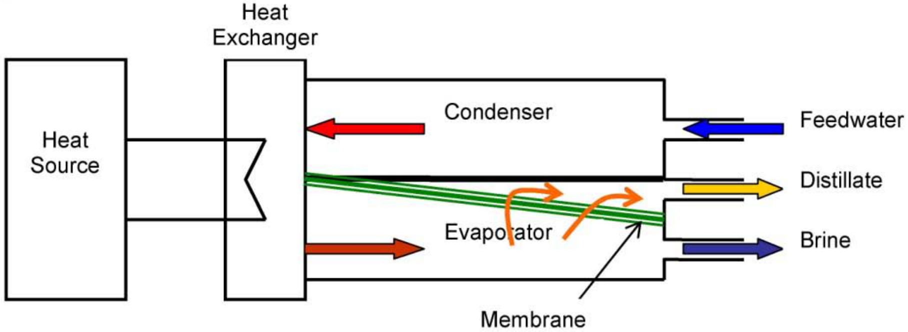


Fig. 1. Membrane distillation principles.

~4 L/m^2-day

Membrane distillation uses a hydrophobic membrane to separate water vapor from brine at 60 to 90° C

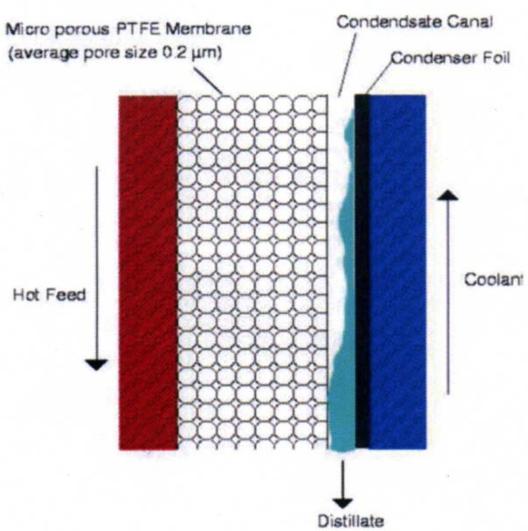


Fig. 1. Principle of membrane distillation.

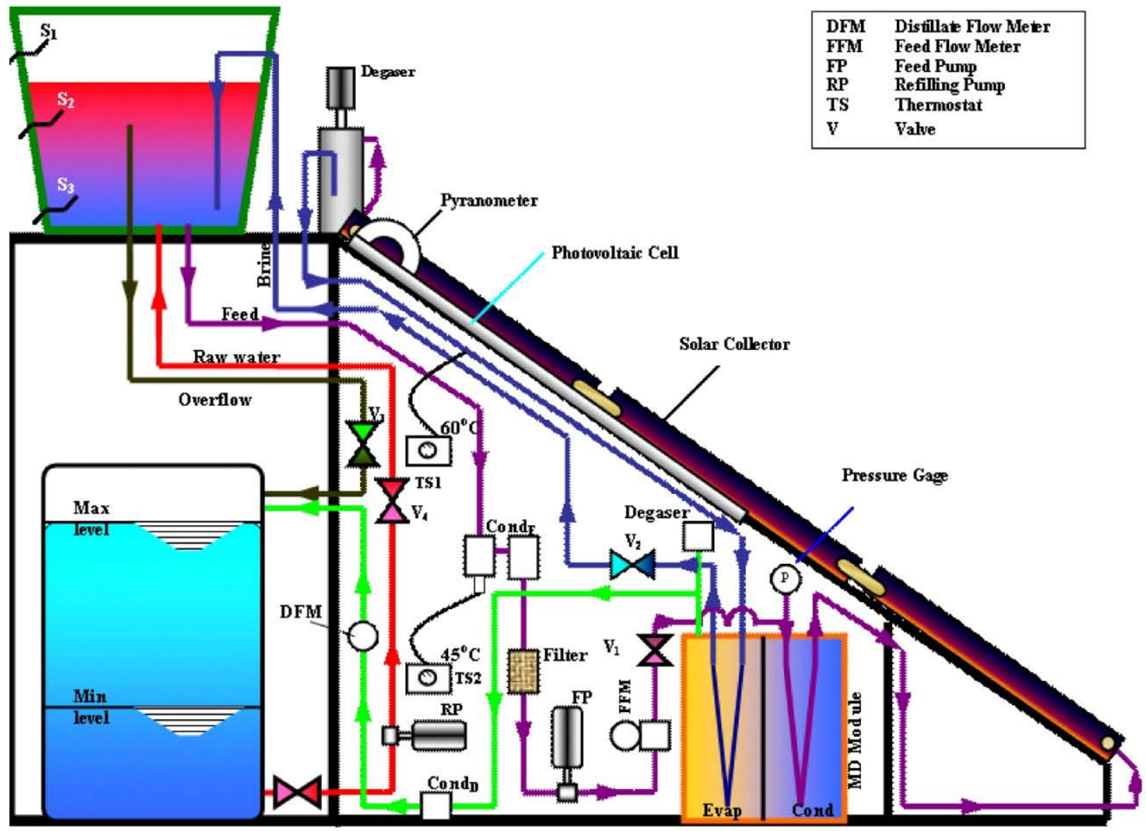
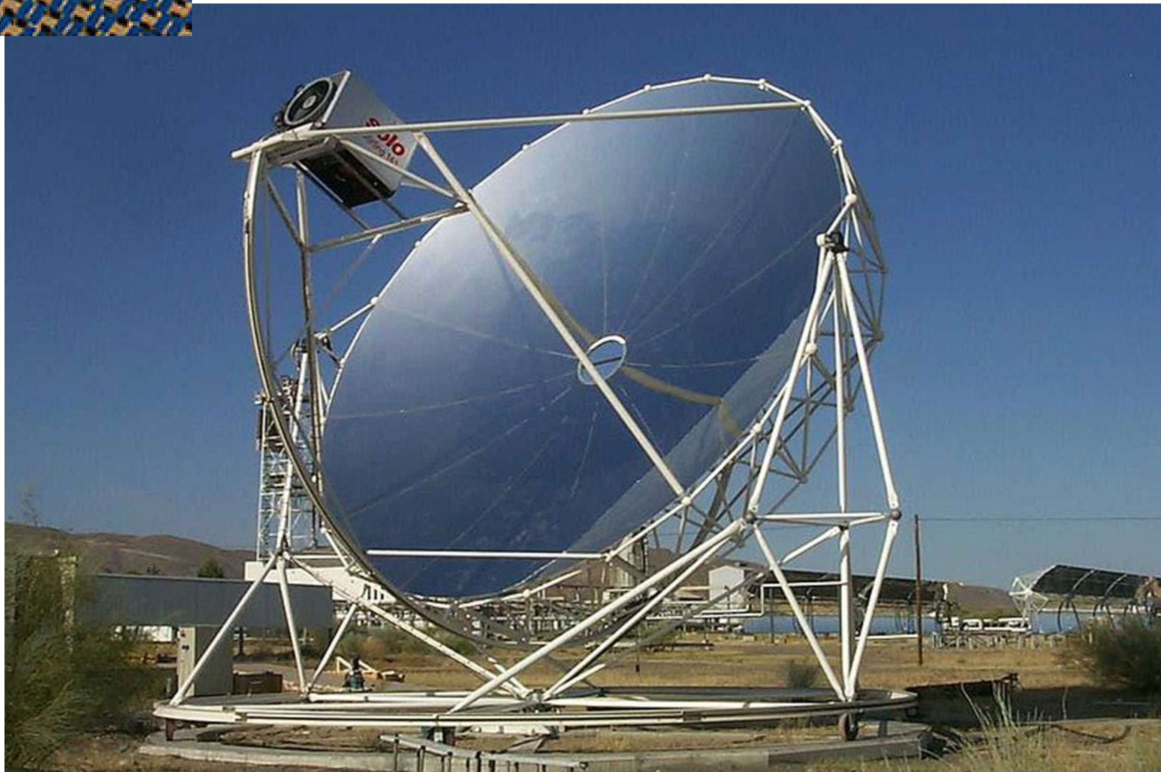


Fig. 4. Flow diagram of MD Alexandria compact system.

Concentrating solar power…



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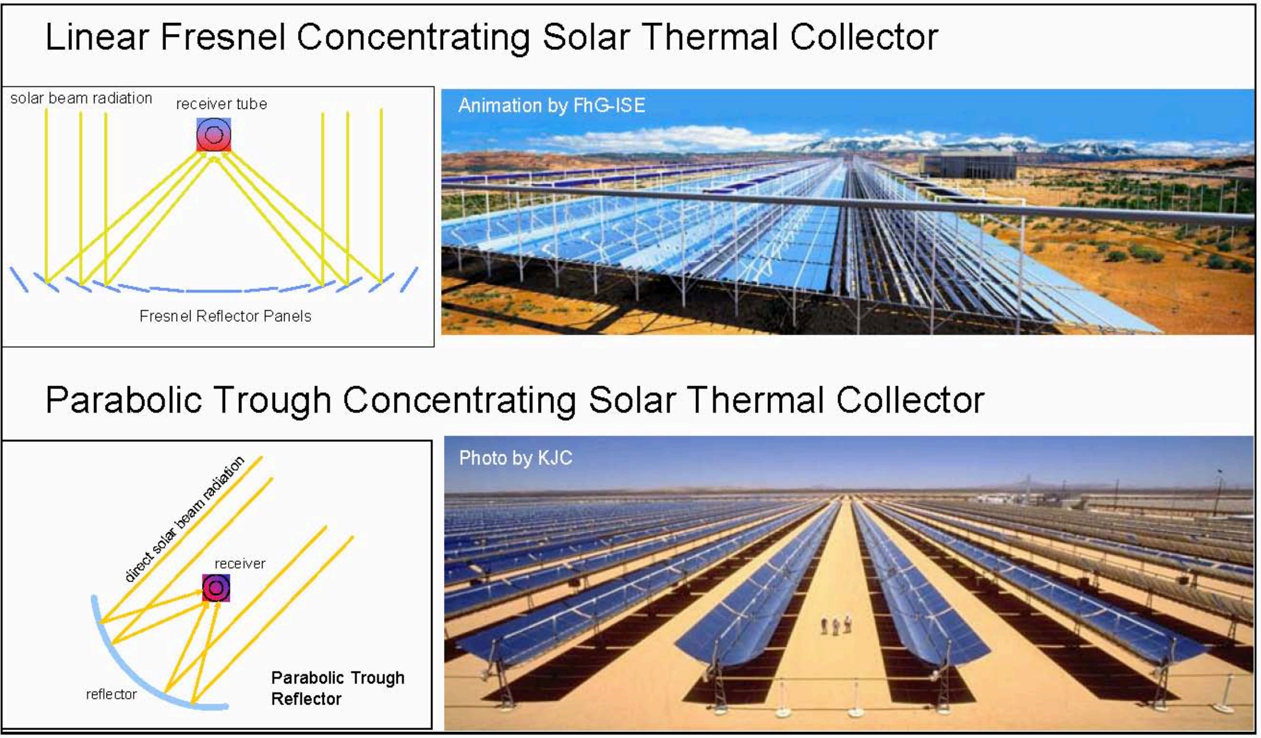
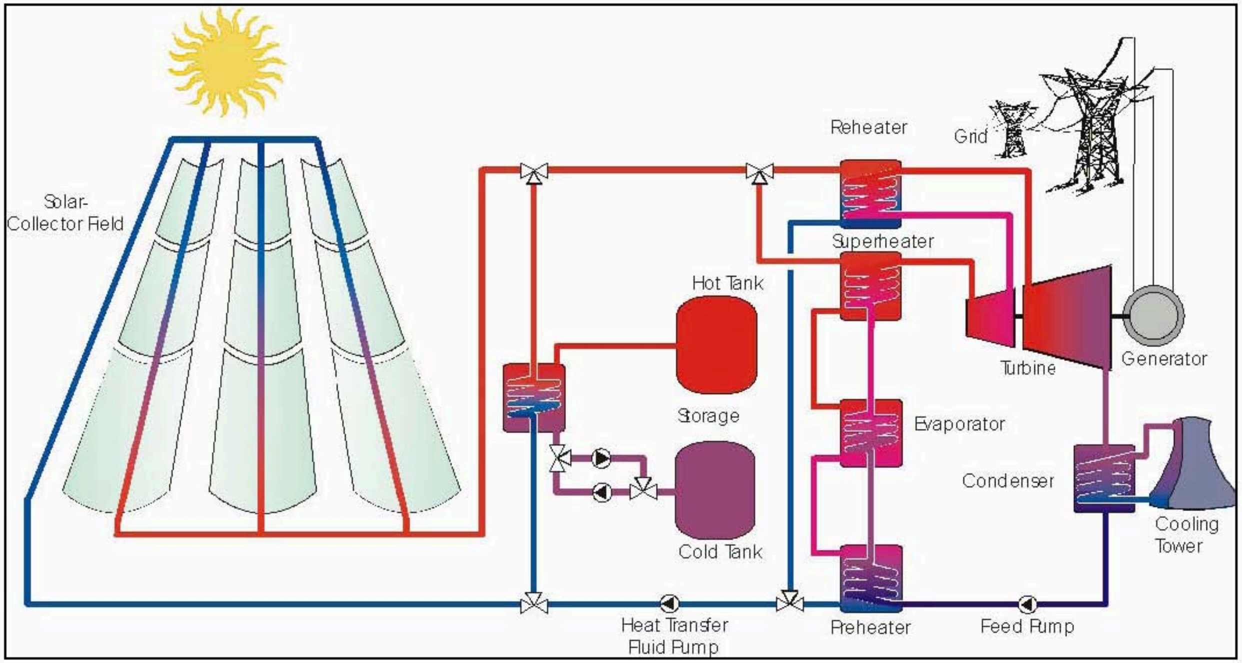
…achieves higher *T* and higher thermodynamic efficiency



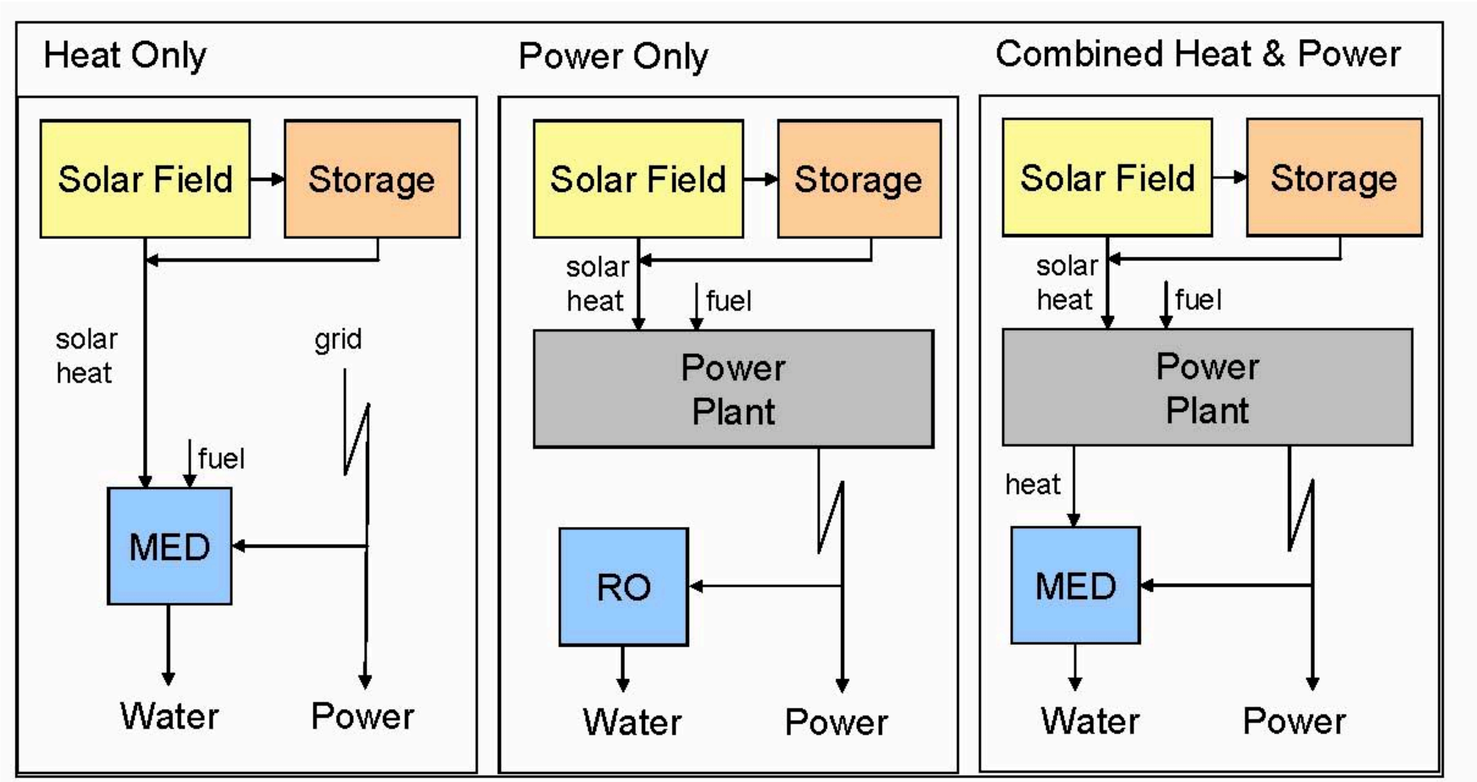
Concepts from concentrating solar power can be applied to solar distillation…generate electricity, then make water from waste heat or electricity

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

Ref: Trieb et al., Nov. 2007



Combined concentrating solar power and desalination



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

Performance of 35 to 185 L/m^2-day

Cost at present is still high by ~2x or more

Ref: Trieb et al., Nov. 2007

Relative performance of desalination techniques

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,…

Energy used	thermal		mechanical	
Process	MSF	MED/TVC	MVC	RO
State of the Art	commercial	commercial	commercial	commercial
World Wide Capacity 2004 (Mm^3/d)	13	2	0.6	6
Heat Consumption (kJ/kg)	**250 – 330**	145 - 390	--	--
Electricity Consumption (kWh/m^3)*	**3 - 5**	1.5 - 2.5	**8 - 15**	2.5 - 7
Plant Cost ($\$/m^3/d$)**	**1500 - 2000**	900 - 1700	**1500 - 2000**	900 -1500
Time to Commissioning (months)	24	18 - 24	12	18
Production Unit Capacity (m^3/d)	< 76000	< 36000	**< 3000**	< 20000
Conversion Freshwater / Seawater	**10 - 25%**	23 - 33%	23 - 41%	20 - 50%
Max. Top Brine Temperature (°C)	**90 - 120**	55 - 70	70	45 (max)
Reliability	very high	very high	high	moderate (for seawater)
Maintenance (cleaning per year)	0.5 - 1	1 - 2	1 - 2	several times
Pre-treatment of water	simple	simple	very simple	demanding
Operation requirements	simple	simple	simple	demanding
Product water quality (ppm)	< 10	< 10	< 10	200 - 500

Ref: Trieb et al., Nov. 2007

Table 4. Desalination Costs ($\$/m^3$ fresh water – multiply by 3.8 for \$/1000 gal)

Reference	MSF	MEE	VC	Seawater RO	Brackish RO	Brackish ED
A	1.10-1.50	0.46-85	0.87-0.92	0.45-0.92	0.20-0.35	
B	0.80	0.45		0.72-0.93		
C	0.89	0.27-0.56		0.68		
D	0.70-0.75			0.45-0.85	0.25-0.60	
E				1.54	0.35	
F				1.50	0.37-0.70	0.58
G	1.31-5.36			1.54-6.56		
H	1.86	1.49				
I		1.35		1.06		
J				1.25		
K	1.22					
L					0.18-0.56	
M			0.46			
N				1.18		
O		1.17				
P			0.99-1.21			
Q				0.55-0.80	0.25-0.28	
R				0.59-1.62		
S				1.38-1.51		
T				0.55-0.63		
U				0.70-0.80		
V					0.27*	
W				0.52		

Ref: Miller (2003)

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.

References

1. *Water for People, Water for Life*, United Nations World Water Development Report. Paris: UNESCO Publishing, 2003.
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/
5. J.E. Miller, “Review of water resources and desalination technologies,” Sandia report SAND-2003-0800, 2003. Albuquerque: Sandia National Laboratory.
6. Water quality results obtained from web sites of the Massachusetts Water Resources Authority, the Cambridge City Water Department, and the Poland Spring Water Company, 2007, 2008.
7. A.C. Twort, D.D. Rathnayaka, and M.J. Brandt, *Water Supply*, 5th ed., IWA Publishing.
8. M. Wilf, *The Guidebook to Membrane Desalination Technology.* L’Aquila Italy: Balaban Desalination Publications, 2007.
9. C. Fritzmann, J. Lowenberg, T. Wintgens, T. Melin, “State-of-the-art reverse osmosis desalination,” *Desalination*, 216 (2007) 1-76.
10. S.D. Faust and O.M. Aly, *Chemistry of Water Treatment*, 2nd ed. Boca Raton: Lewis Publishers/CRC, 1998.
11. M. Wilf and M. Balaban, *Membrane Desalination and Membrane Water Filtration*, European Desalination Society intensive course notes, L’Aquila, Italy, February 2007.
12. H. Strathmann, *Electromembrane processes: State-of-the-art processes and recent developments, lecture notes,* 2007.
13. *WHO Guidelines for drinking-water quality,* 3rd edition. Geneva: World Health Organization, 2006.
14. M. Al-Ghamdi, *Saline Water Conversion Corporation: Challenge, Achievement, and Future Prospective.* Lecture notes, April 2006.
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. Dr. Franz Trieb et al., *Concentrating Solar Power for Seawater Desalination*, German Aerospace Center (DLR), Institute of Technical Thermodynamics, Nov. 2007.

References (continued)

17. J.A. Duffie and W.A. Beckman, *Solar Engineering of Thermal Processes*. Wiley, 2006.
18. H. Ettouney and L. Rizzuti, “Solar desalination: a challenge sustainable fresh water in the 21st century,” in *Solar desalination for the 21st century*, Springer, 2006.
19. H.E.S. Fath et al.,“PV and thermally driven small-scale, stand-alone solar desalination systems with very low maintenance needs,” *Desalination* 225 (2008) 58–69.
20. C. Sommariva, *Thermal desalination processes and economics*, European Desalination Society intensive course notes, L’Aquila, Italy, July 2007.
21. T.D. Reynolds and P.A. Richards, *Unit Operations and Processes in Environmental Engineering*, 2nd ed. Boston: PWS Publishing Co., 1995.