# 2.500 Desalination & Water Purification

Spring 2009
*Summary*

Haiti

Ghana

Photos by Amy Smith. Used with permission.

Department of Mechanical Engineering
Massachusetts Institute of Technology

# 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.

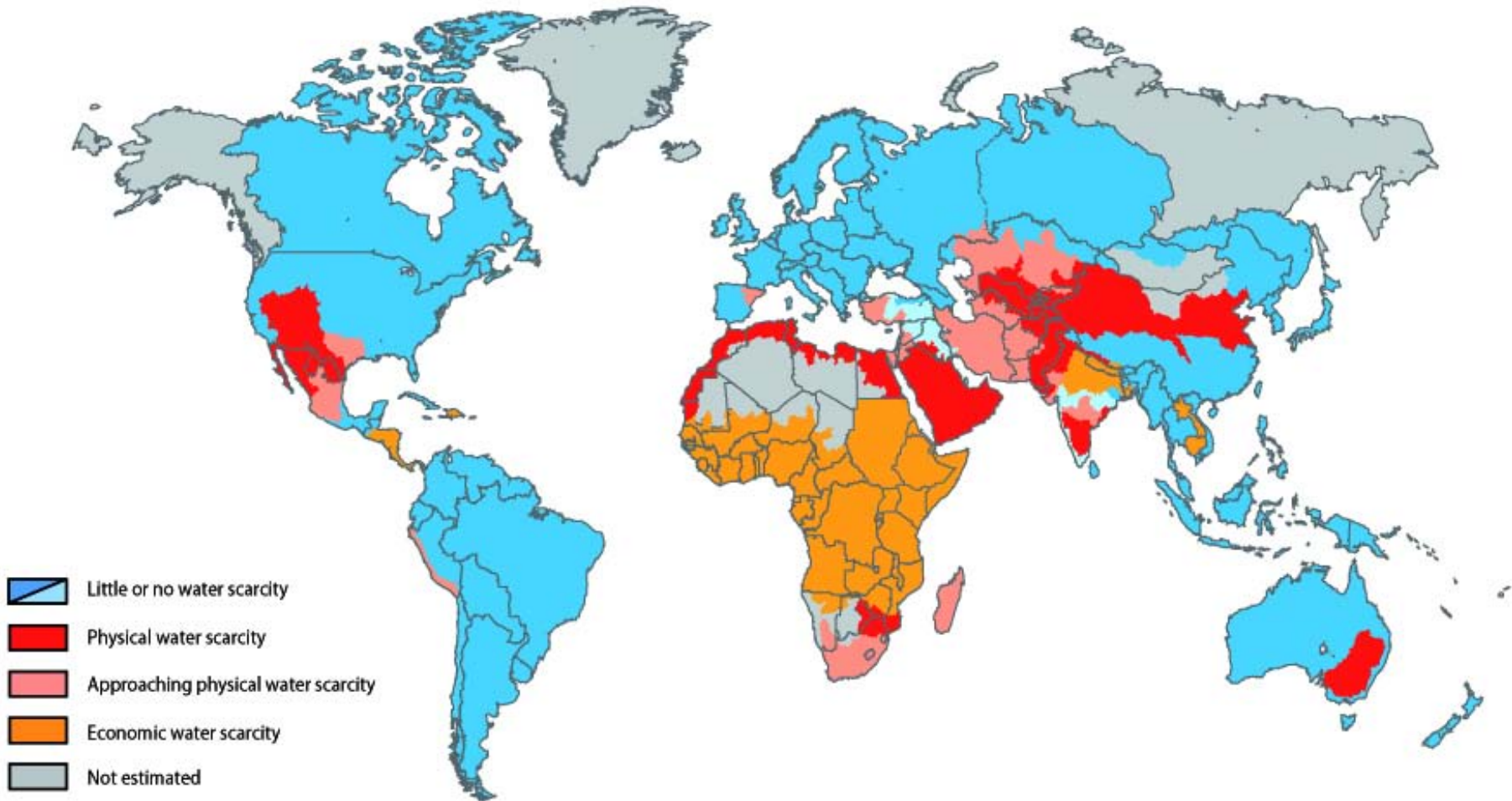In 2000, unsafe water mortality amounted to 80 million years of lost life (*Science*, 25 Jan 2008)

This situation is expected to get WORSE.

Images removed due to copyright restrictions. Please see
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



**Legend:**
- Little or no water scarcity
- Physical water scarcity
- Approaching physical water scarcity
- Economic water scarcity
- Not estimated

Source: IMWI report, Insights from the Comprehensive Assessment of Water Management in Agriculture, 2006 / p8

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.

**Yangon, Myanmar**

**May 2008**
**…after cyclone**

Images removed due to copyright restrictions.
Please see http://www.nytimes.com/slideshow/2008/05/05/world/0505-MYANMAR_index.html
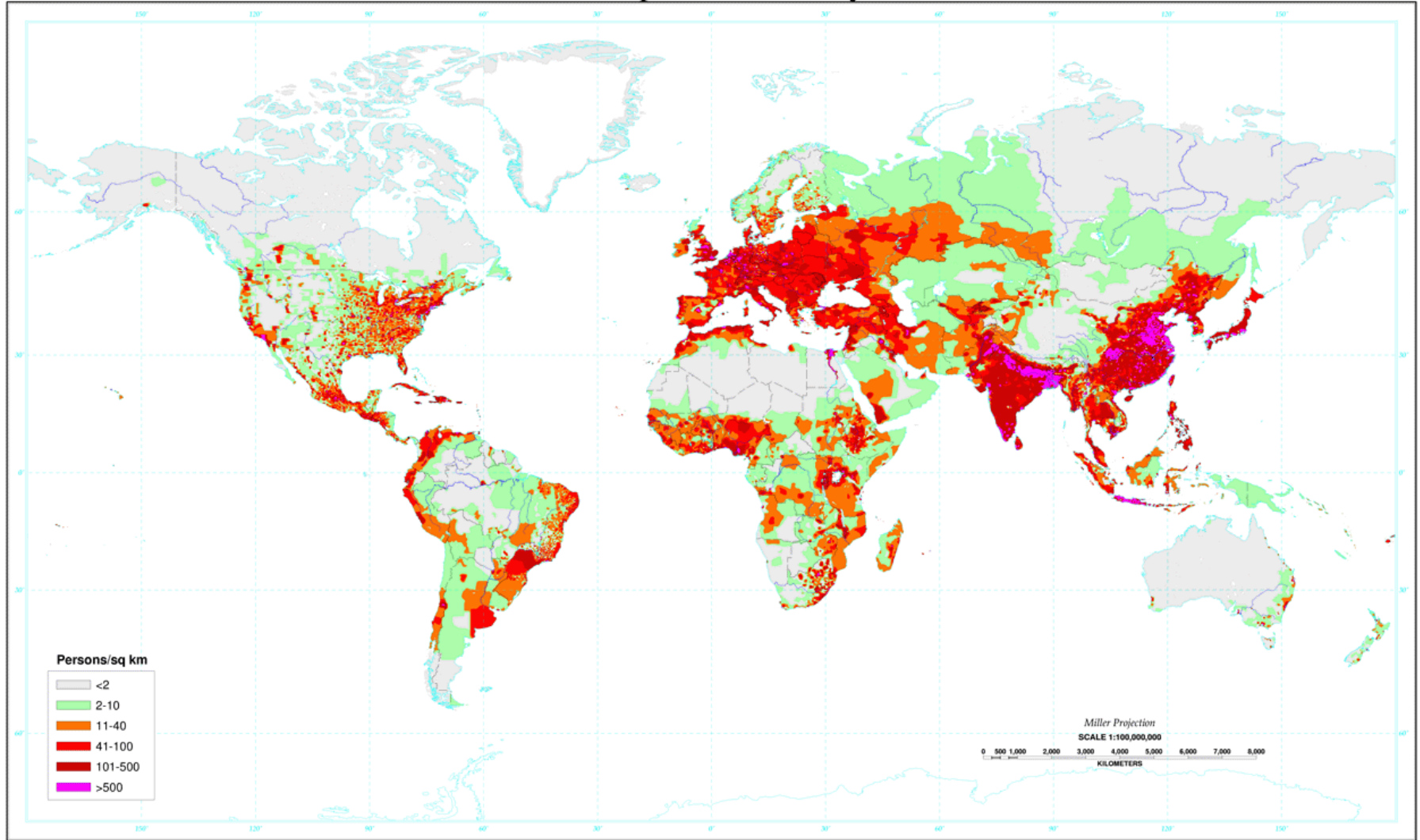http://graphics8.nytimes.com/images/2008/05/05/nytfrontpage/23097528.JPG

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.
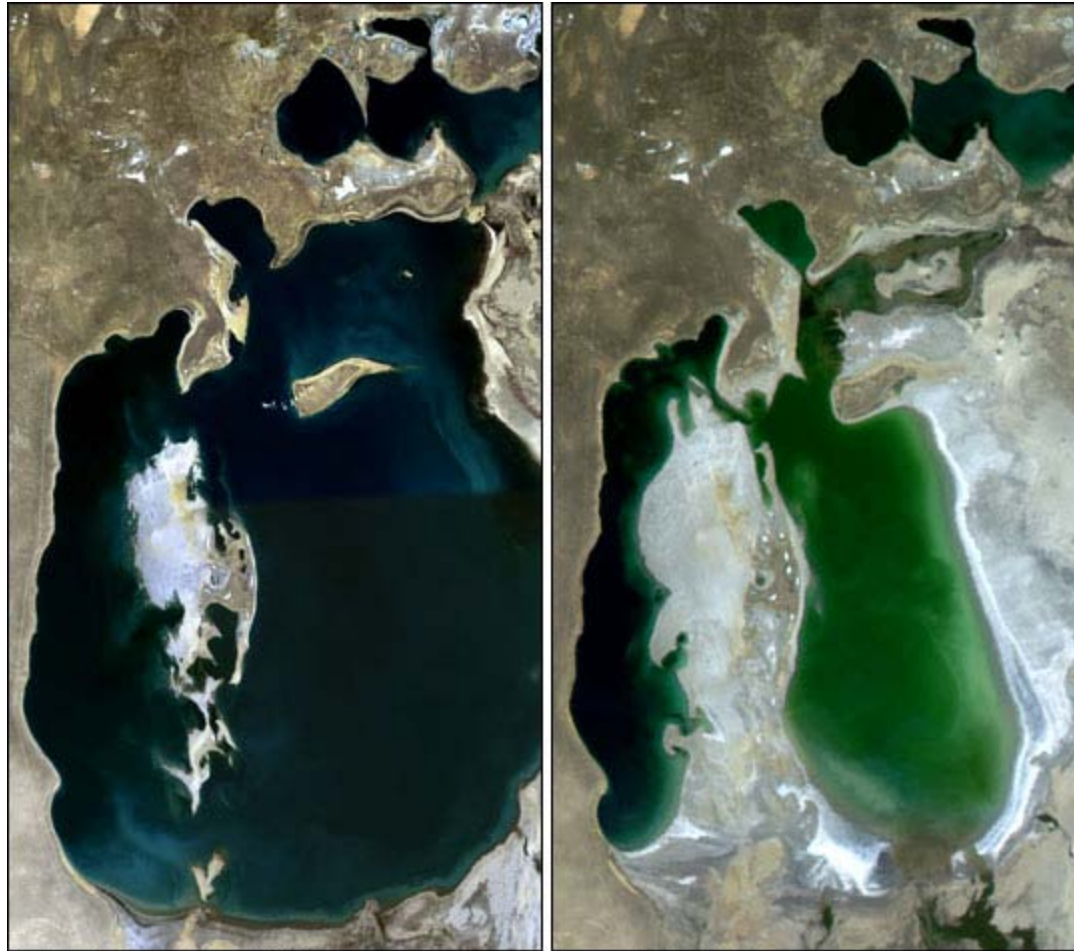
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# Per capita water consumption (m³/y)

- Worldwide average      800
- Nigeria      50
- China      300
- Mexico      800
- Italy      1000
- USA      2000

- World desalting capacity      2

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

Image removed due to copyright restrictions.
Please see http://www.flickr.com/photos/peggyarcher/975676140/in/set-72157601398334771/

Cleaning a sidewalk in Long Beach, CA

July - September, 1989          August 12, 2003
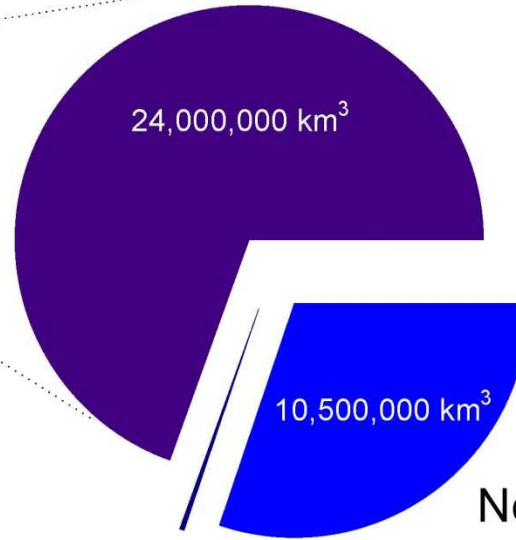
Images from NASA Earth Observatory.

*Aral Sea – water diverted for agriculture*

*Source:* infranetlab.org

Fresh Water - 2.5 %

Glaciers and Ice Caps - 69.5 %

Total = 1.4 billion km$^3$

24,000,000 km$^3$

10,500,000 km$^3$

Nonrenewable - 30.2 %

(Ground water: lakes, etc.)

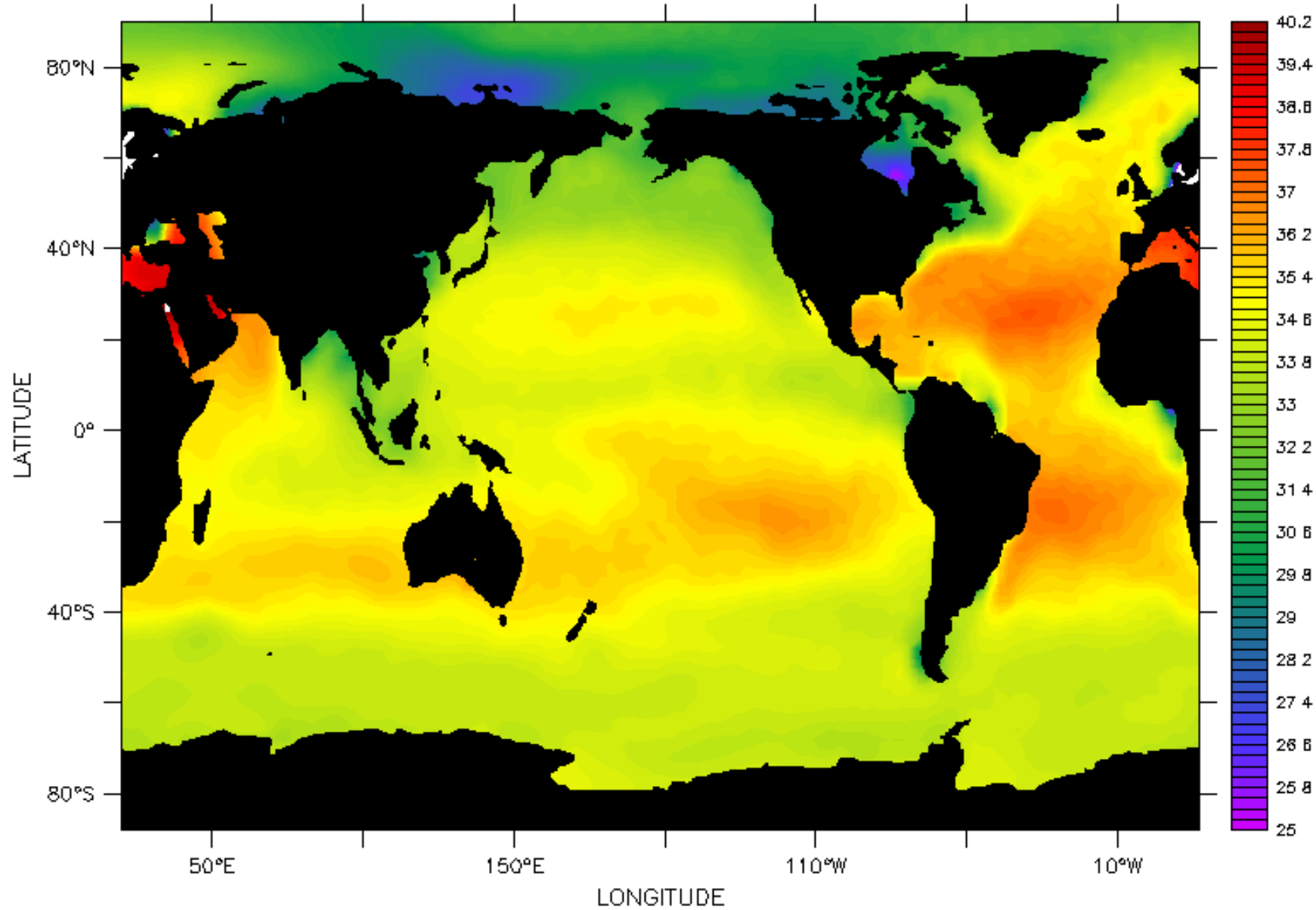110,000 km$^3$

Salt Water - 97.5 %

Renewable - 0.3 %

(Precipitation over land)

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.*

Annual Mean Sea Surface Salinity

Salinity Data from Levitus (1982)

Courtesy of Robert H. Stewart. Used with permission.

Time: Sep. 4, 1997

# Water flows (km³/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

World desalting capacity = 13 km³/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 | - |

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[1] nr = not reported.

# Concepts from Physical Chemistry

- Gibbs energy

- Chemical activity

- Colligative properties
(especially osmosis)

- Electrolyte behavior

- Osmotic coefficient

- Ion transport

- Colloidal Stability
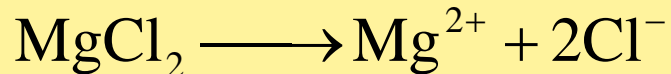
$$G = H - TS$$

# 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

$$A_{\nu+}B_{\nu-} \longrightarrow \nu_+ A^{z+} + \nu_- B^{z-}$$
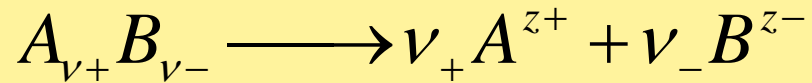
Electroneutrality: $\begin{cases} \nu_+ z_+ + \nu_- z_- = 0 \\ z_+ c_+ + z_- c_- = 0 \end{cases}$

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

Salts that dissociate completely are called *strong electrolytes.*

NaCl, MgCl$_2$, MgSO$_4$, CaSO$_4$, K$_2$SO$_4$, 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

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

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

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

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, $\phi$, is a function of solute, solvent, temperature, and molality*

# Osmotic pressure

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

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

$$\Pi_{seawater} \approx \left(7.6 \times 10^{-4}\right)\left(\text{TDS in ppm}\right)$$

# 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
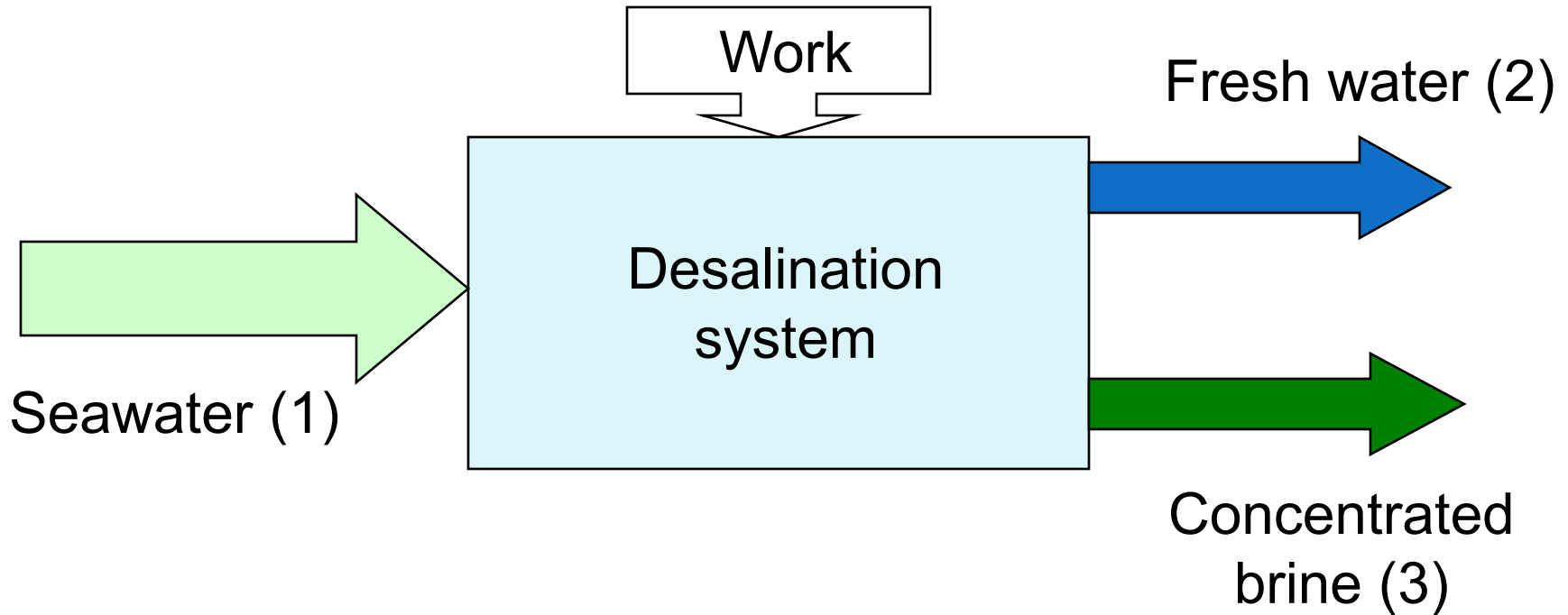


Ideally, this requires 2.5 to 7 kJ per kg fresh water produced.

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)
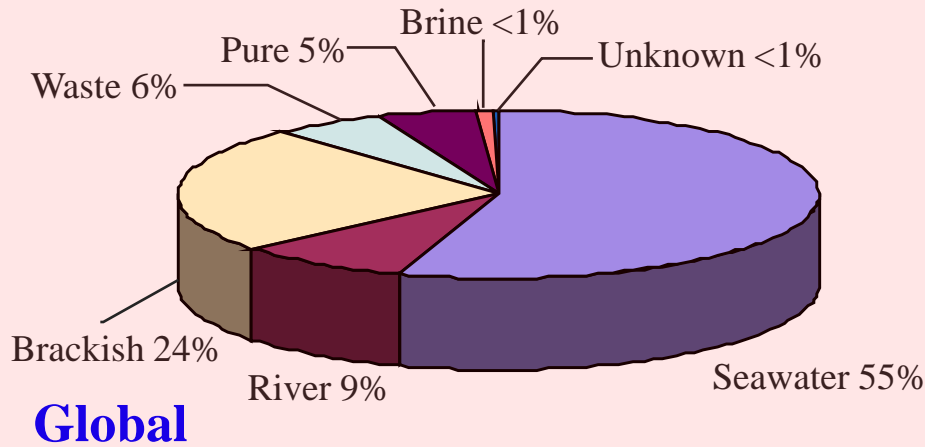
# Scale Formation

- 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
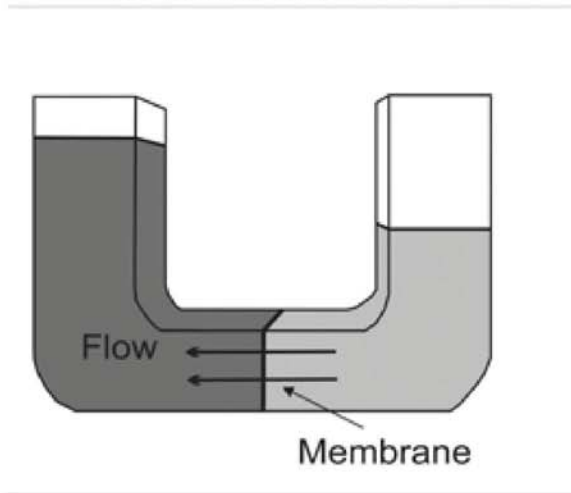  - Water softening

# Installed desalination capacity



SOURCE

Global

Brine <1%
Pure 5%
Waste 6%
Unknown <1%
Brackish 24%
River 9%
Seawater 55%

US

Brine <1%
Pure 7%
Waste 9%
Unknown <1%
Seawater 7%
River 26%
Brackish 51%

Ref: Wagnick/ GWI 2005

PROCESS

Global

Multi-Effect Distillation 2%
Vapor Compression 3%
Others 2%
Electrodialysis 5%
Multi-Stage Flash 40%
Reverse Osmosis 44%

US

Nano-Filtration 15%
Others 2%
Multi-Effect Distillation 1%
Vapor Compression 3%
Electrodialysis 9%
Multi-Stage Flash 1%
Reverse Osmosis 69%

Ref: Wagnick/ GWI 2005

# Reverse Osmosis

OSMOSIS REVERSE OSMOSIS
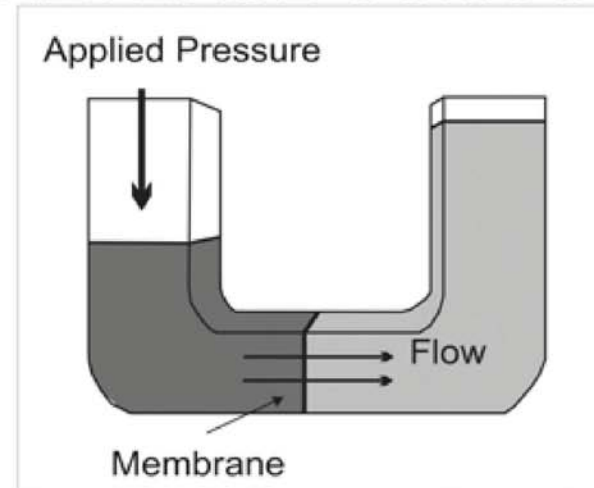
Concentrate Solution  Diluted Solution

Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

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*
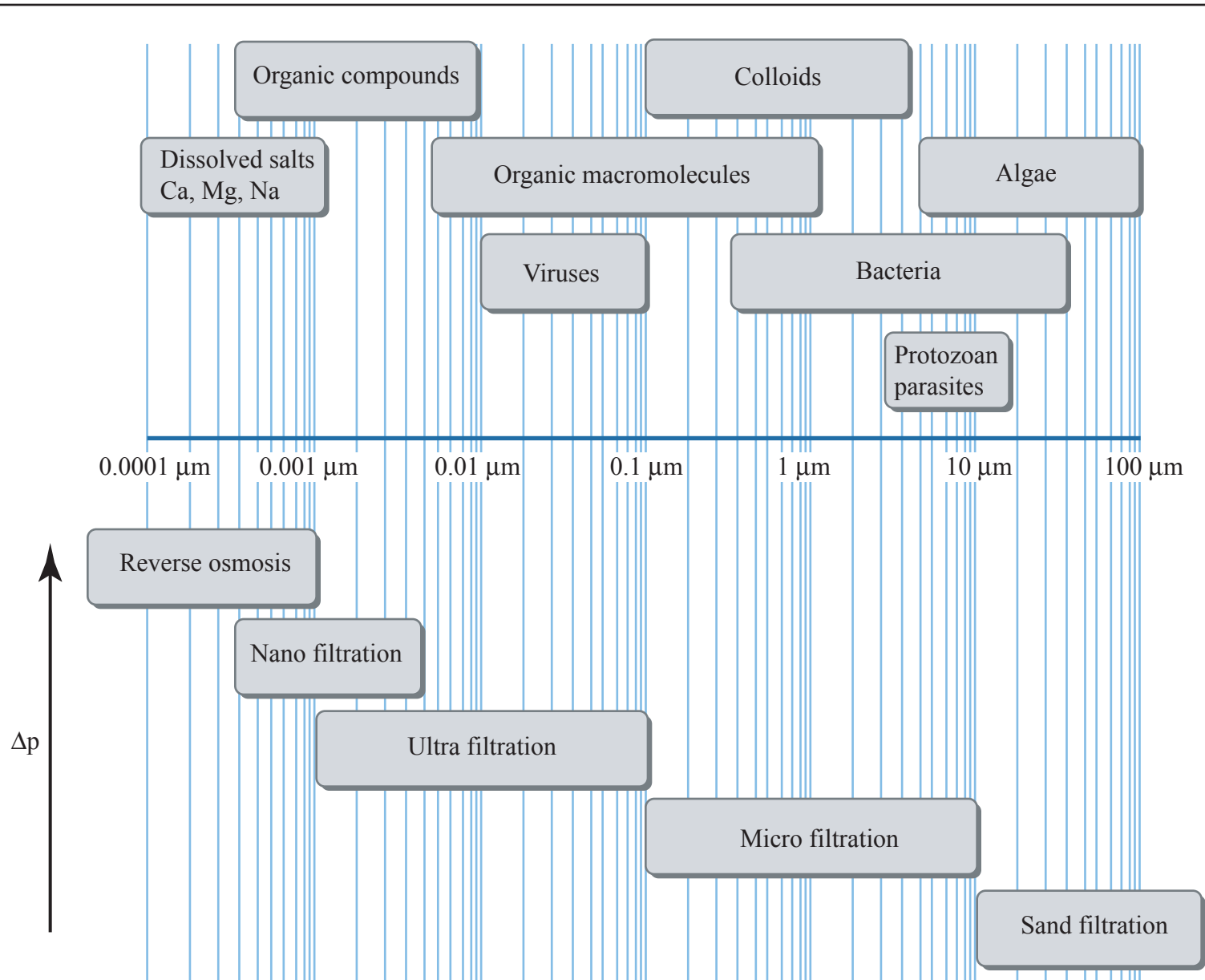
**Comparison of treatment methods with particle size.**

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/m²-s

$$J_s = B(c_{s,f} - c_{s,p})$$ Salt flux, mol/m²-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
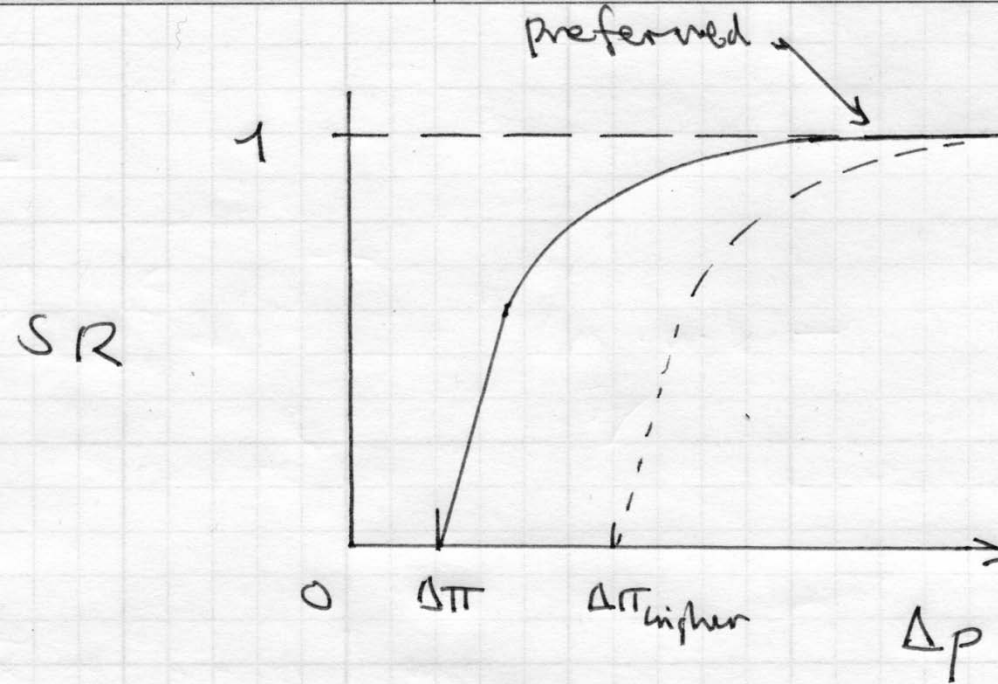
# Salt rejection as a function of driving pressure

# 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

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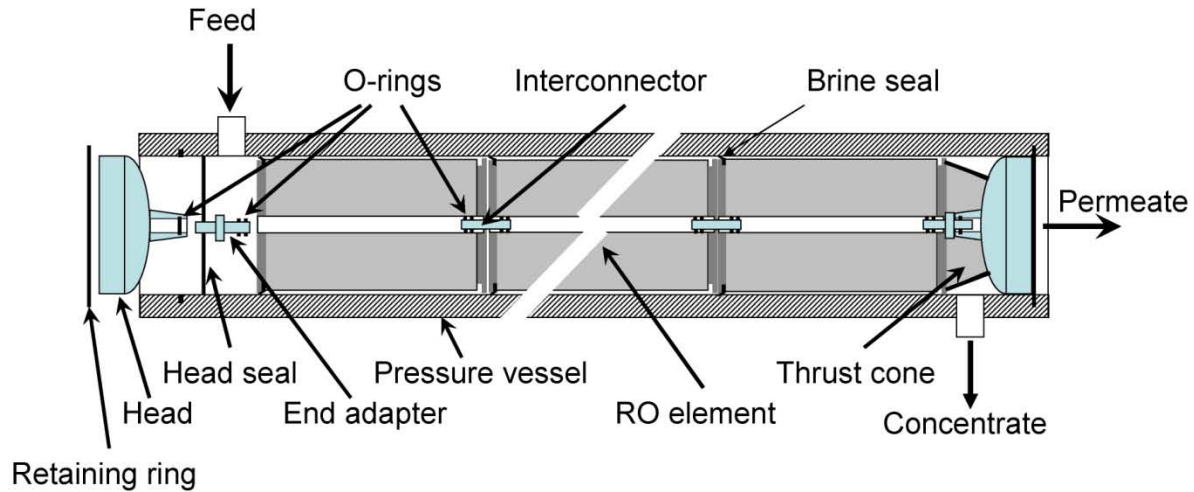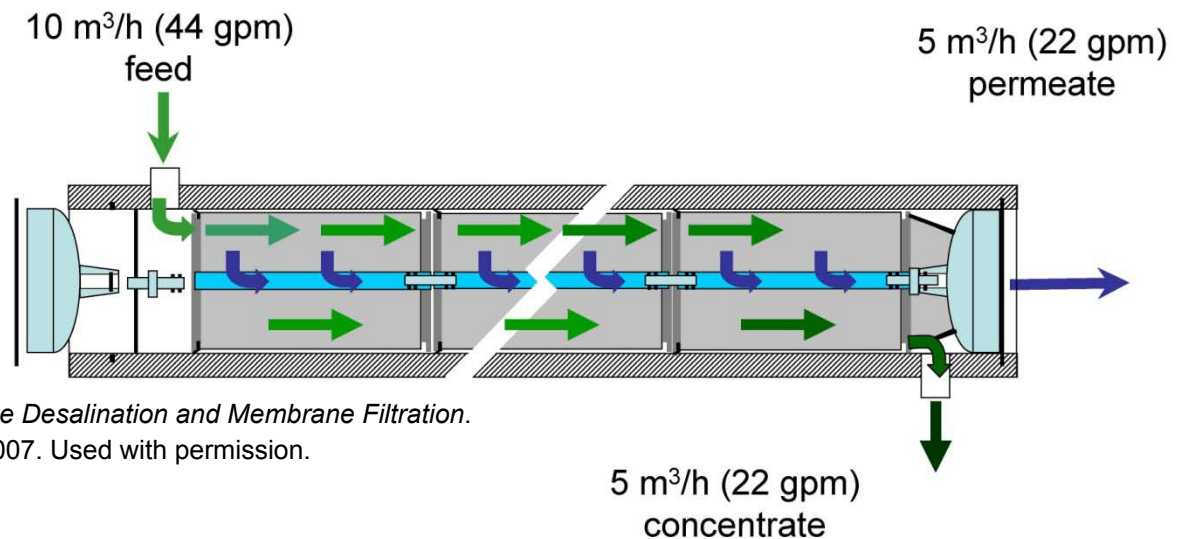
Average salt concentration of permeate

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.

# Configuration of a pressure vessel assembly



Feed · O-rings · Interconnector · Brine seal · Permeate · Concentrate · Head seal · Pressure vessel · Thrust cone · Head · End adapter · RO element · Retaining ring

# Water flow in a pressure vessel assembly



10 m³/h (44 gpm) feed

5 m³/h (22 gpm) permeate

5 m³/h (22 gpm) concentrate

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

| Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Flow, m³/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 |

$R_{p1}=64\%$          $R_p=80\%$

$R_{p2}=44\%$
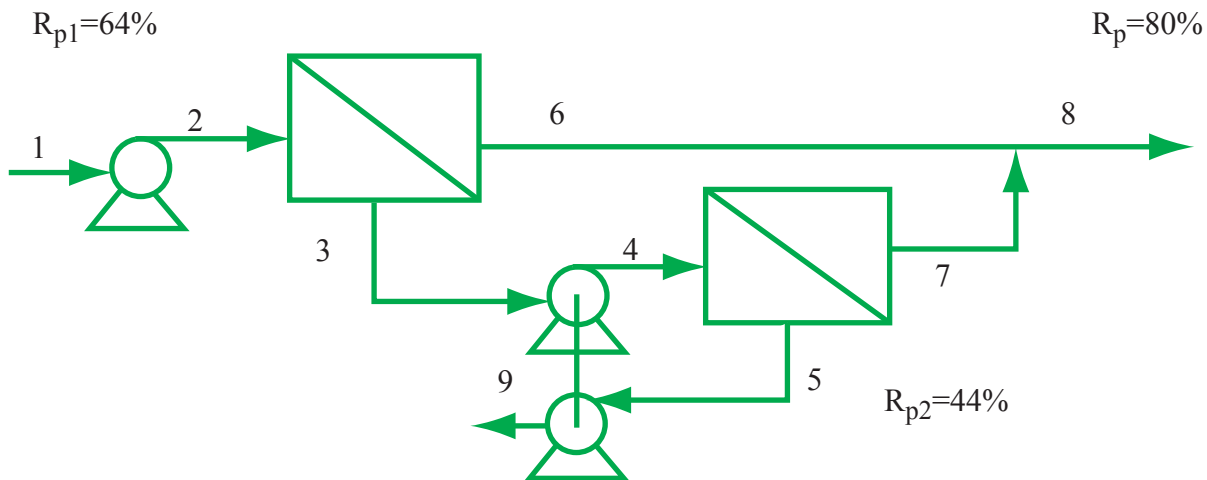
Figure by MIT OpenCourseWare.

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.
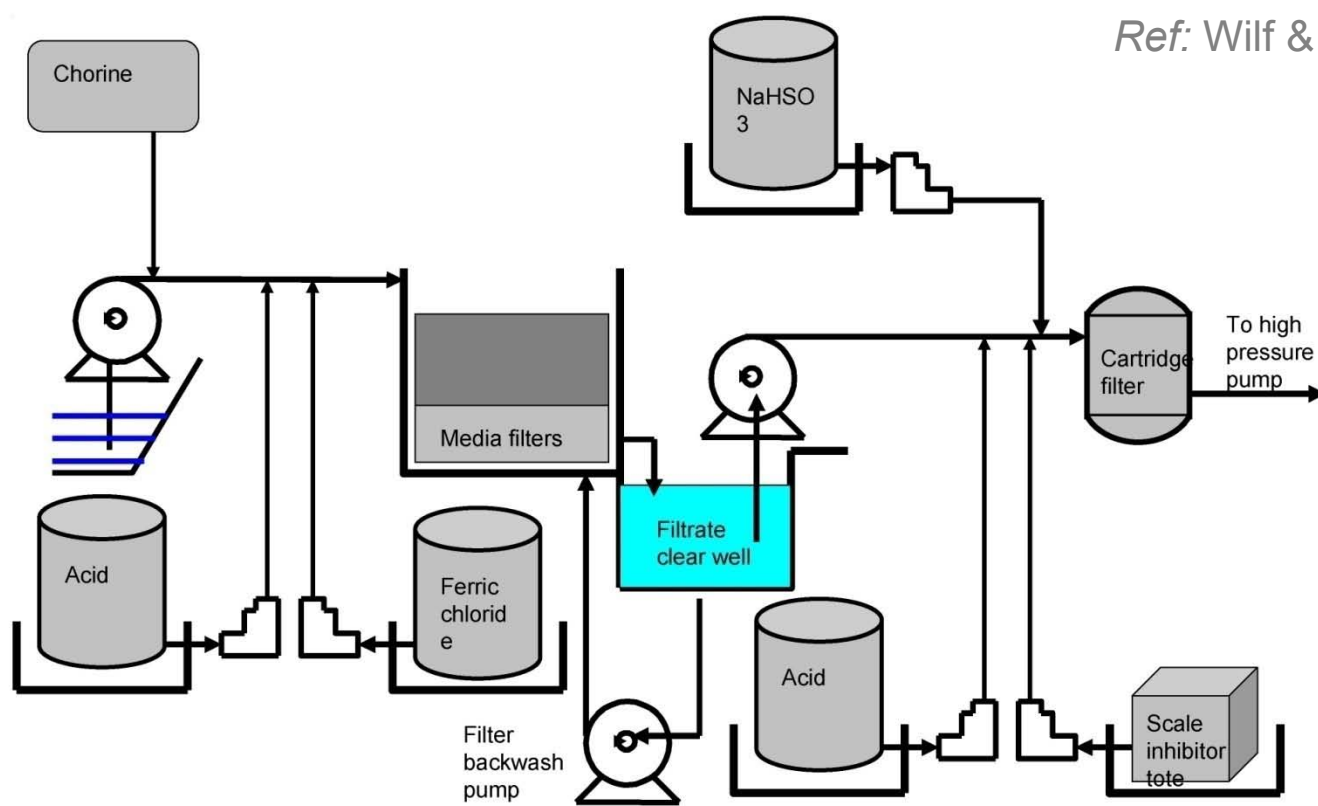L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Turbocharger applied as interstage booster pump

*Ref:* Wilf & Balaban,2007

Pumping system at Larnaca plant.   (Cyprus)

Ref: Wilf & Balaban, 2007

Chorine

NaHSO 3

Media filters

Filtrate clear well

Cartridge filter

To high pressure pump

Acid

Ferric chloride

Acid

Filter backwash pump

Scale inhibitor tote

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

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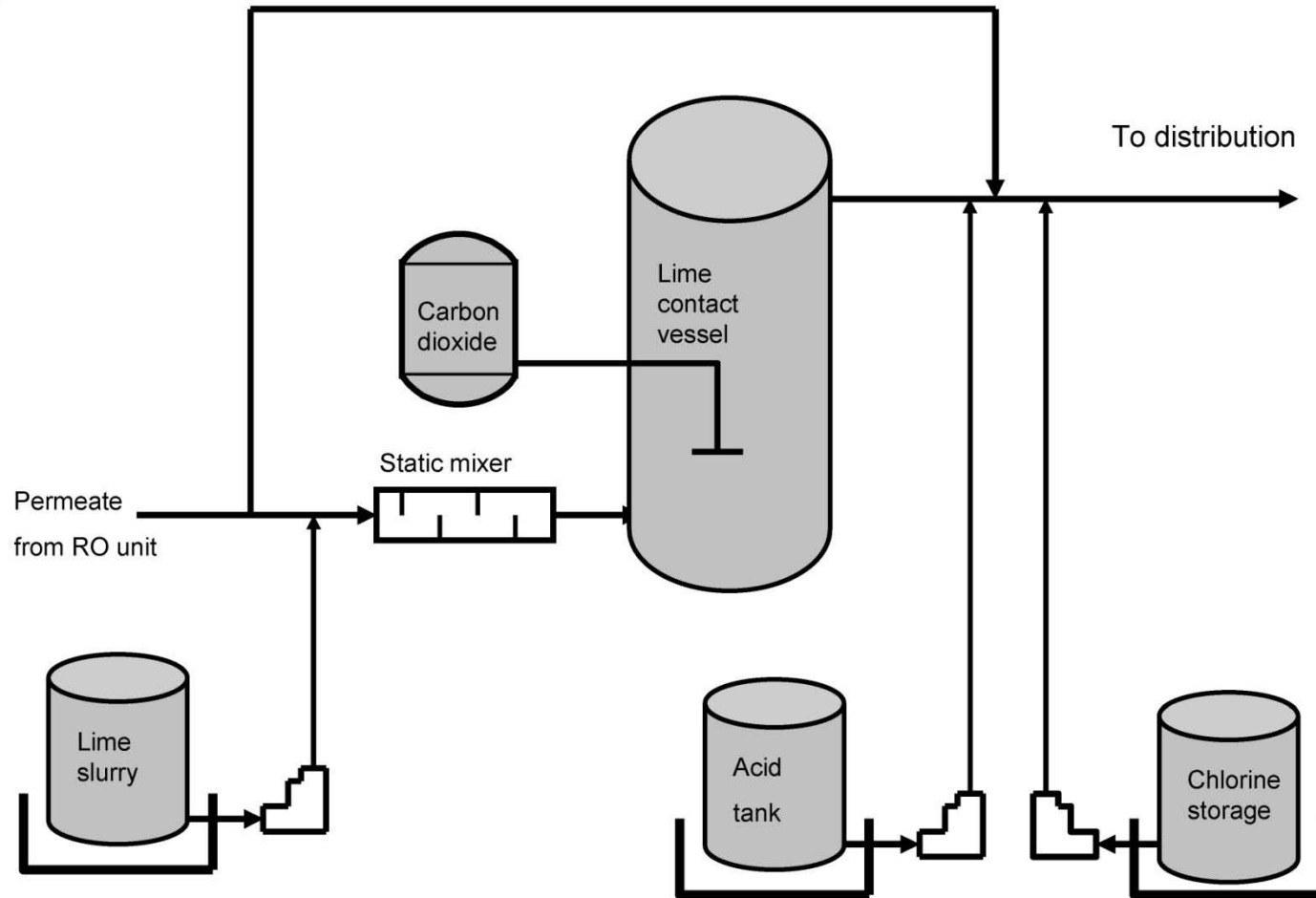
Figures from Wilf, M., and M. Balaban. Membrane Desalination and Membrane Filtration. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

**Seawater RO Post-treatment.**

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

Disinfect with additional chlorine, control pH

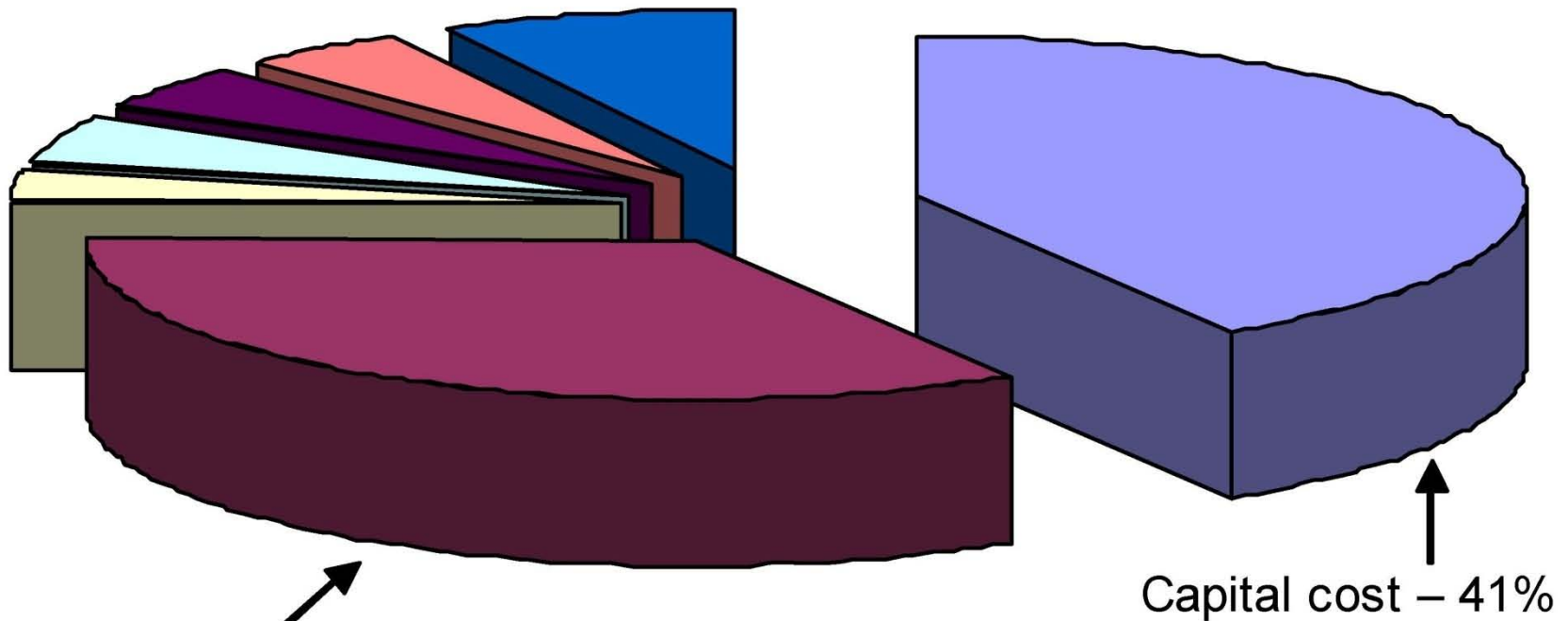*Ref:* Wilf & Balaban, 2007

# Total water cost distribution in SWRO

Membrane replacement – 3%      Consumables – 5%

Labor – 5%                     Others & contingency – 7%

Maintenance and parts – 5%



Energy – 34%

Capital cost – 41%

*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.

# Electrodialysis

## Ion Exchange Membranes

Cation exchange

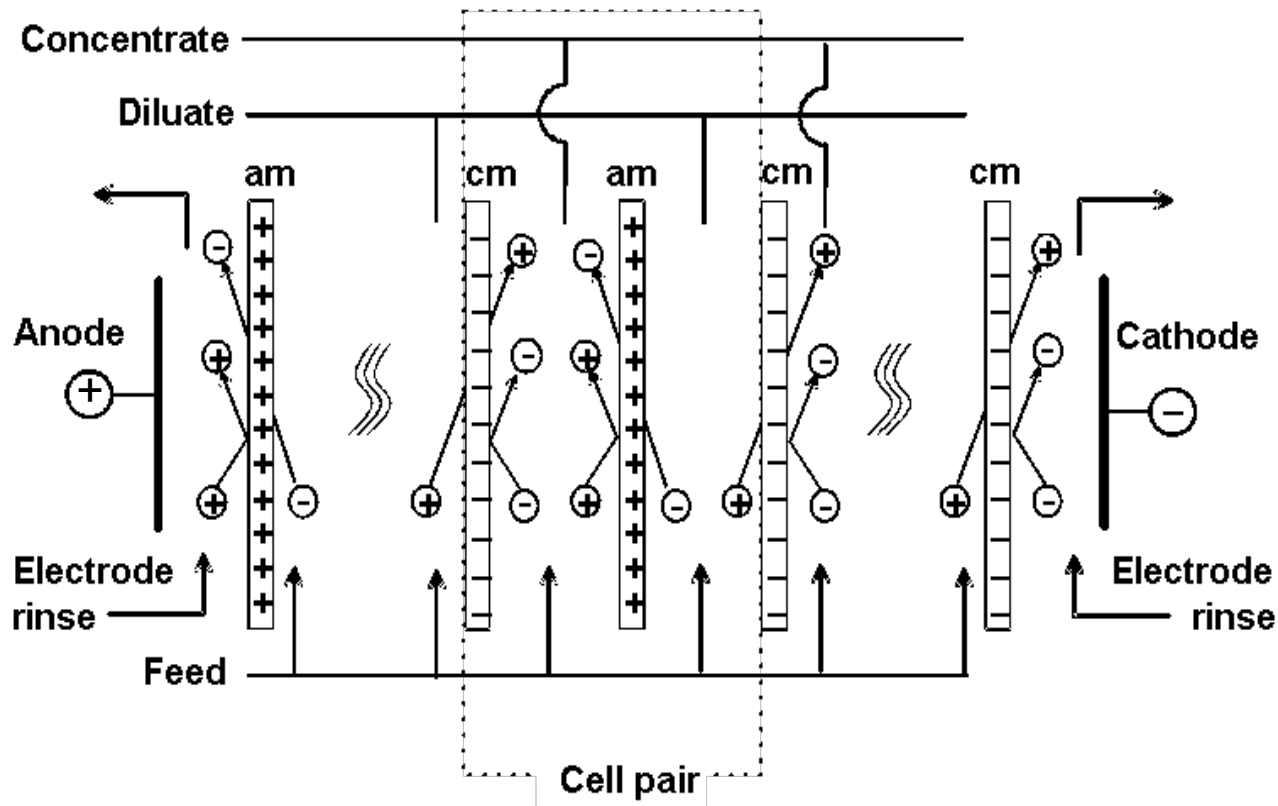$\vec{E}$ ──→
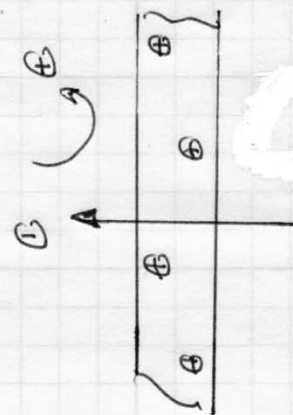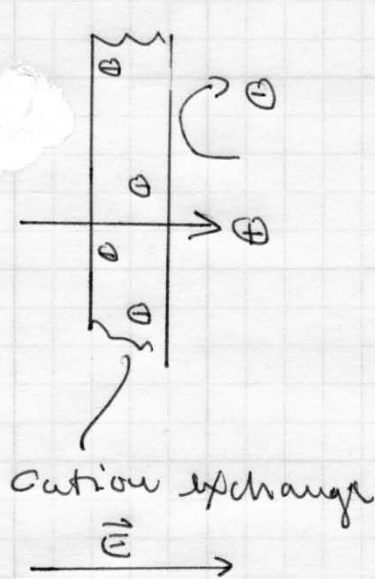
polymer resins with fixed charge groups

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

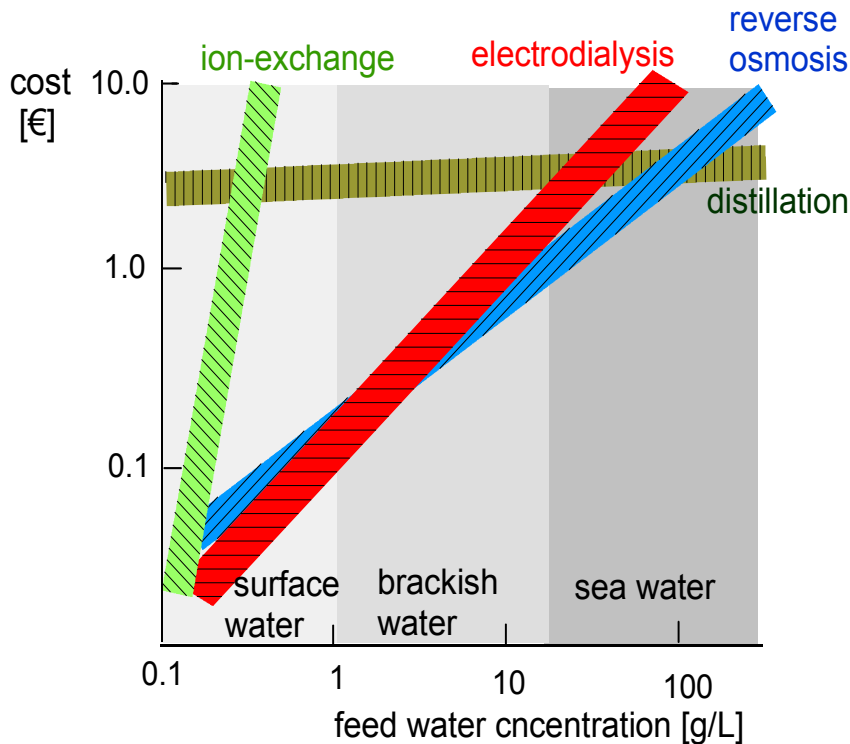$$I = \frac{\Delta c_d \dot{V}_d F |z| \nu}{\xi}$$

Operating current

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

Limiting current density, due to concentration polarization
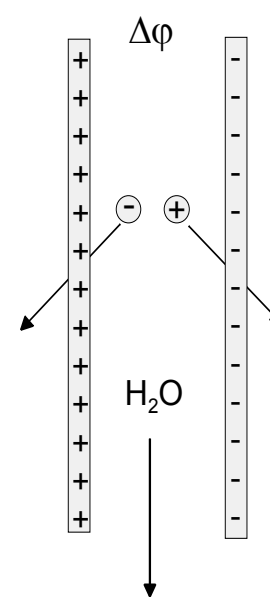
# *CONVENTIONAL ELECTRODIALYSIS*
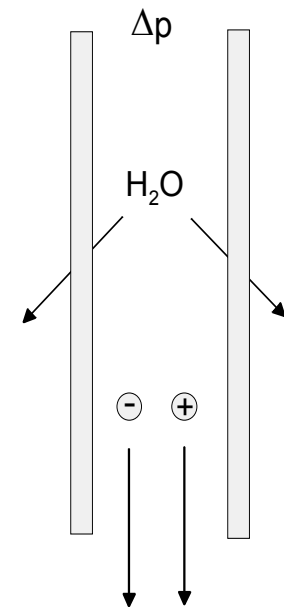
## *Water desalination costs*



## *Process principles of electrodialysis and reverse osmosis*



electrodialysis

reverse osmosis

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

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

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

Courtesy of Heiner Strathmann. Used with permission.

*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: $q\,(\mathrm{kJ/kg}) \approx h_{fg}$

- 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)
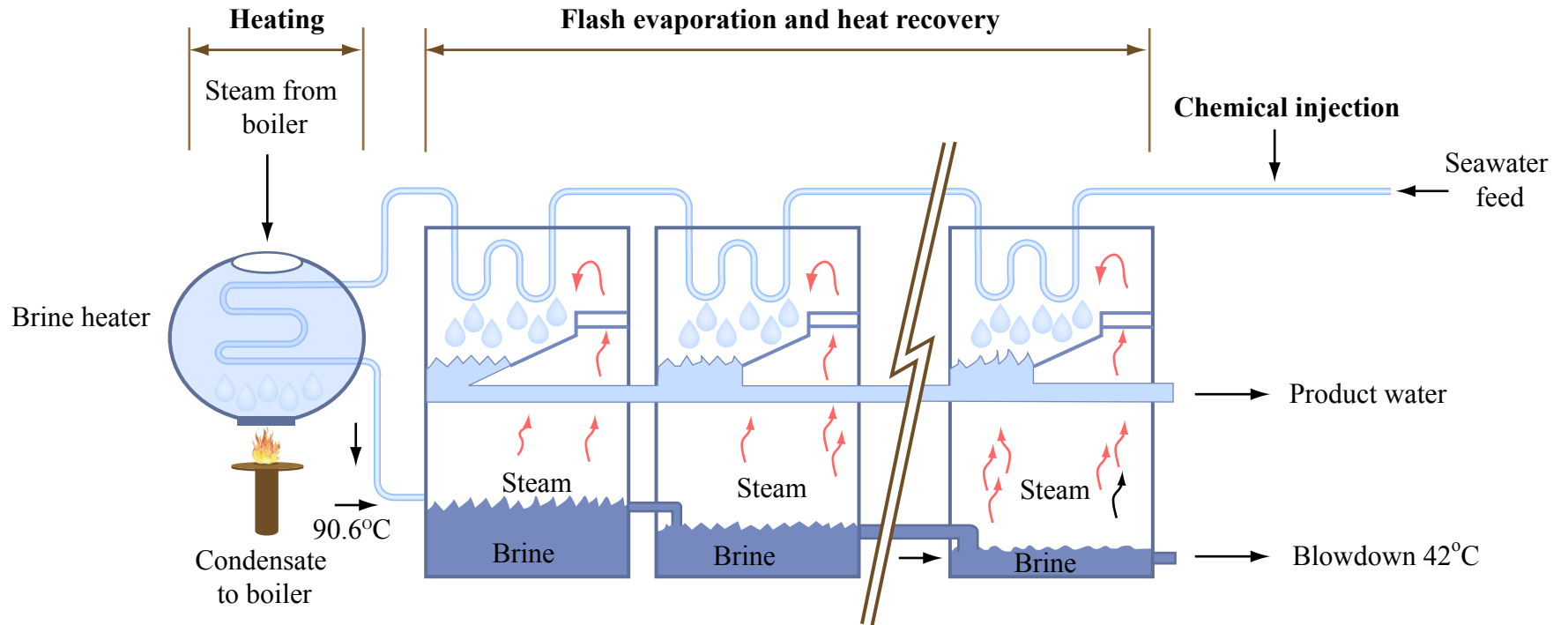- Can achieve performance ratios $R{\sim}10$ with these methods
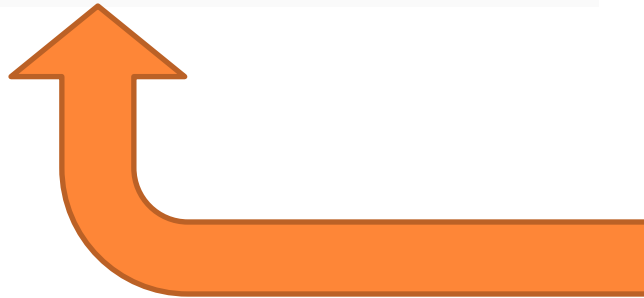
# 1) Multi Stage Flash - MSF
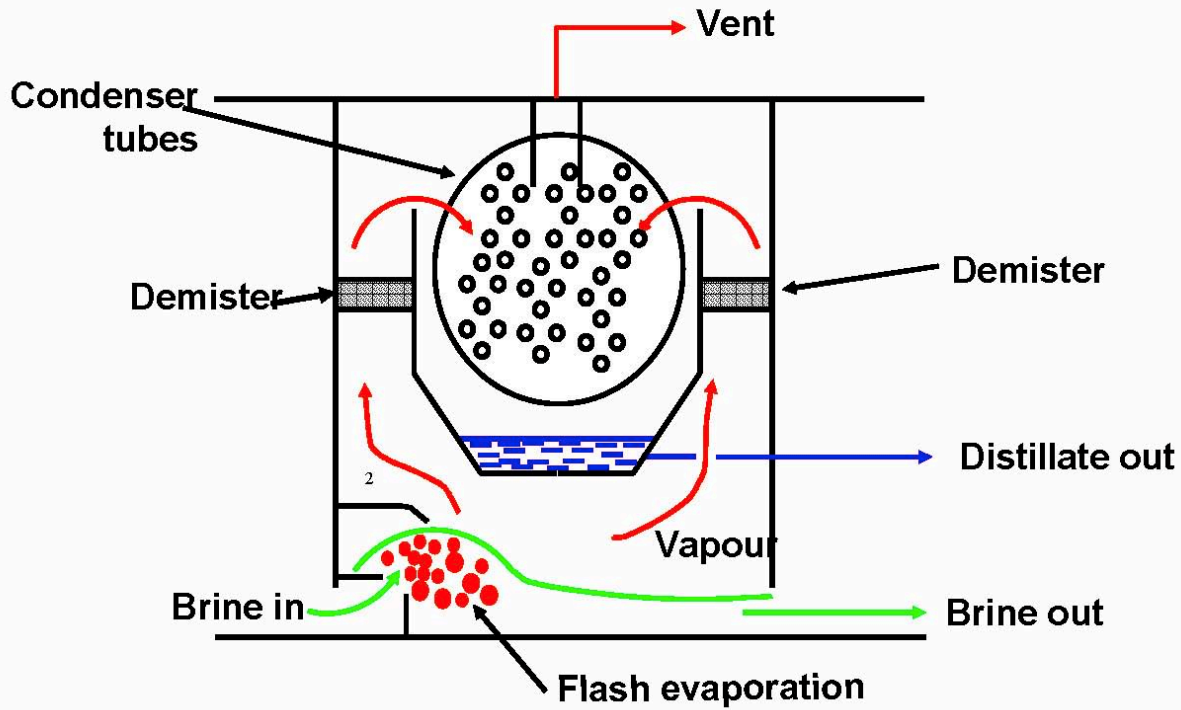


Figure by MIT OpenCourseWare.

# Typical stage arrangement of a large MSF plant



Condenser tubes

Vent

Demister

Demister

Distillate out

Vapour

2

Brine in

Brine out

Flash evaporation

# Multi stage flash



## Cross Tube

Recirculated brine flow in

Recirculated brine flow out

Flashing brine flow in

Stages
1 2 3 4 5 6

## Long Tube Distiller

Recirculated brine flow out

Flashing brine flow out

tubes igh

Flashing brine flow in

Stages
1 2 3 4 5 6

*Ref:* Sommariva, 2007

# Multieffect distillation concept



Courtesy of Corrado Sommariva. Used with permission.

Seawater spray

Condensate vapor (distillate)

Released vapor

Vapor box previous effect

Demisters

Brine pool

MED: horizontal tube evaporators



Inlet end

Tube support grid

Feed distributor headers

NCG removal system cover

Spray nozzles

NCG outlet

Tube plate

Feed inlet manifold

Evaporator tube bundle

Access door

Condensate box covers

Outet end

Vapor demisters
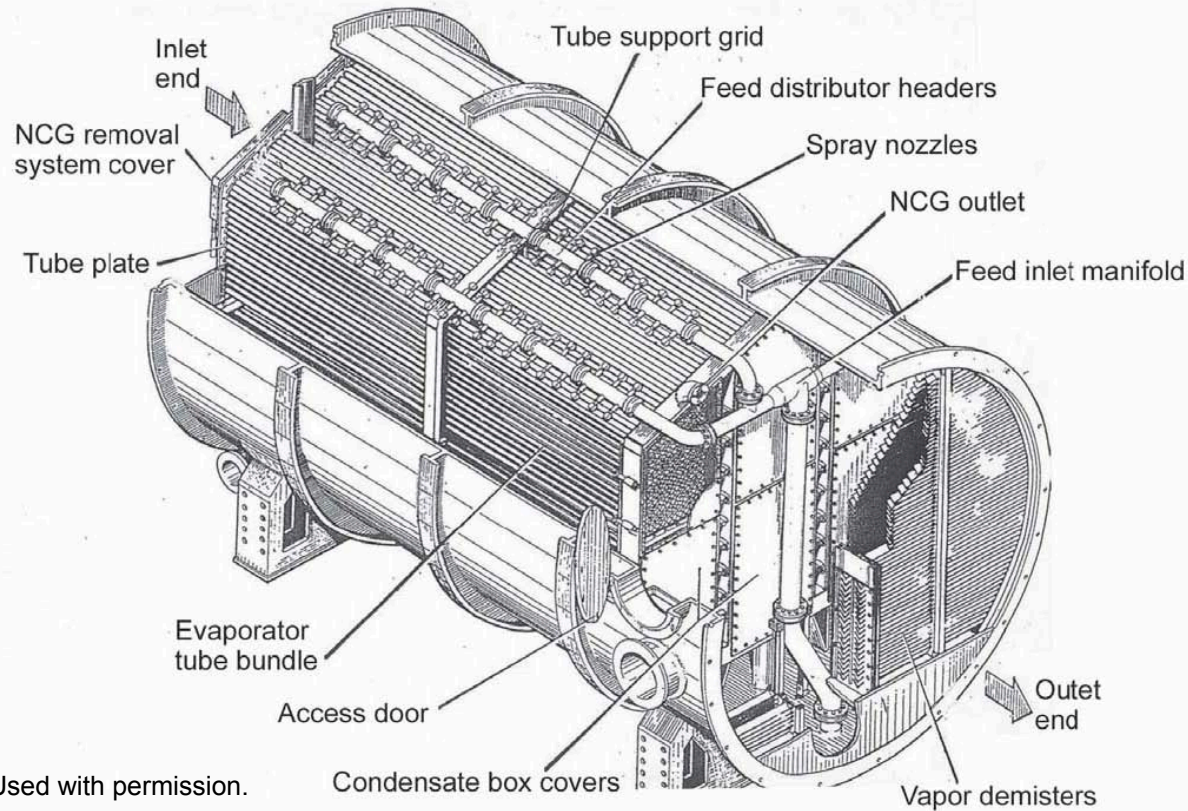
*Ref:* Sommariva, 2007

# 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/m²-day)



| | | | | | | |
|---|---|---|---|---|---|---|
| 0.0-0.9 | 1.0-1.9 | 2.0-2.9 | 3.0-3.9 | 4.0-4.9 | 5.0-5.9 | 6.0-6.9 |
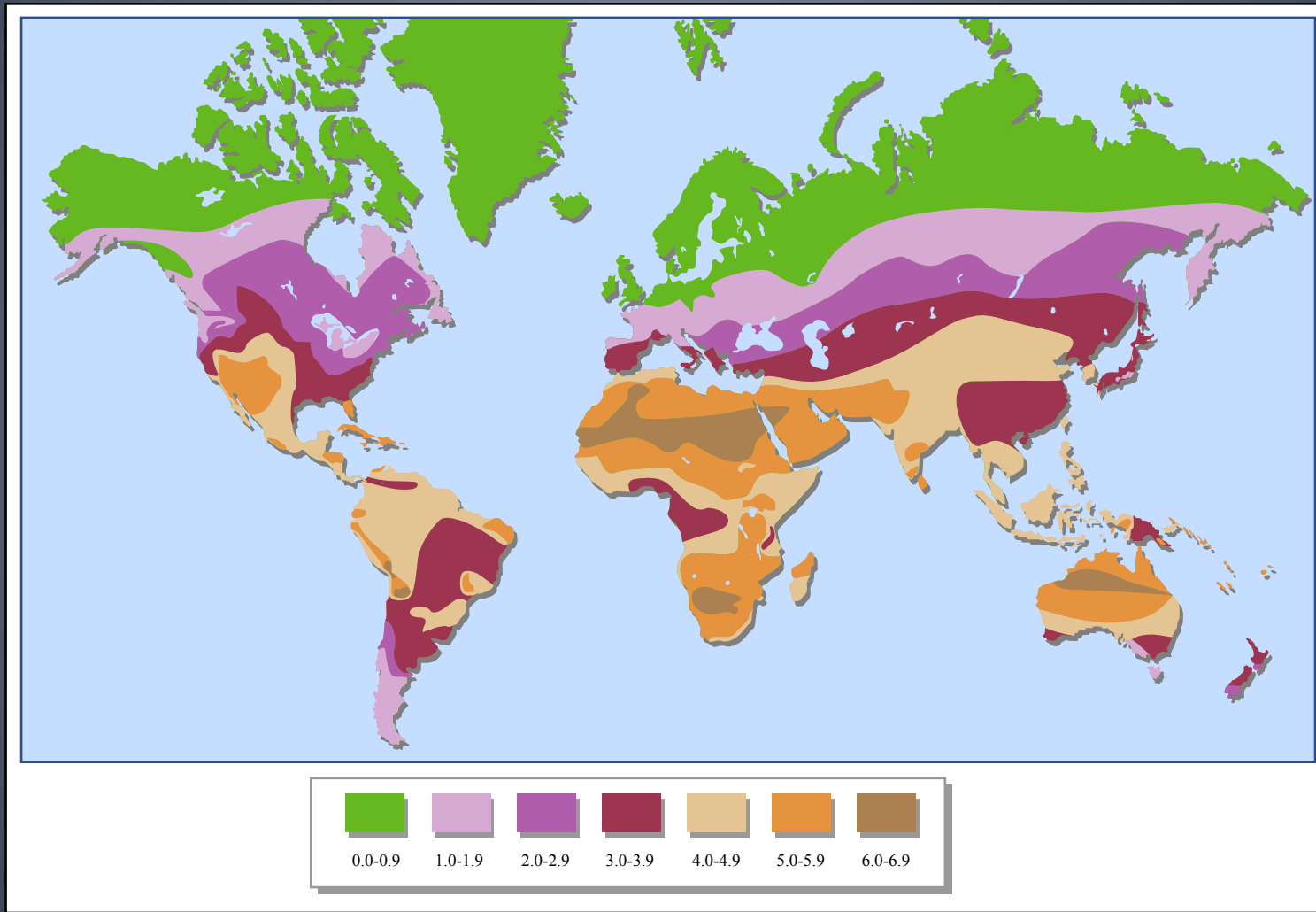
Figure by MIT OpenCourseWare.

# Solar Distillation



Sun radiation

Product

Brine

Water vapor

Feed seawater
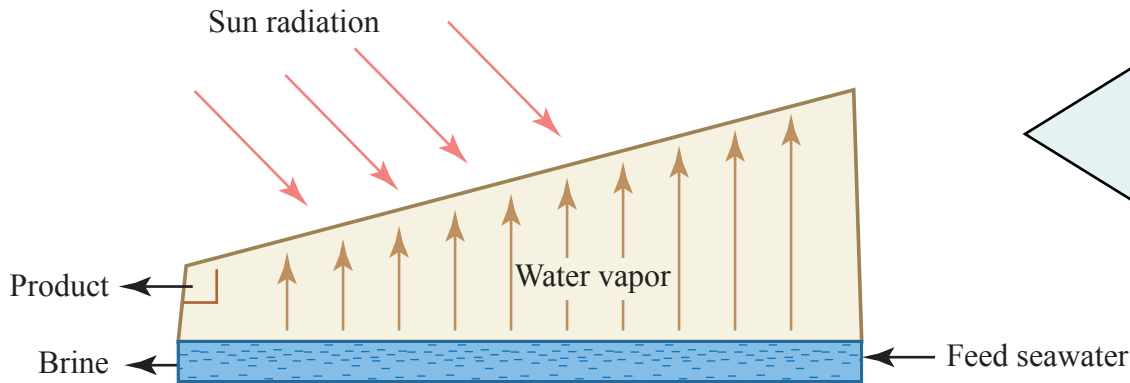
**Schematic of simple solar still.**

Figure by MIT OpenCourseWare.

*Optimally bad?*

~ 1 L/m²-day



Solar radiation

Reflection

2nd cover

1st cover

Absorber plate

Bond

Tube

Insulation
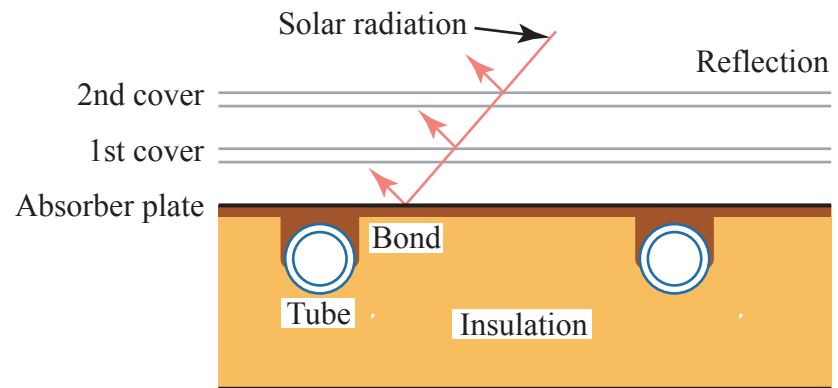
**Sheet-and-tube solar collector.**

Figure by MIT OpenCourseWare.

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

69

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

Humidification-Dehumidification Desalination (HDH)

Air heating, open cycle

Preheated seawater

Humidifier

Warm humid air

Dehumidifier

Condensate

Dry air in

Solar Collector

Brine out

Cold seawater in

Air out
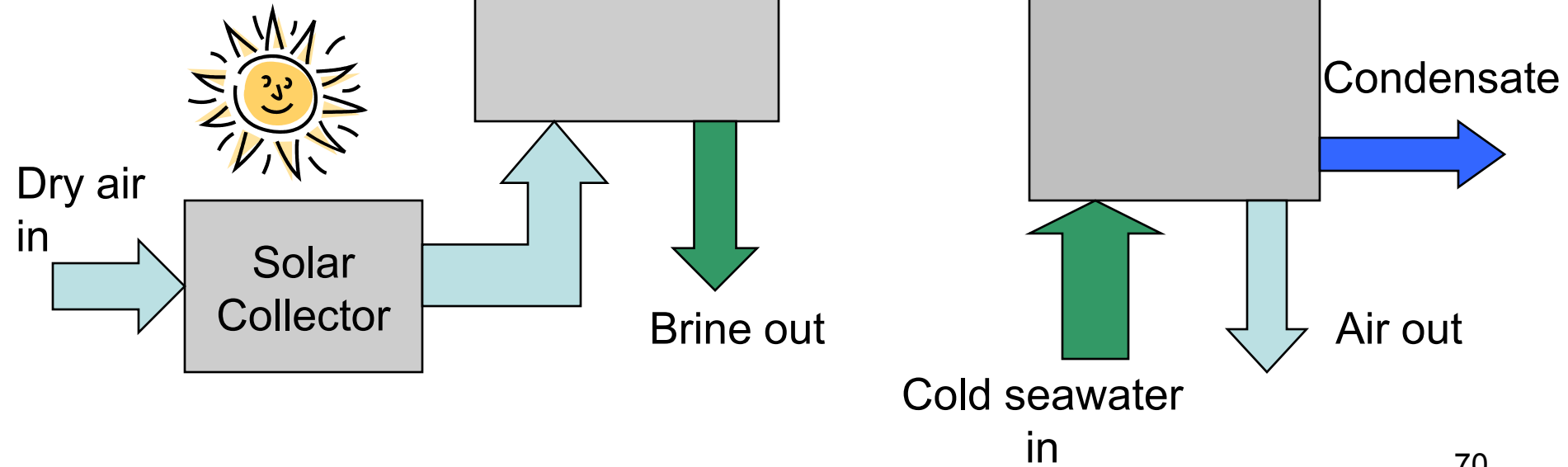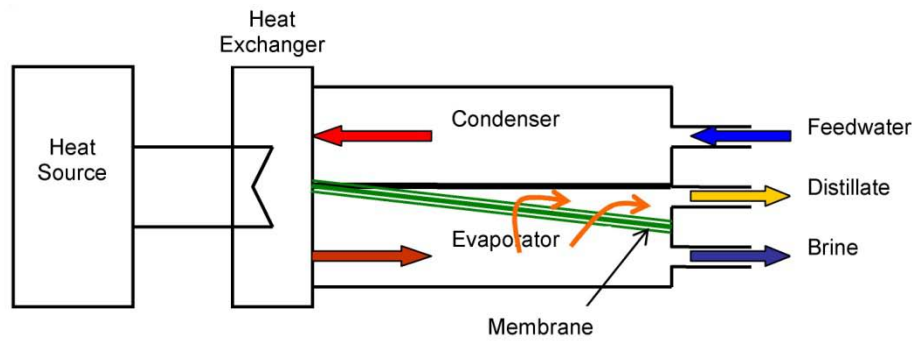
Fig. 1. Membrane distillation principles.

~4 L/m²-day

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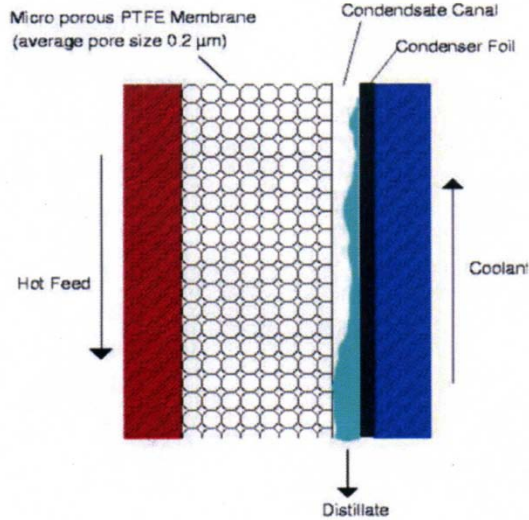


Fig. 1. Principle of membrane distillation.



| DFM | Distillate Flow Meter |
| FFM | Feed Flow Meter |
| FP | Feed Pump |
| RP | Refilling Pump |
| TS | Thermostat |
| V | Valve |

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

# Concentrating solar power…





Images by NREL and Schlaich Bergermann und Partner,
from Wikimedia Commons, http://commons.wikimedia.org

## …achieves higher *T* and higher thermodynamic efficiency

## Linear Fresnel Concentrating Solar Thermal Collector



solar beam radiation · receiver tube · Fresnel Reflector Panels · Animation by FhG-ISE
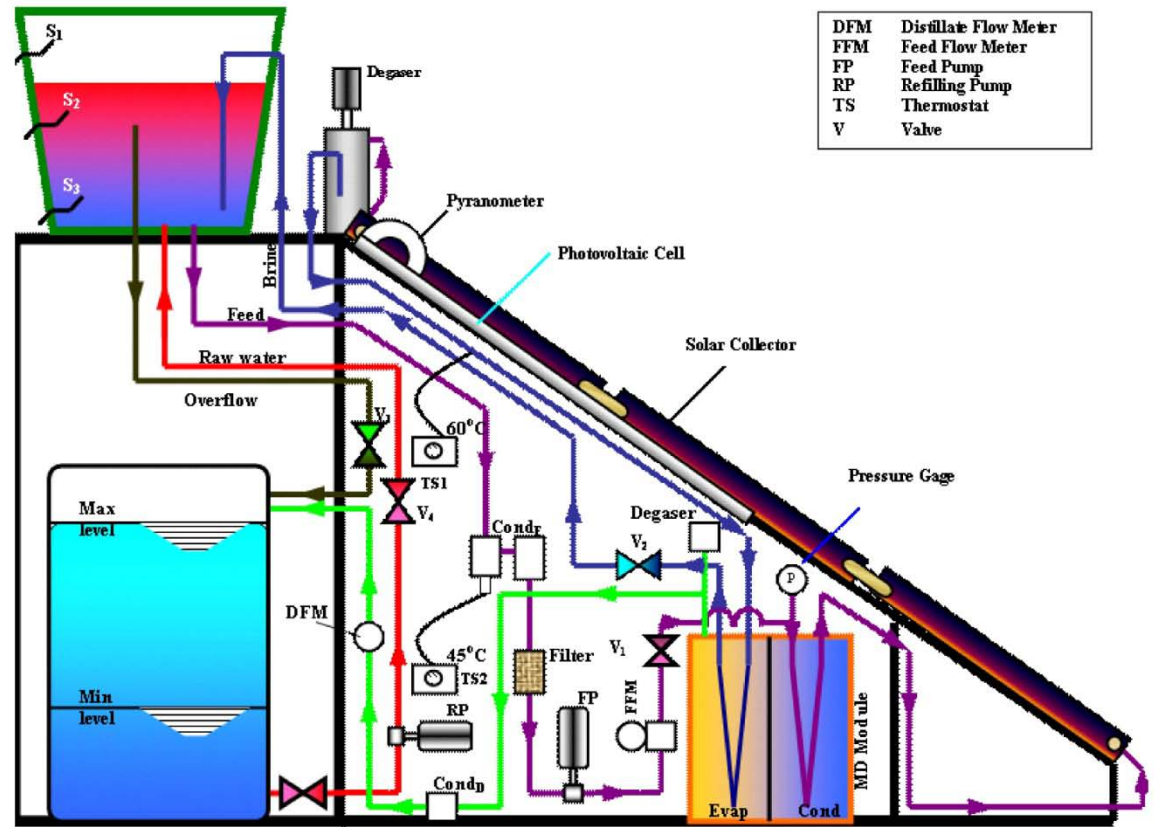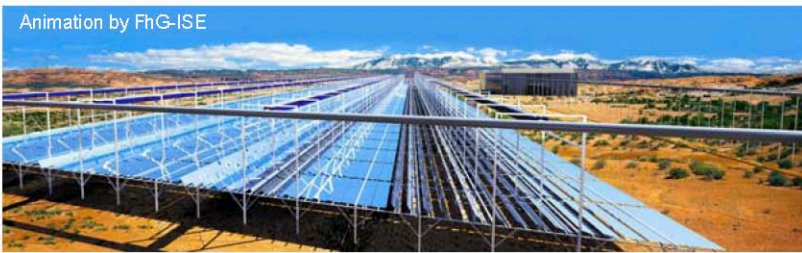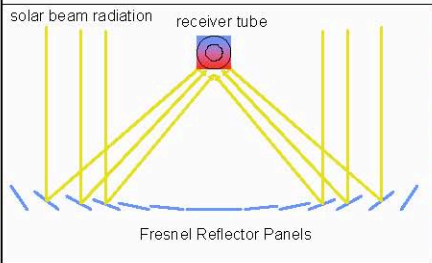
## Parabolic Trough Concentrating Solar Thermal Collector



direct solar beam radiation · receiver · reflector · Parabolic Trough Reflector · Photo by KJC

Courtesy of Franz Trieb and DLR. See
www.dlr.de/tt/aqua-csp. Used with permission.
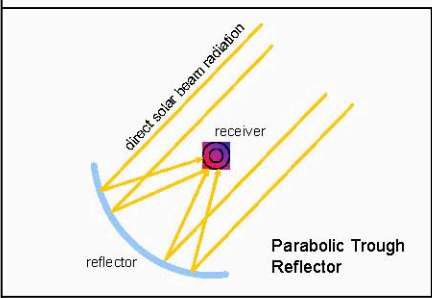
Concepts from concentrating solar power can be applied to solar distillation…generate electricity, then make water from waste heat or electricity

…theoretical performance can be ~100X better than solar still
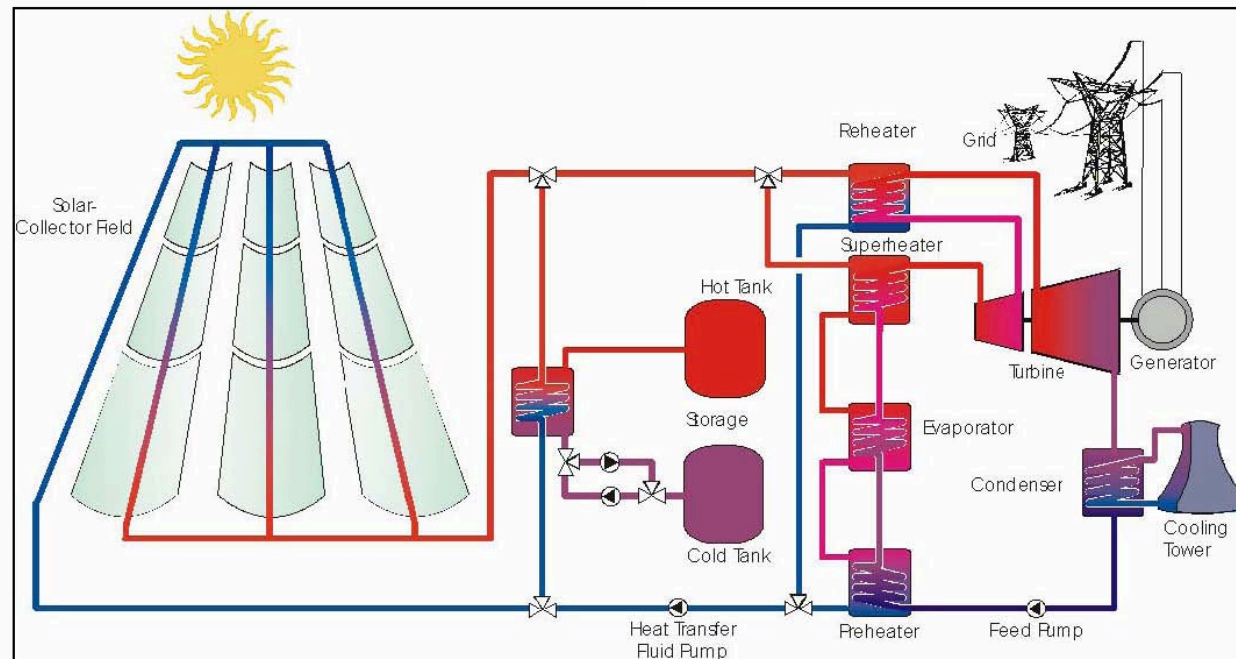
*Ref:* Trieb et al., Nov. 2007

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



Solar-Collector Field · Reheater · Grid · Superheater · Hot Tank · Turbine · Generator · Storage · Evaporator · Condenser · Cold Tank · Cooling Tower · Heat Transfer Fluid Pump · Preheater · Feed Pump

# Combined concentrating solar power and desalination
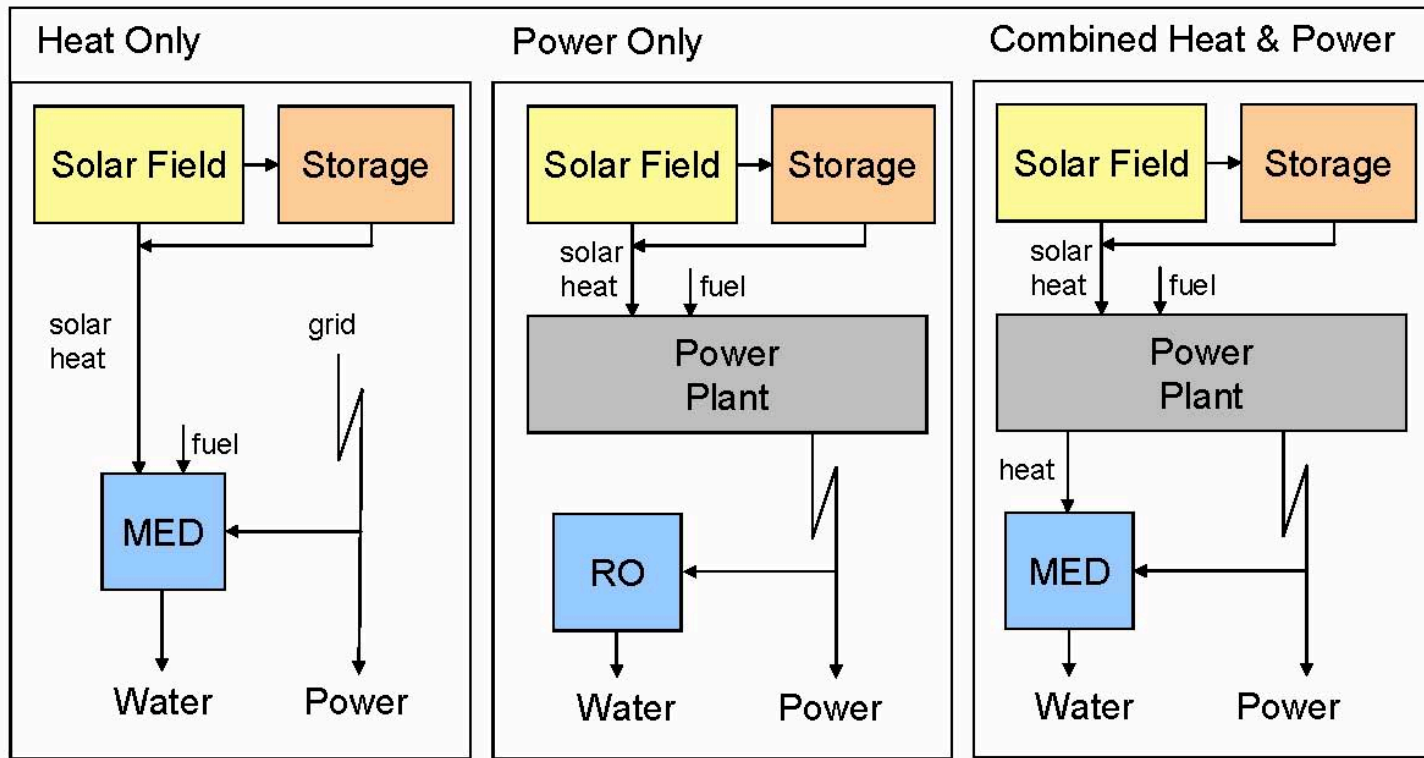


Courtesy of Franz Trieb and DLR. See www.dlr.de/tt/aqua-csp. Used with permission.

Performance of 35 to 185 L/m²-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 (Mm³/d) | 13 | 2 | 0.6 | 6 |
| Heat Consumption (kJ/kg) | **250 – 330** | 145 - 390 | -- | -- |
| Electricity Consumption (kWh/m³)* | **3 - 5** | 1.5 - 2.5 | **8 - 15** | 2.5 - 7 |
| Plant Cost ($/m³/d)** | **1500 - 2000** | 900 - 1700 | **1500 - 2000** | 900 -1500 |
| Time to Commissioning (months) | 24 | 18 - 24 | 12 | 18 |
| Production Unit Capacity (m³/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 |

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

*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 | | |

Courtesy of Sandia National Labs. Used with permission.

*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.

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