# Optimal Planning and Design of Seawater Reverse Osmosis Plants.
# A Holistic Approach

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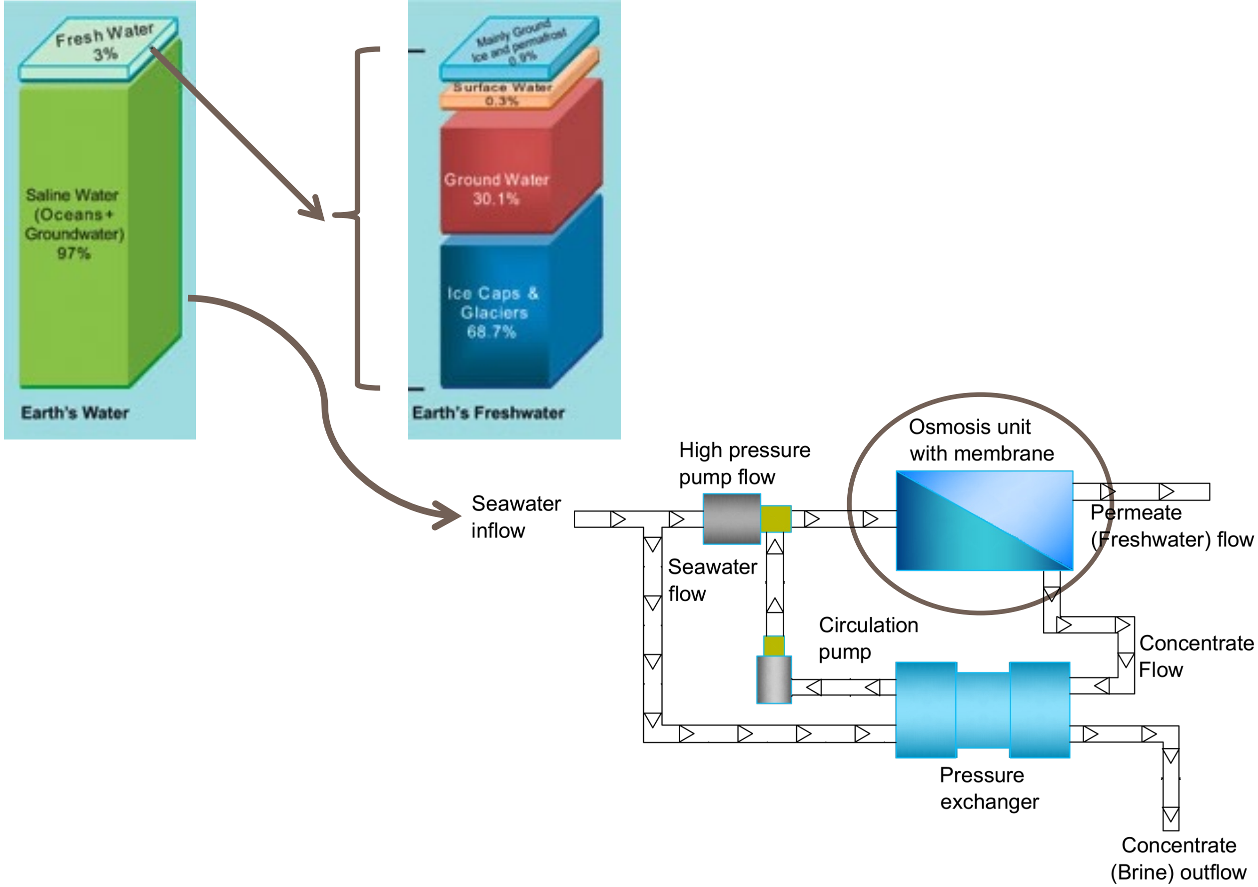
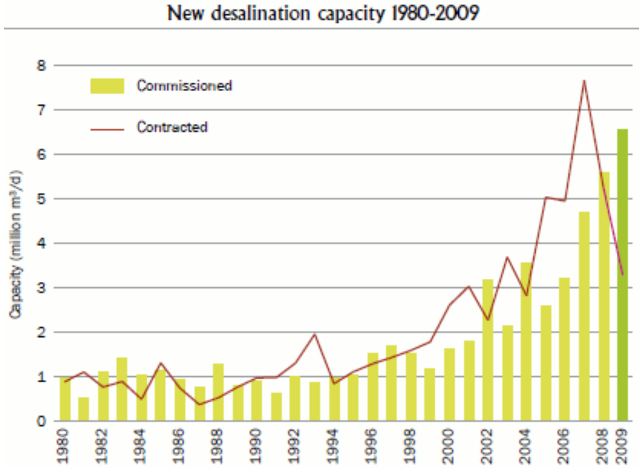
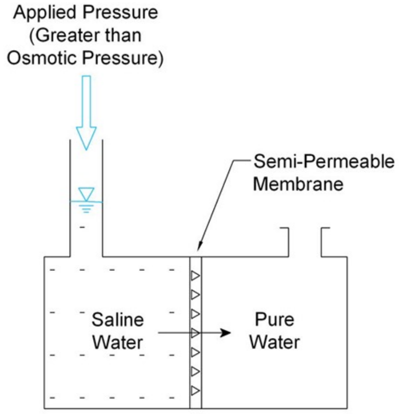
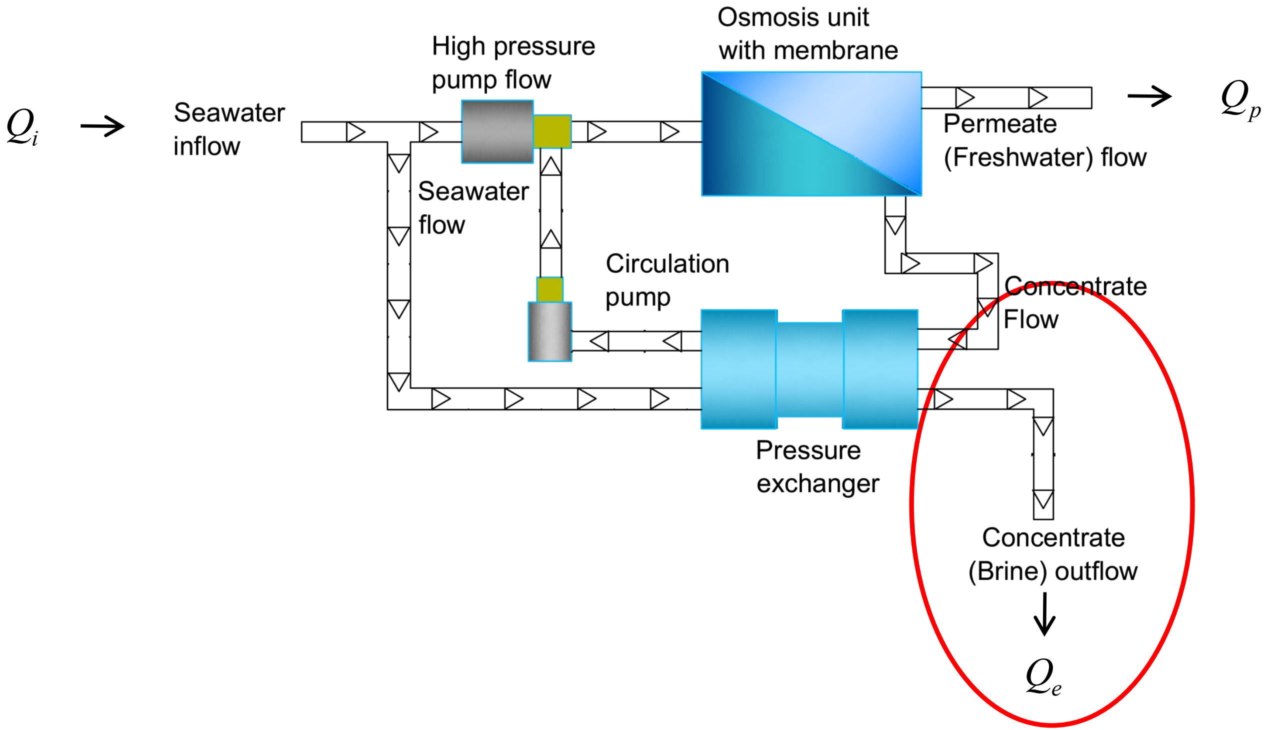
# Background


Fresh Water
3%
Saline Water
(Oceans+
Groundwater)
97%
Earth's Water
Mainly Ground
ice and permafrost
0.9%
Surface Water
0.3%
Ground Water
30.1%
Ice Caps &
Glaciers
68.7%
Earth's Freshwater
Seawater
inflow
High pressure
pump flow
Osmosis unit
with membrane
Permeate
(Freshwater) flow
Seawater
flow
Circulation
pump
Concentrate
Flow
Pressure
exchanger
Concentrate
(Brine) outflow


New desalination capacity 1980-2009
Commissioned
Contracted
Capacity (million m³/d)
0
1
2
3
4
5
6
7
8
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2009


Applied Pressure
(Greater than
Osmotic Pressure)
Semi-Permeable
Membrane
Saline
Water
Pure
Water


$Q_i$
Seawater inflow
High pressure pump flow
Osmosis unit with membrane
$Q_p$
Permeate (Freshwater) flow
Seawater flow
Circulation pump
Concentrate Flow
Pressure exchanger
Concentrate (Brine) outflow
$Q_e$

# Effluent Flow Computations

Influent, Permeate and Brine Flow Rates

$$R_w = \frac{Q_P}{Q_i} \quad \text{and} \quad Q_i = Q_e + Q_P$$

$$\text{or,} \quad Q_P = Q_i - Q_e$$

where

$R_w$ = water recovery rate [-];
$Q_e$ = brine (concentrate ) flow rate [$L^3T^{-1}$];
$Q_i$ = intake (feed) flow rate [$L^3T^{-1}$];
$Q_P$ = permeate (fresh/produced) flow rate [$L^3T^{-1}$].

Example:

$Q_i$ = 2,000 gpm (0.1262 m$^3$/s);
$R_w$ = 50%;

$$R_w = 1 - \frac{Q_e}{Q_i}$$

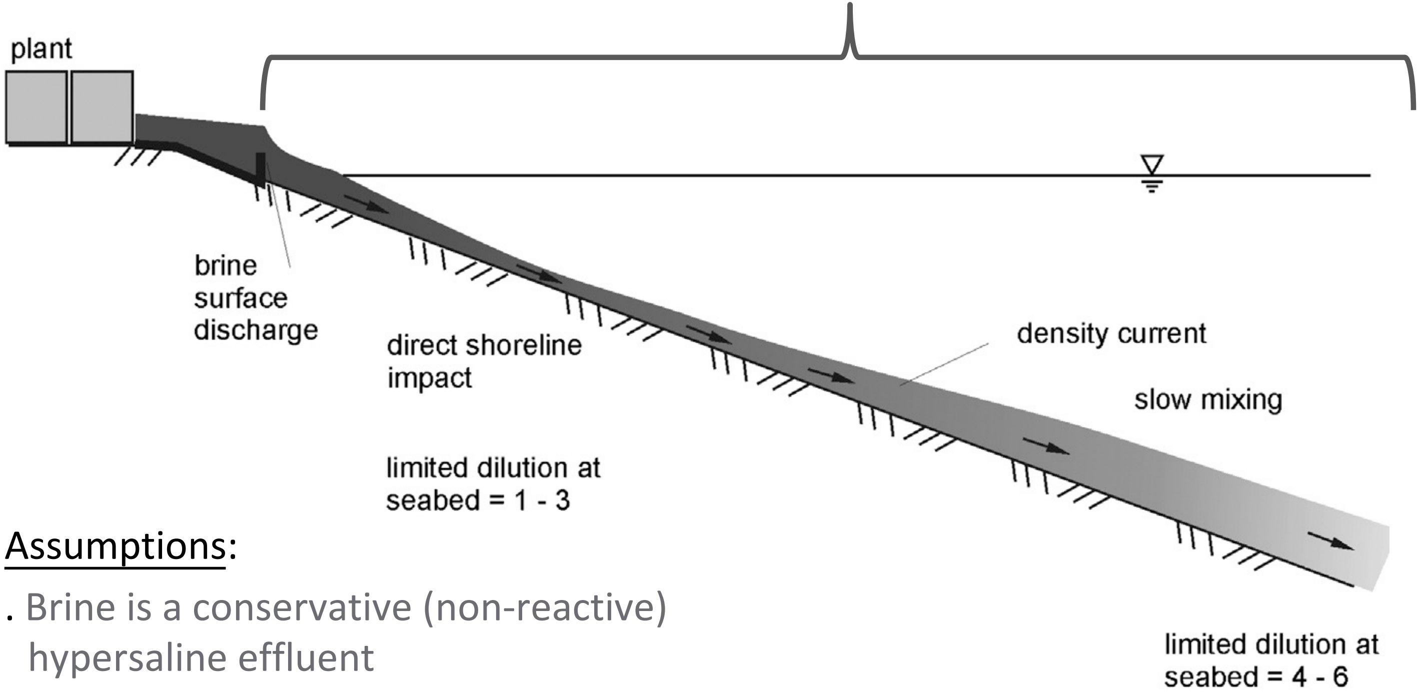
$$Q_e = Q_i(1 - R_w)$$

$Q_e$ = 2,000 (1-0.5) = 1,000 gpm
$Q_e$ = 0.0631 m$^3$/s

$Q_p$ = 0.5 x $Q_i$ = 1,000 gpm (0.0631 m$^3$/s)

$$\boxed{\begin{array}{c} \rho_e > \rho_a \\ \bar{S}_e \gg \bar{S}_a \end{array}}$$

# Impacts of surface discharge on coastal water quality



## Assumptions:

. Brine is a conservative (non-reactive)
  hypersaline effluent

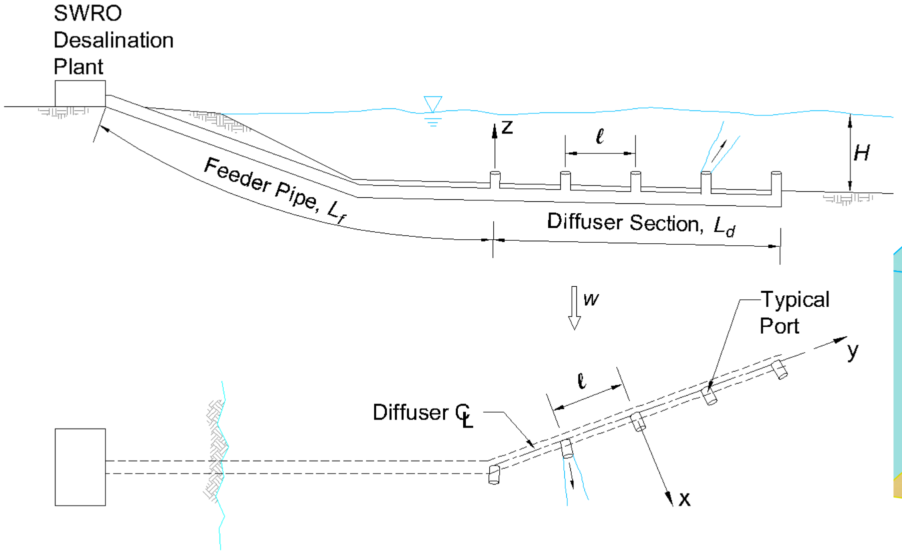
. It is an incompressible, Newtonian fluid

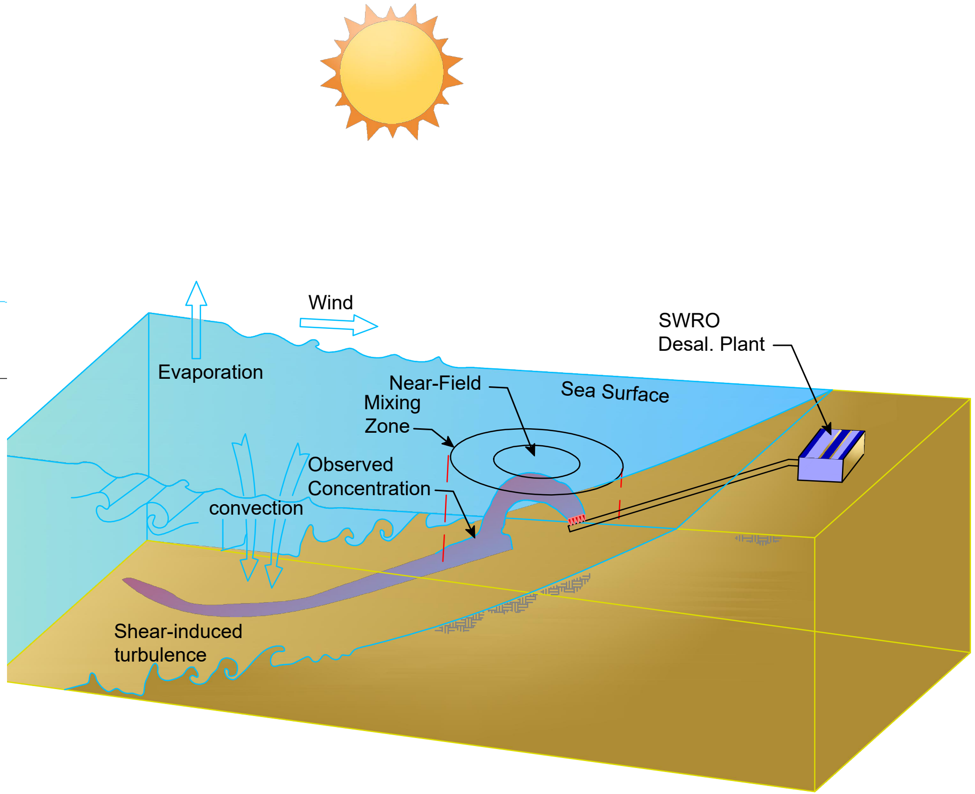
. Steady-state flow

Surface discharge
(Al Ghubrah Plant, Oman)

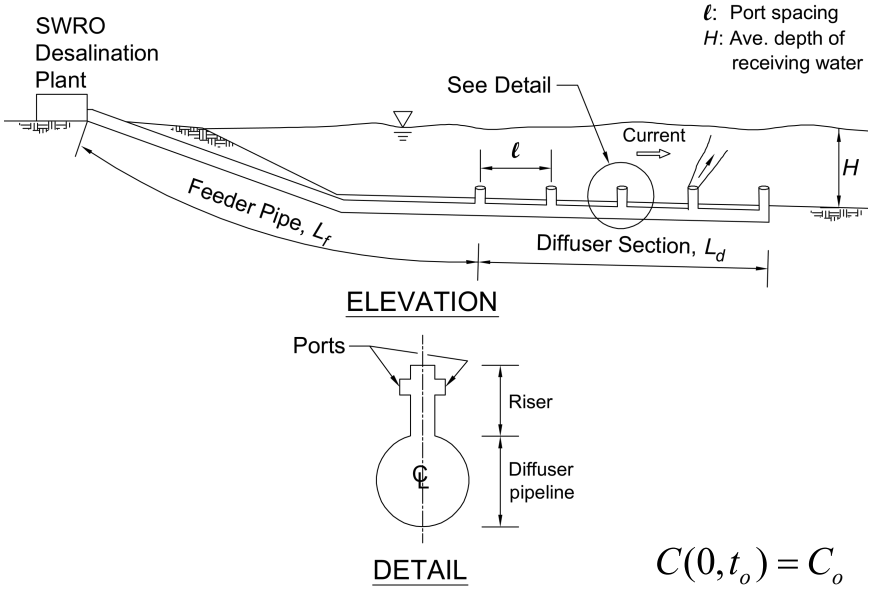
Surface discharge
(Ashkelon Plant, during a backwash)

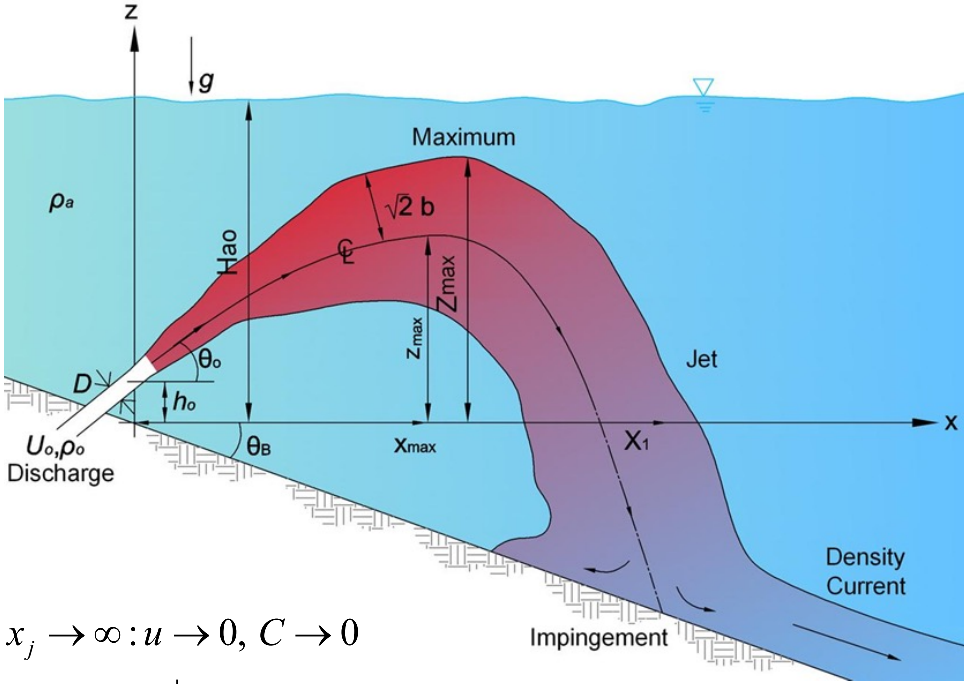
# To minimize the impact…





# To minimize the impact…





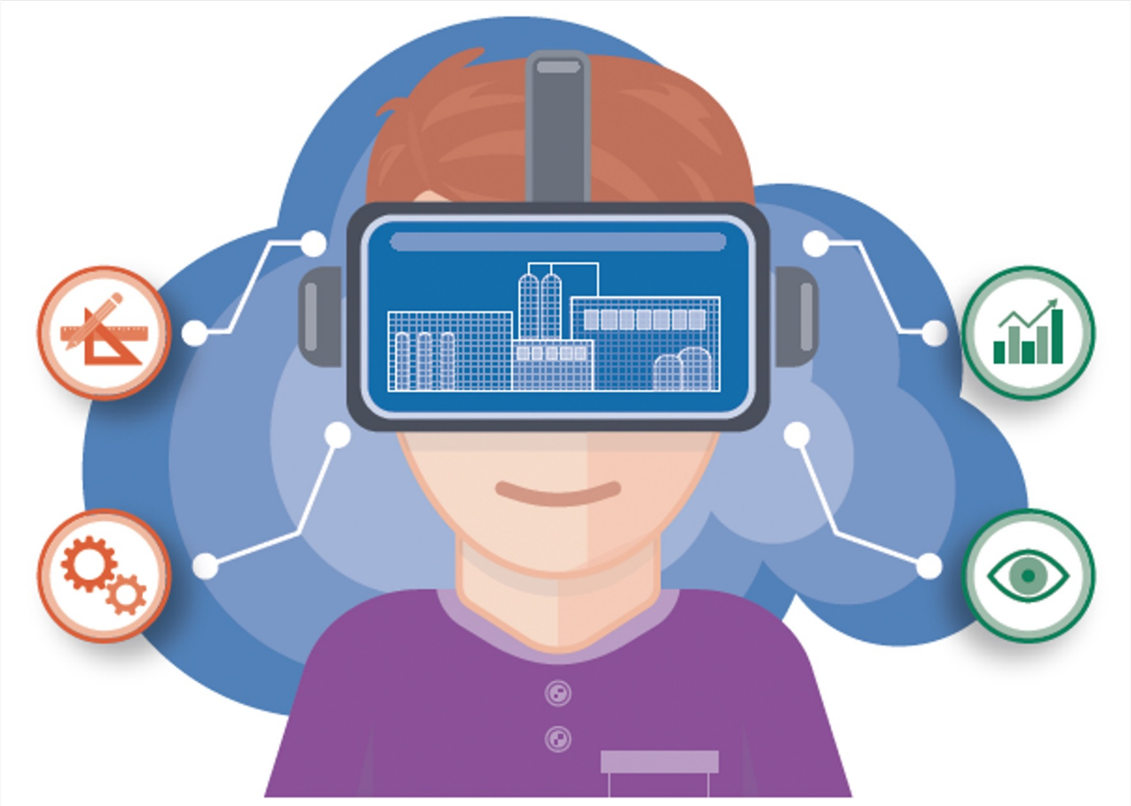
$$C(0,t_o)=C_o$$

$$u(0,t_o)=u_o$$

$$v(0,t_o)=v_o$$

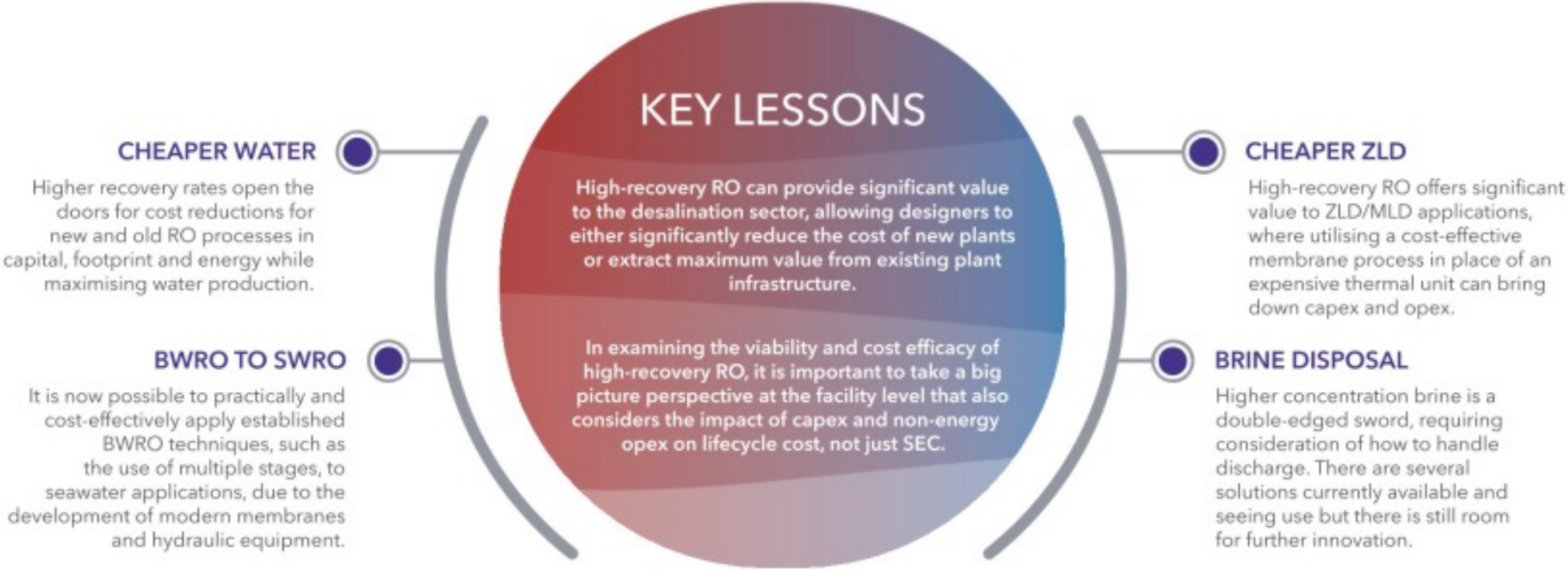
$$x_j\rightarrow\infty : u\rightarrow 0,\ C\rightarrow 0$$

$$\left.\frac{\partial C}{\partial x_j}\right|_B = 0$$



(Credit: GWI 2022)

# State-of-the-Art Summary



## KEY LESSONS

High-recovery RO can provide significant value to the desalination sector, allowing designers to either significantly reduce the cost of new plants or extract maximum value from existing plant infrastructure.

In examining the viability and cost efficacy of high-recovery RO, it is important to take a big picture perspective at the facility level that also considers the impact of capex and non-energy opex on lifecycle cost, not just SEC.

### CHEAPER WATER

Higher recovery rates open the doors for cost reductions for new and old RO processes in capital, footprint and energy while maximising water production.

### BWRO TO SWRO

It is now possible to practically and cost-effectively apply established BWRO techniques, such as the use of multiple stages, to seawater applications, due to the development of modern membranes and hydraulic equipment.

### CHEAPER ZLD

High-recovery RO offers significant value to ZLD/MLD applications, where utilising a cost-effective membrane process in place of an expensive thermal unit can bring down capex and opex.

### BRINE DISPOSAL

Higher concentration brine is a double-edged sword, requiring consideration of how to handle discharge. There are several solutions currently available and seeing use but there is still room for further innovation.

(Credit: GWI 2022)

Minimize: Cost

Subject to:

a. Initial Dilution (Length of Outfall, Pipe Diameter, Number of Ports, other drivers)
b. Water Quality Constraints (Mixing Zone)

Area of mixing zone;
Viability of chosen location;
System reliability.

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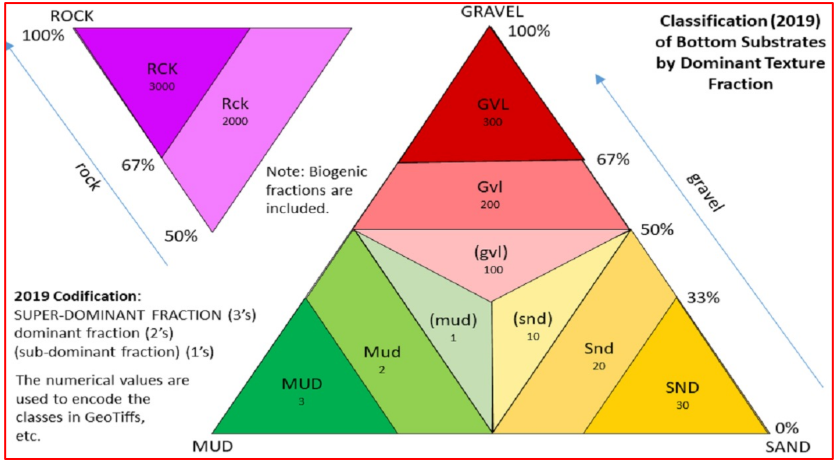
$$\text{Min} \quad Z = \mathrm{w}_1 L + \mathrm{w}_2 D + \mathrm{w}_3 N$$

Subject to: a. Initial Dilution

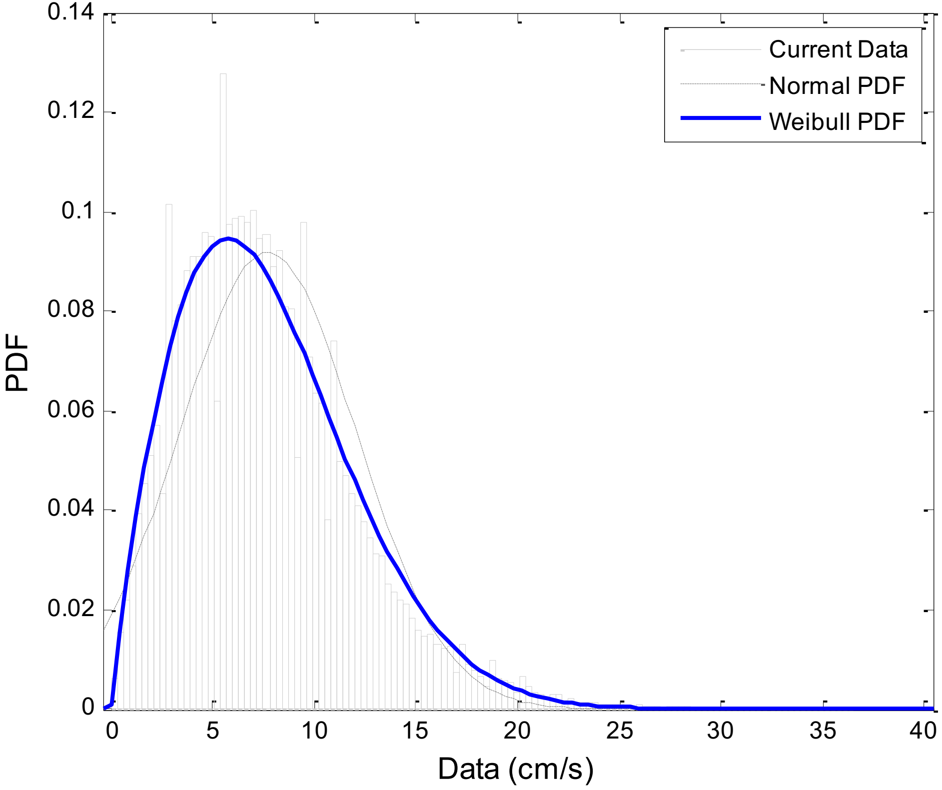
$$\left\{ \begin{array}{l} S \geq S_{rid} \\ S = f(L, D, N, \ldots) \\ S = f(x, \xi) \\ L_p^l \leq L_p \leq L_p^u \qquad \forall p \\ D_m^l \leq D_m \leq D_m^u, \qquad m \in \mathbb{Z}^+ \\ N_n^l \leq N_n \leq N_n^u, \qquad n \in \mathbb{Z}^+ \end{array} \right.$$

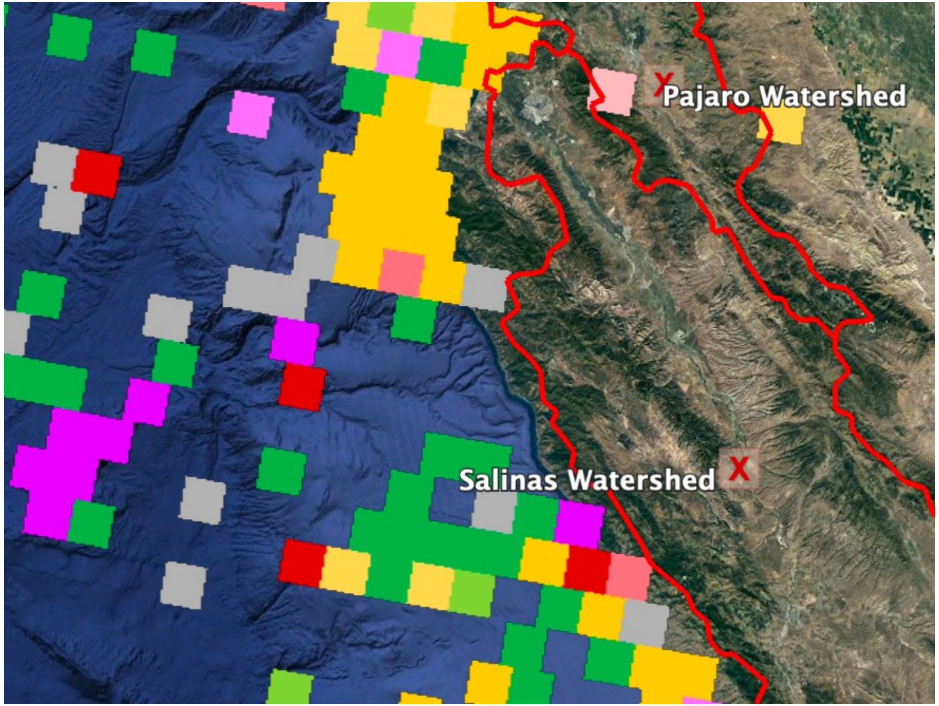


b. Water Quality Constraint

$$C_e \leq C_{rr}^{\max}$$

Our Work at CSUN





## Initial Dilution:

$$S = f(x,\xi)$$

$$S = f(L, D, N, w, T, W \ldots)$$

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## Current speed constraint:

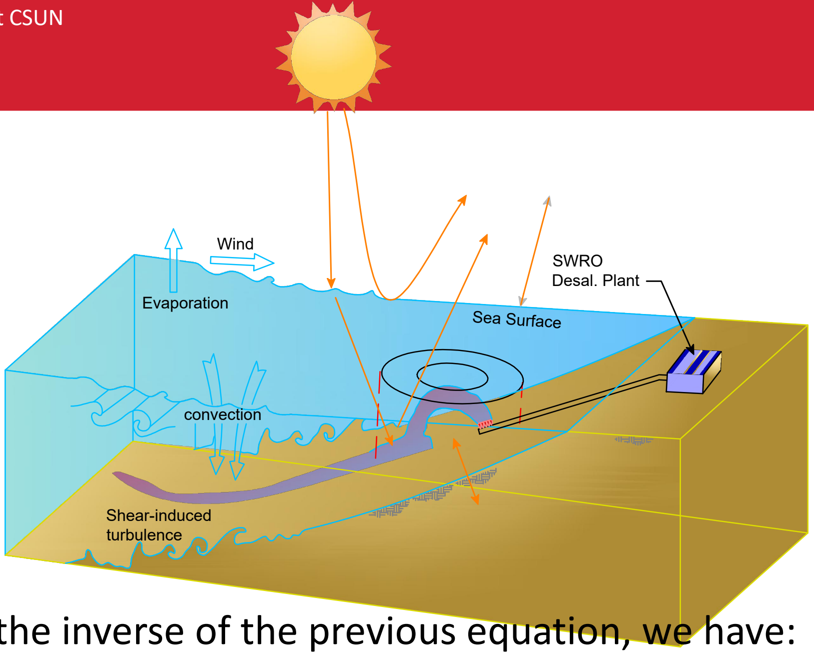
$$\Pr\left\{\overline{w}_i \le \overline{w}_{max_i}\right\} \ge \alpha_i, \quad \forall i$$

$$\alpha_i \in (0,1), \quad \forall i$$

Deterministic equivalent:

$$F_\psi\left(\frac{w_i - E(w_i)}{\left[Var(w_i)\right]^{0.5}}\right) \ge \alpha_i$$

$$F_\psi\left(\frac{w_i - E(w_i)}{\left[Var(w_i)\right]^{0.5}}\right) \le 1 - \alpha_i$$



Taking the inverse of the previous equation, we have:

$$w_i \le E(w_i) + \left(F_\psi^{-1}(1-\alpha_i)\right)\left[Var(w_i)\right]^{0.5}$$

Replacing $w_i$ with $\overline{w}_i$ we have:

$$\boxed{\overline{w} = \overline{w}_{max} - \left(F_\psi^{-1}(\alpha)\right)\left[Var(w)\right]^{0.5}}$$