State of the Art of Model Based Research in Seawater Desalination

Iqbal M Mujtaba
School of Engineering, University of Bradford
UK

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MT Sowgath, K Al-Ameri, A Villafafila, N Al-Nahari, E. Hawaidi,

S.A. Said, S. Alsadaie, G. Patroklou

Outlines

Introduction

Desalination Processes

State of the Art (MSF – Thermal)

Future Challenges and Opportunities

INTRODUCTION: Importance of Water

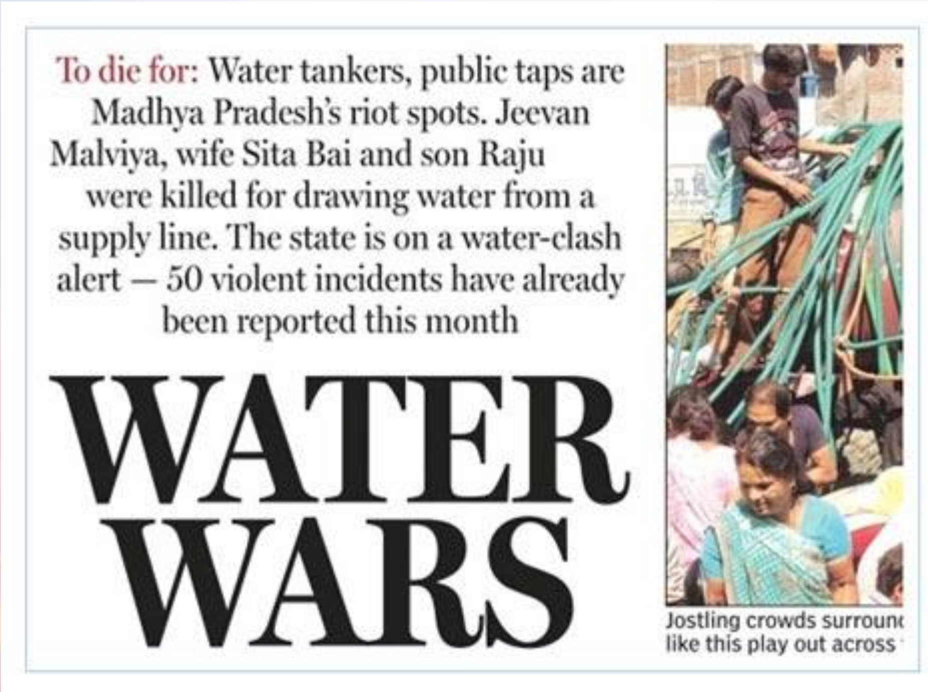
Quality water and quality life go hand in hand. The food we eat, the house we live in, the transports we use and the things we cannot do without in 24/7/365 determine our quality of life and require sustainable and steady water supplies [Technical Roadmap, IChemE, 2007] .

China (2006). 2.4 million people affected

Kenya: drought stricken in February 2006

India: struggle for freshwater (regular event)

Source: http://www.guardian.co.uk/gallery/2007



To die for: Water tankers, public taps are Madhya Pradesh's riot spots. Jeevan Malviya, wife Sita Bai and son Raju were killed for drawing water from a supply line. The state is on a water-clash alert — 50 violent incidents have already been reported this month

WATER WARS

Jostling crowds surroun
like this play out across

25 May 2009: http://www.treehugger.com/clean-water/violence-over-water-already-happening-in-india.html

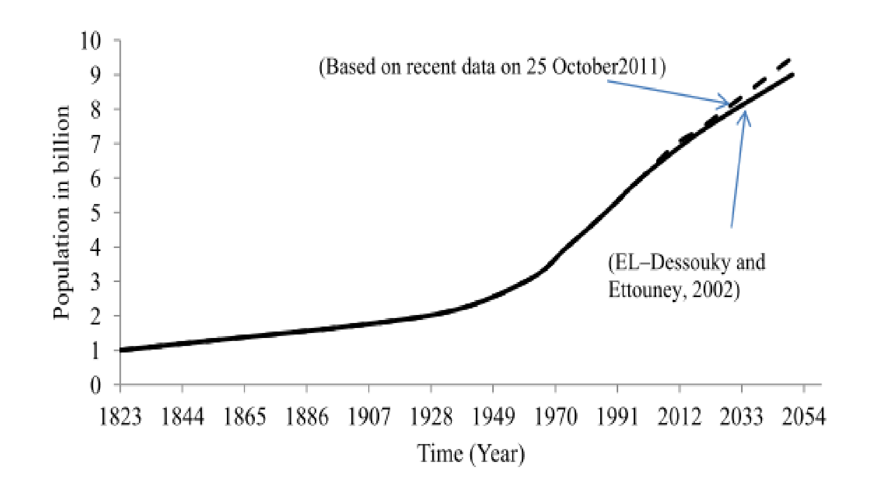
9 May 2012: http://www.rainharvest.co.za/2012/05/africa-u-s-response-to-future-water-crisis-takes-shape/

Without more effective water management systems, lack of water availability will become a problem threatening national security in many countries important to the United States – US Intelligence (9 May 2012)

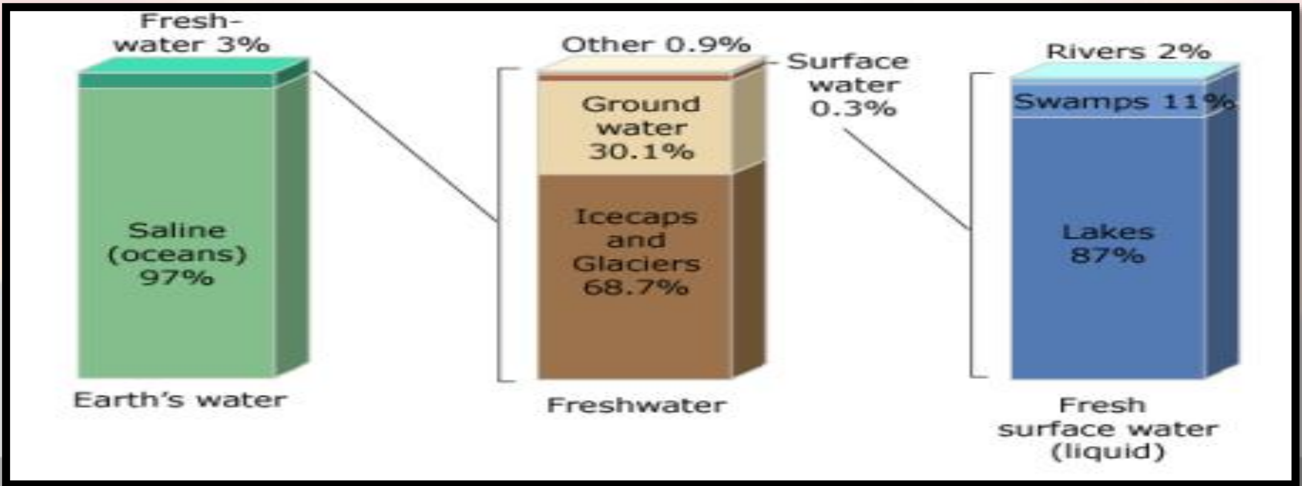
INTRODUCTION: Water Use and Source

- Increase in population
- Increase in standards of living
- Increase in water demand
- Increase in water pollution
- Only limited resources of freshwater

Freshwater consumption is increasing at the rate of 4-8%/yr, 2.5-times the population growth [Lior, 2006]



1804 – 1 billion: 1927 – 2 billion [El-Dessouky and Ettouney, 2002]
2011 – 7 billion



INTRODUCTION: What Do We Do?

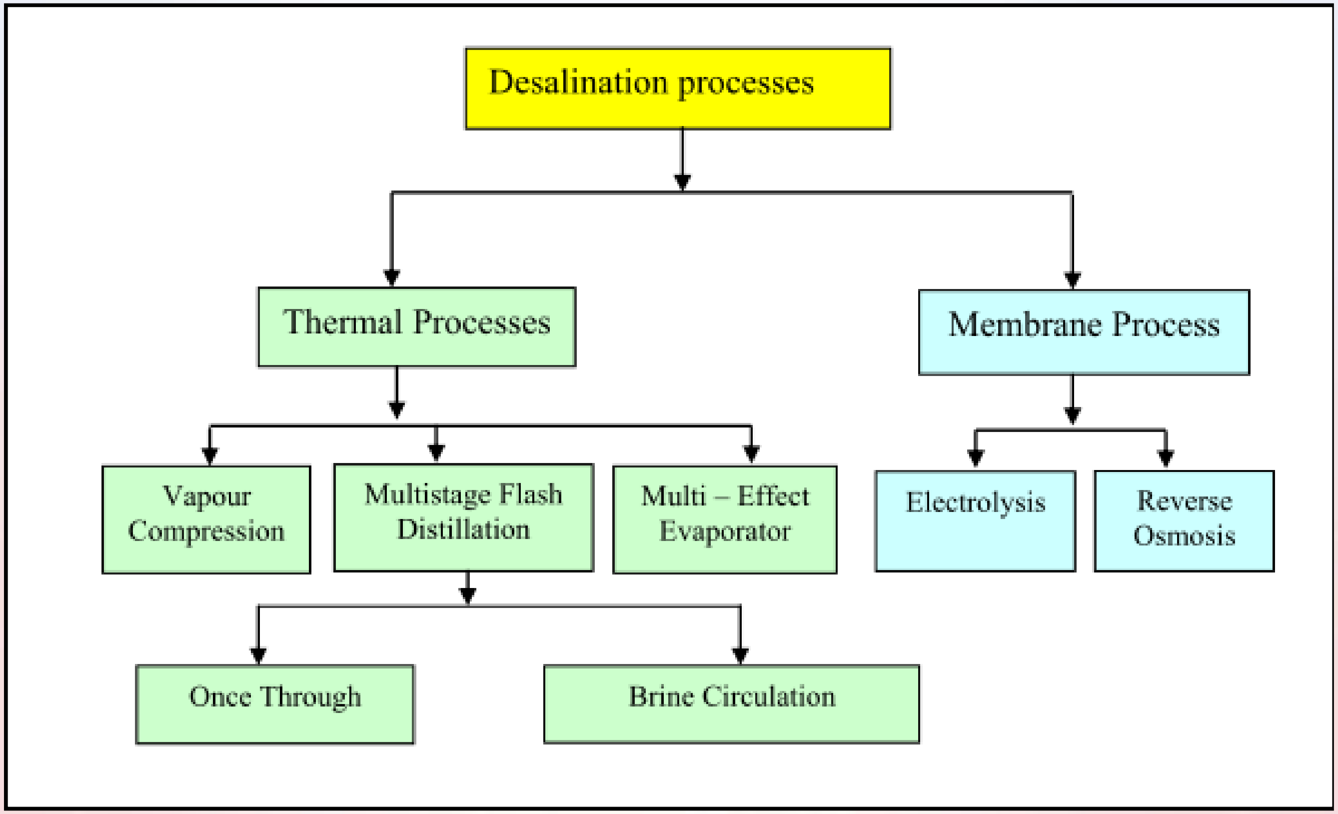
Certainly we do not want to resort to 70% locked up glacial ice, permafrost, or permanent snow.

The alternative is desalination of huge amount of saline water around us.

Different desalination processes are around us for many decades. The questions are:

- Are these energy efficient ?
- Cost effective?
- Environment friendly?

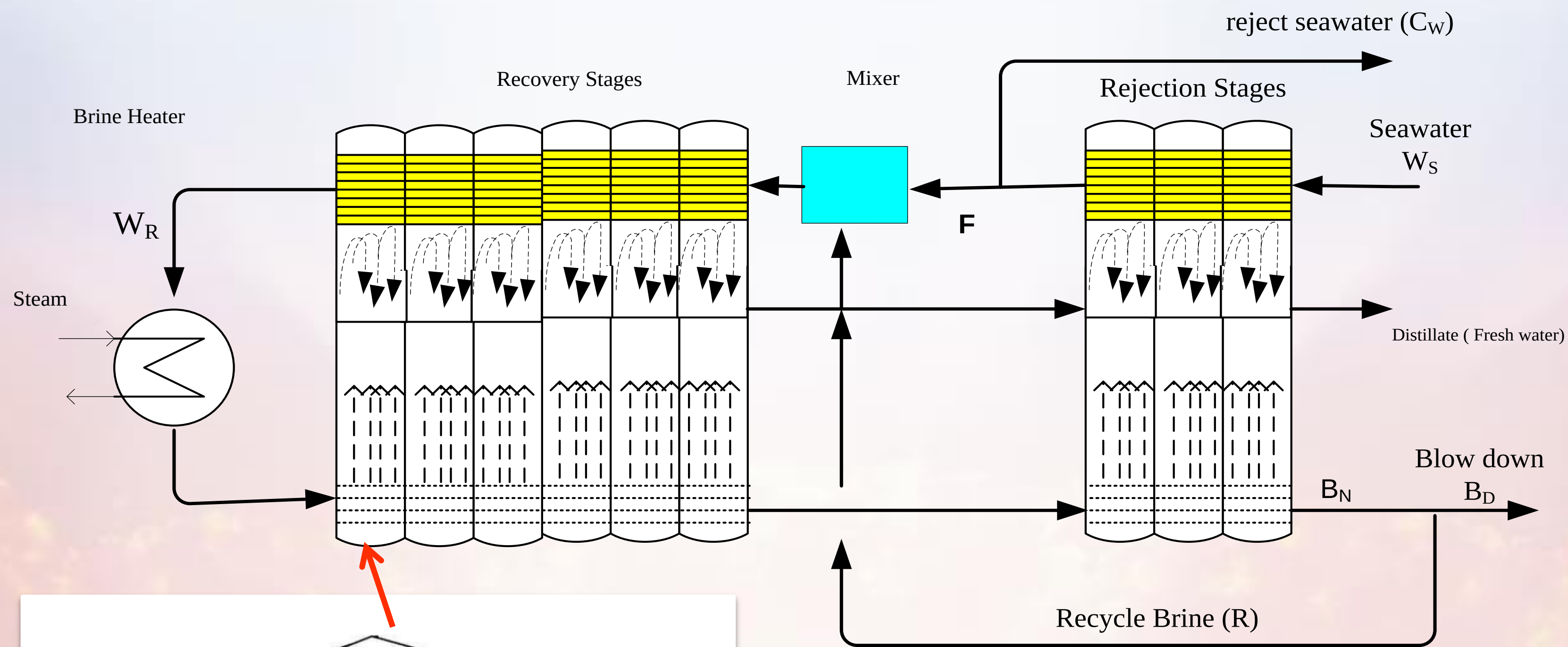
DESALINATION PROCESSES: Different Types

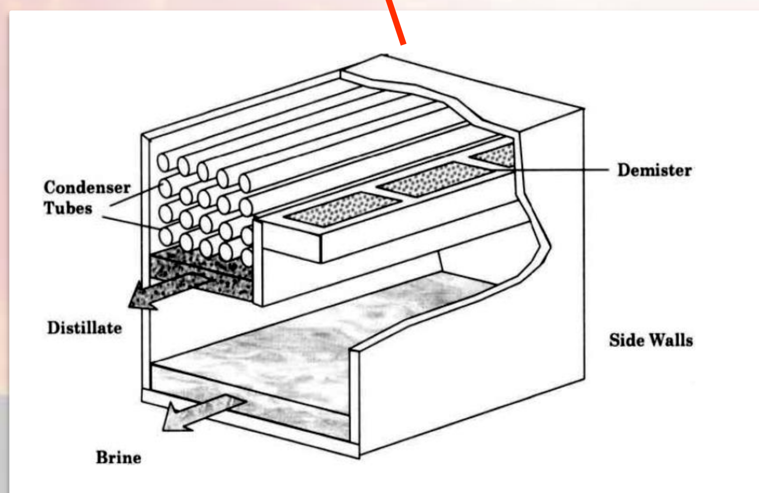


- MSF is the dominant thermal processes
- RO is the dominant membrane process.

MSF: 9 $/m3 (1955) to 1.044 $/m3 (2001) to 0.5 $/m3 (2007)
RO: ~ 3.5 $/m3 (1970) to 0.8 $/m3 (2000) to 0.53 $/m3 (2005) (Reddy & Ghaffour, 2007) - to 0.25 $/m3 (Sassi & Mujtaba, 2010)

Thermal Desalination Process: MSF [1950 -]





Many alternative configurations possible depending on the way the seawater is fed, brine is recycled

[Spiegler, 1977; El-Dessouky and Ettouney, 2002; Tanvir & Mujtaba, 2008; Hawaidi & Mujtaba, 2011]

CAPE COMMUNITY & MSF DESALINATION

- CAPE community makes extensive use of model based techniques in design, operation, control and synthesis addressing sustainable production of goods with minimum environmental impact.

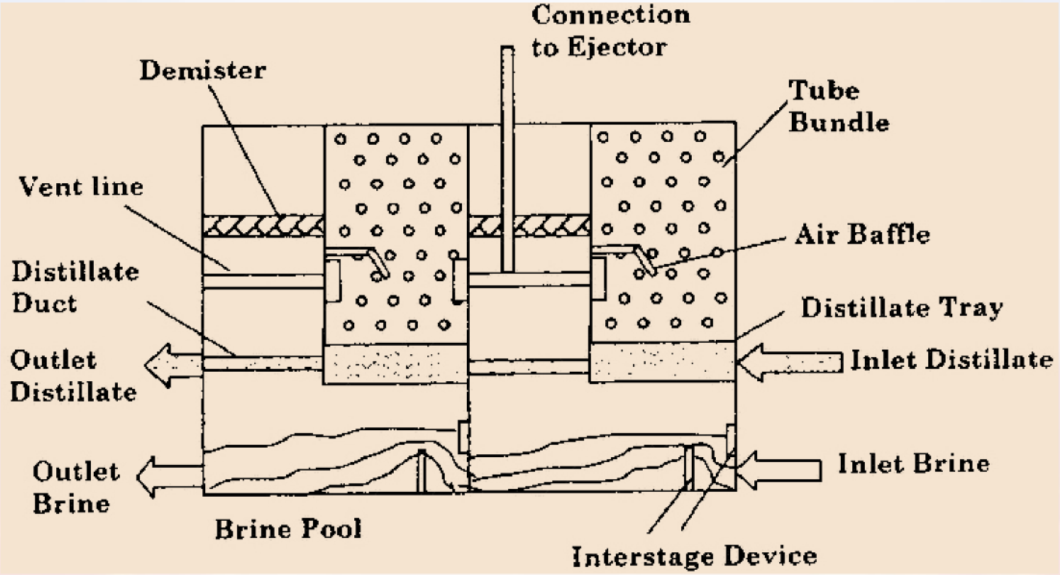
- The yearly event of ***European Symposium on Computer Aided Process Engineering*** (since 1992) and 3-yearly event of ***International Symposium on Process Systems Engineering*** (since 1985) and the ***Computers and Chemical Engineering Journal*** (published by Elsevier since 1979) cover design, operation, control, process integration of **many processes but desalination (very limited)**.

MSF DESALINATION IN PUBLIC DOMAIN

- Flash distillation existed from the beginning of the century
- Office of Saline Water, USA established in 1952 to develop economical flash distillation based desalination process – Cadwallader (1967)
- First patent of MSF process for desalination in 1957 - Silver
- First published paper on MSF process in *Engineering*, 1958 - Silver
- First commercial plant installed and commissioned in 1960 - Silver
- *Desalination* Journal begun in 1966 with first paper on MSF (design and optimisation) – Clelland & Stewart
- First paper in *Ind. Eng. Chem.* in 1967 on MSF (scaling) - Cadwallader
- First paper in *Chem. Eng. Sci.* in 1970 on MSF (optimisation) – Mandil & Ghafour
- First paper in *Comput. Chem. Eng.* in 1986 on MSF (modelling) – Helal et al.

MSF DESALINATION & CAPE COMMUNITY

MSF Process Model



Mass balance Energy Balance Thermal Efficiency

Physical Properties (heat capacity, density, BPE, heat of vaporisation)

HTC (fouling, noncondensables) Pressure/Temperature drop

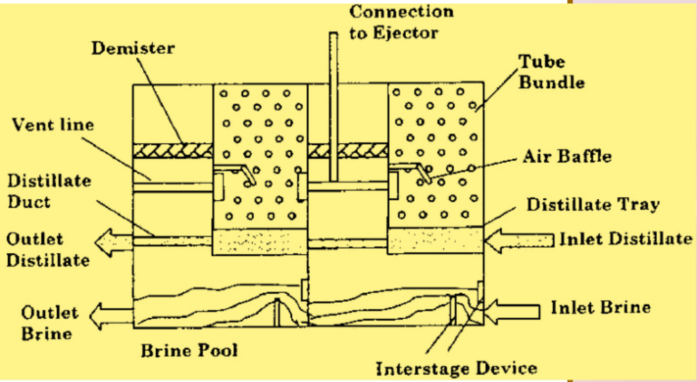
Heater, Demister, Condenser, Stages, Vents (materials, geometry)

Inter-stage flow (orifice) Salt deposition/corrosion (kinetic model)

STATE OF THE ART: MSF Process Model

Helal, Medani, Soliman & Flower, *comput chem eng,* 1986

- Detailed Stage to Stage Model
- Nonlinear BPE correlation and other physical properties as f(T, X)
- Temperature loss due to demister included
- OHTC via polynomial fit (fouling included)
- Very high temperature operation
  (Tsteam = 174 C, TBT = 162.7 C)
- Very high seawater temperature, 63 C
- Model equations linearised for easy solution.



El-Dessouky et al., *Desalination*, 1995

Model based on Helal et al. (1986) but included

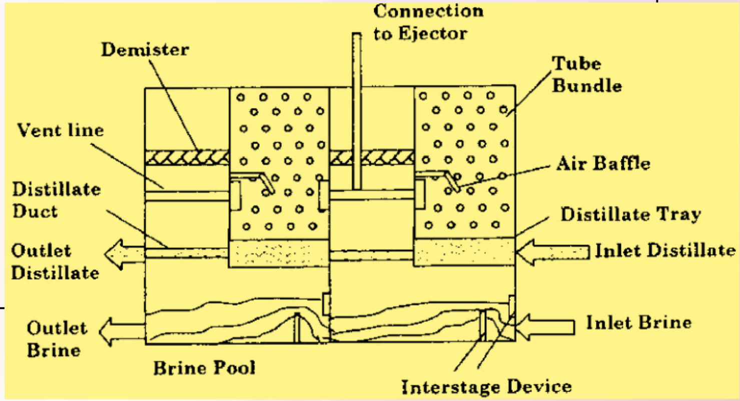
- Heat losses to the surroundings
- Effect of non-condensable gases (air, O_2, CO_2) on heat trans area
- Constant inside/outside tube fouling factors
- Pressure drop across demister
- Constant non-equilibrium allowance (stage thermal efficiency)

STATE OF THE ART: MSF Process Model

Tanvir and Mujtaba, *Desalination*, 2006, 2008; Tanvir and Mujtaba, *ESCAPE-2006 (&PSE), 2007;* Hawaidi and Mujtaba (*ESCAPE-2010*), Said et al. (*ESCAPE-2010*); Hawaidi and Mujtaba (Chem Eng J, 2010; Ind Eng Chem R, 2011)

Model based on Helal et al. (1986) but included

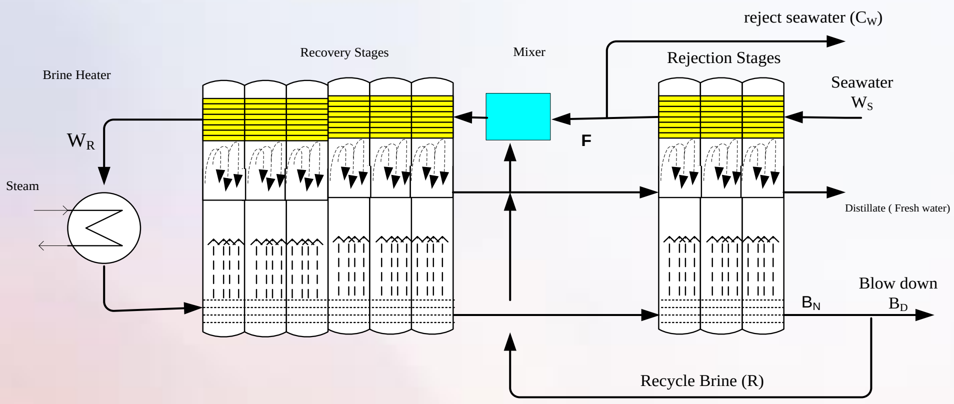
- NN based correlation for BPE calculation.
- Dynamic fouling
- Non-condensable gases on HTC
- Demister fouling

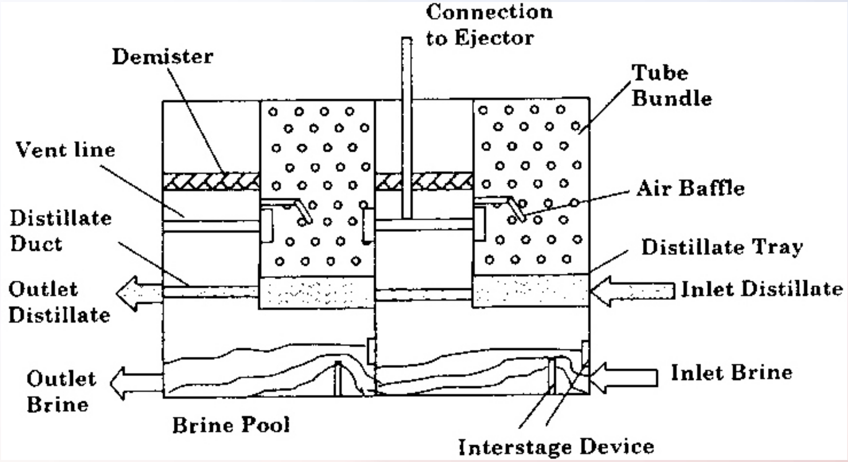


Al-Fulaij, Cipollina, Bogle, Ettouney, *Desalination*, 2011; *Desalination & Water Treatment*, 2011

- Detailed stage modelling
- CFD modelling of demister

USE OF MODEL IN DESIGN AND OPERATION





Basis: Given Freshwater Production Rate, Seawater composition and temperature

Design: Number of stages, Width and height of the stages, Heat transfer area, Materials of construction, Vent line orifice (air and non-condensable), Demister size and materials, inter-stage brine transfer device, Brine heater area

Operation: Steam flow, Top brine temperature, brine recycle, seawater rejection

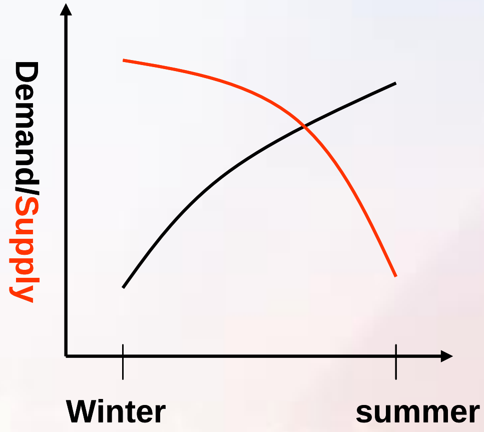
Cost: Capital, Operating (utilities, cleaning), Pre-treatment (chemicals)

[Rosso et al., 1996; El-Dessouky and Ettouney, 2002; Tanvir and Mujtaba, 2006, 2007, 2008]

Model Based Insight - 1

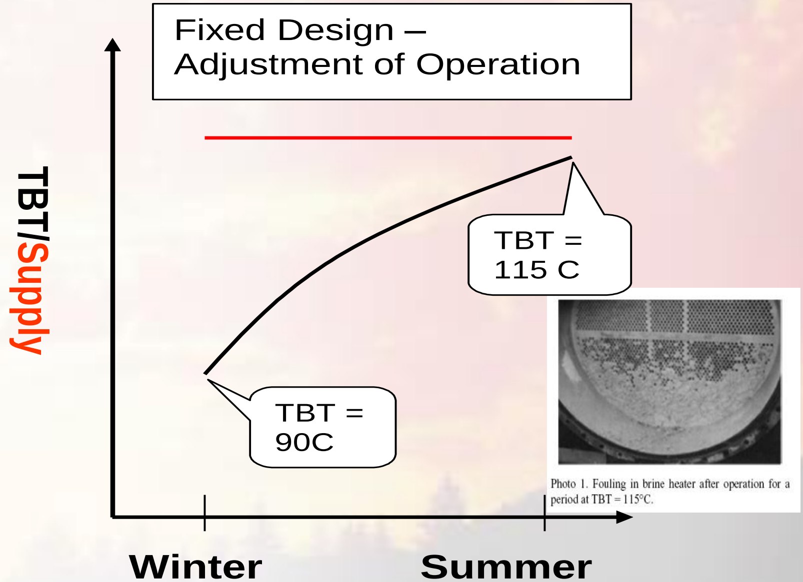
Effect of Seawater Temperature on Water Supply – Tanvir & Mujtaba, *IWC*, 2005; *ESCAPE-2006*

Temp, C	Freshwater, kg/hr	% drop
23 (winter)	1.09E6	-------
35	9.31E5	14.6
45 (summer)	7.88E5	27.7



To supply freshwater at a fixed rate throughout the year or to increase the production at any time of the year, the common industrial practice is to operate the plant at high temperature, leading to more energy consumption and increased environmental impact.

ElMoudir et al., *Desalination*, 2007



STATE OF THE ART: Optimisation

Fixed Freshwater Demand (No fouling, One seawater temperature):

•Qualitative optimisation of large scale MSF, Clelland and Stewart, *Desalination*, 1966

• Quantitative, short-cut model based analytical optimisation, Mandil & Ghafour, *Chem eng Sci*, 1970

• Dynamic Programming based optimisation with simple stage-to-stage model, Coleman, *Desalination*, 1971

• NLP based optimisation with detailed model, Mussati et al., *Desalination*, 2001. NLP based global optimisation with short-cut model, Mussati et al., *Desalination*, 2004

• Mussati et al. (*Desalination*, 2004) – MINLP (Mixed Integer Nonlinear Programming) based optimal design and operation

• MINLP based optimisation with detailed model, Tanvir and Mujtaba, *ESCAPE-2007*, *Desalination*, 2008

STATE OF THE ART: Optimisation

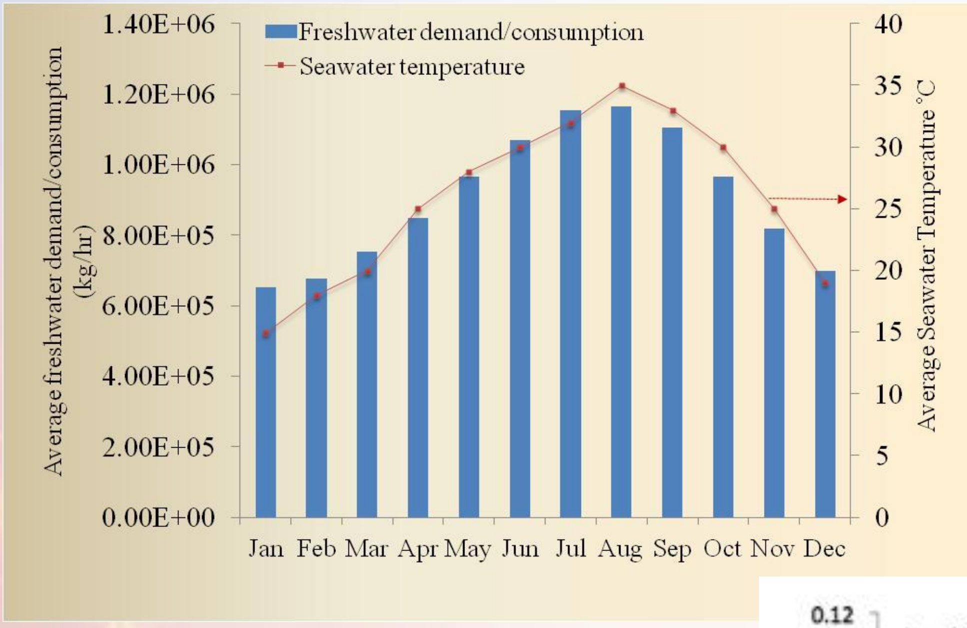
Fixed Freshwater Demand (fouling, NCGs, variable seawater temperature):

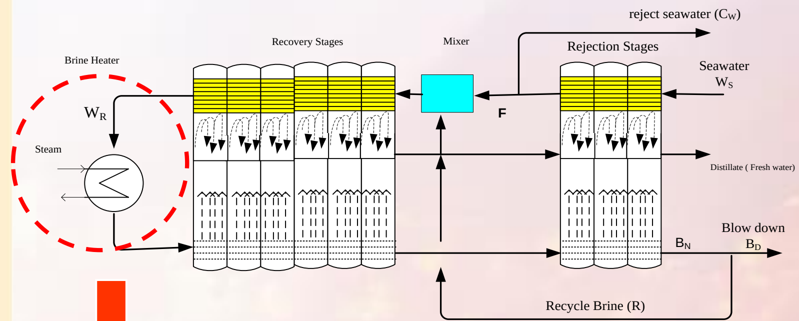
NLP based optimisation with detailed model, Hawaidi and Mujtaba *(ESCAPE-2010, Chemical Eng J (2010)), Said et al. (ESCAPE-2010)*

Variable Freshwater Demand (fouling, NCGs, variable seawater temperature):

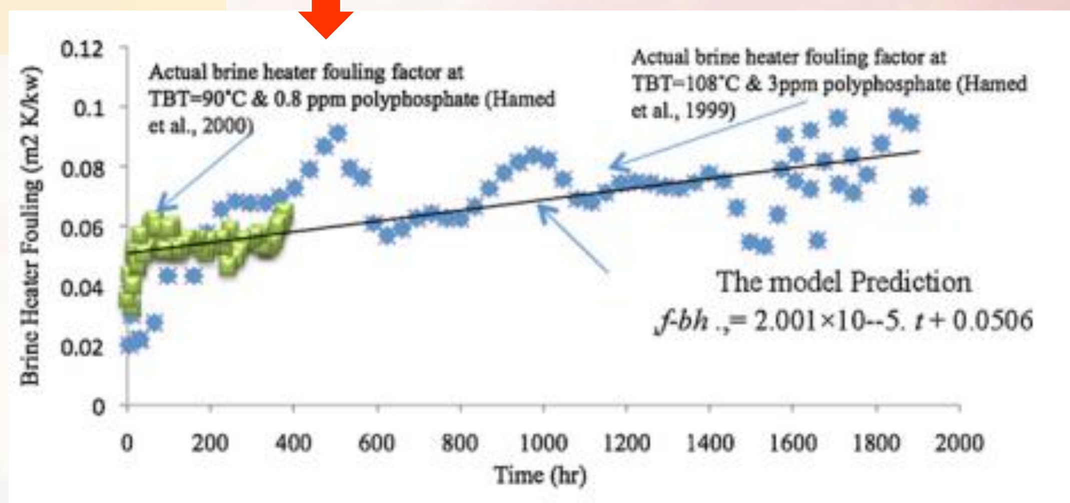
- NLP based optimisation with detailed model, Hawaidi and Mujtaba *(ESCAPE-2011, Ind Eng Chem R (2011)), Said et al. (CMS-2012)*

Average monthly seawater temperature and freshwater demand/consumption profiles during a year



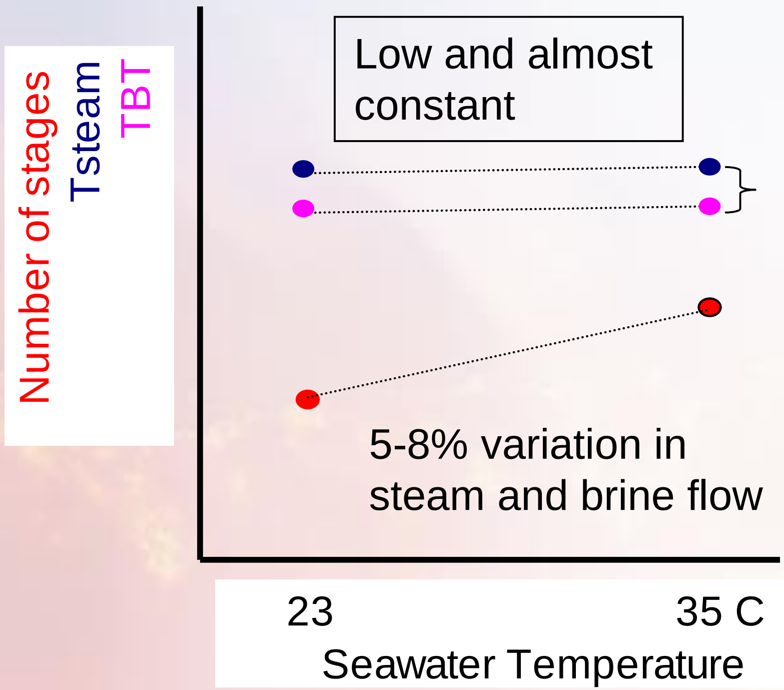


Brine Heater Fouling

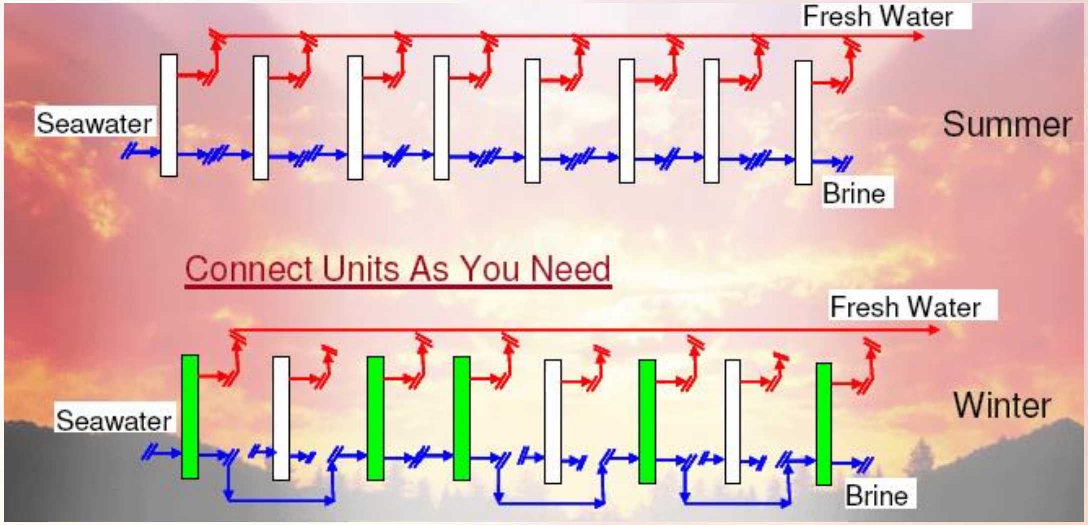


Model Based Insight - 2

Seawater Temperature vs Design for Fixed Water Demand and Minimum Energy Consumption/Minimum Cost

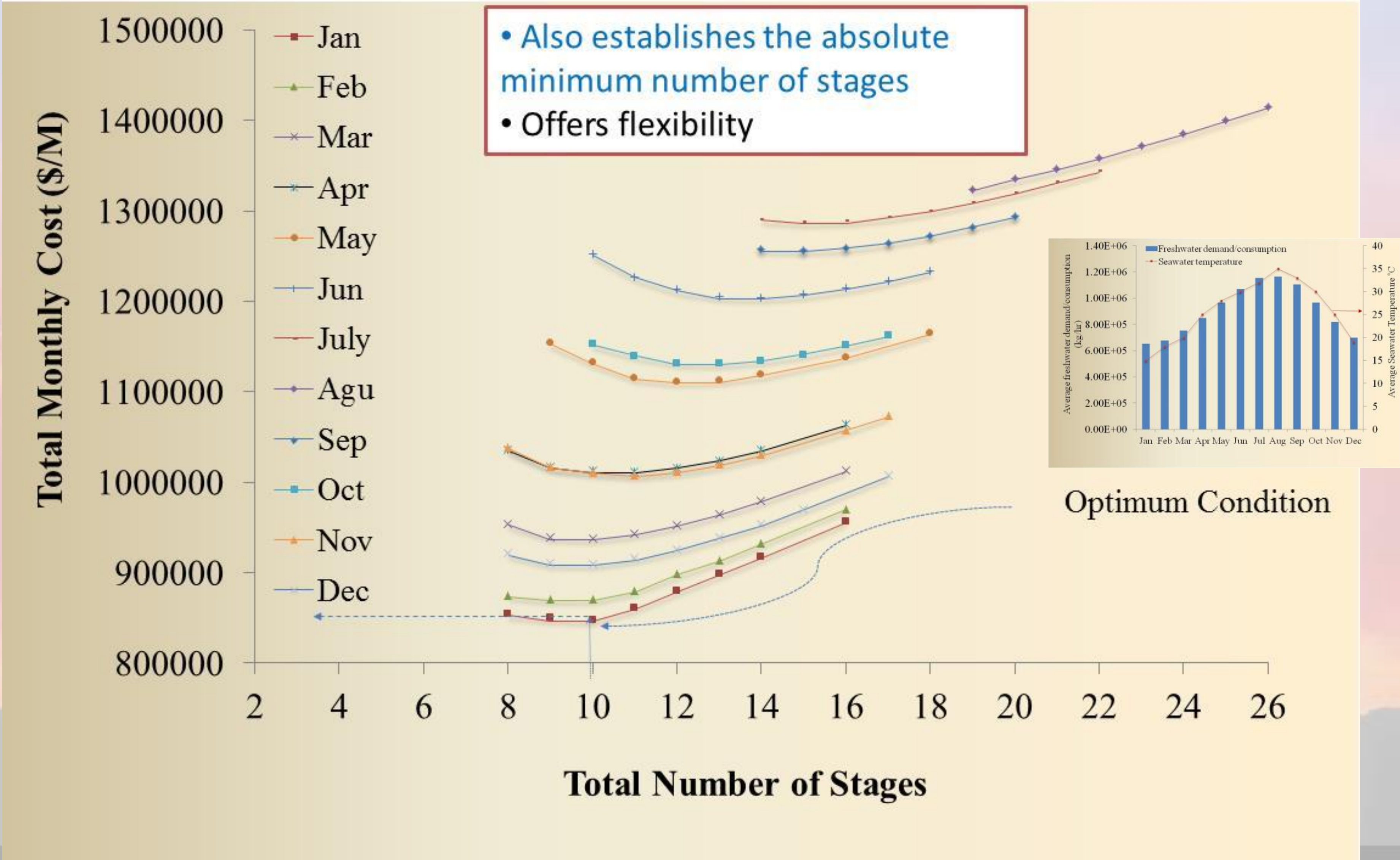


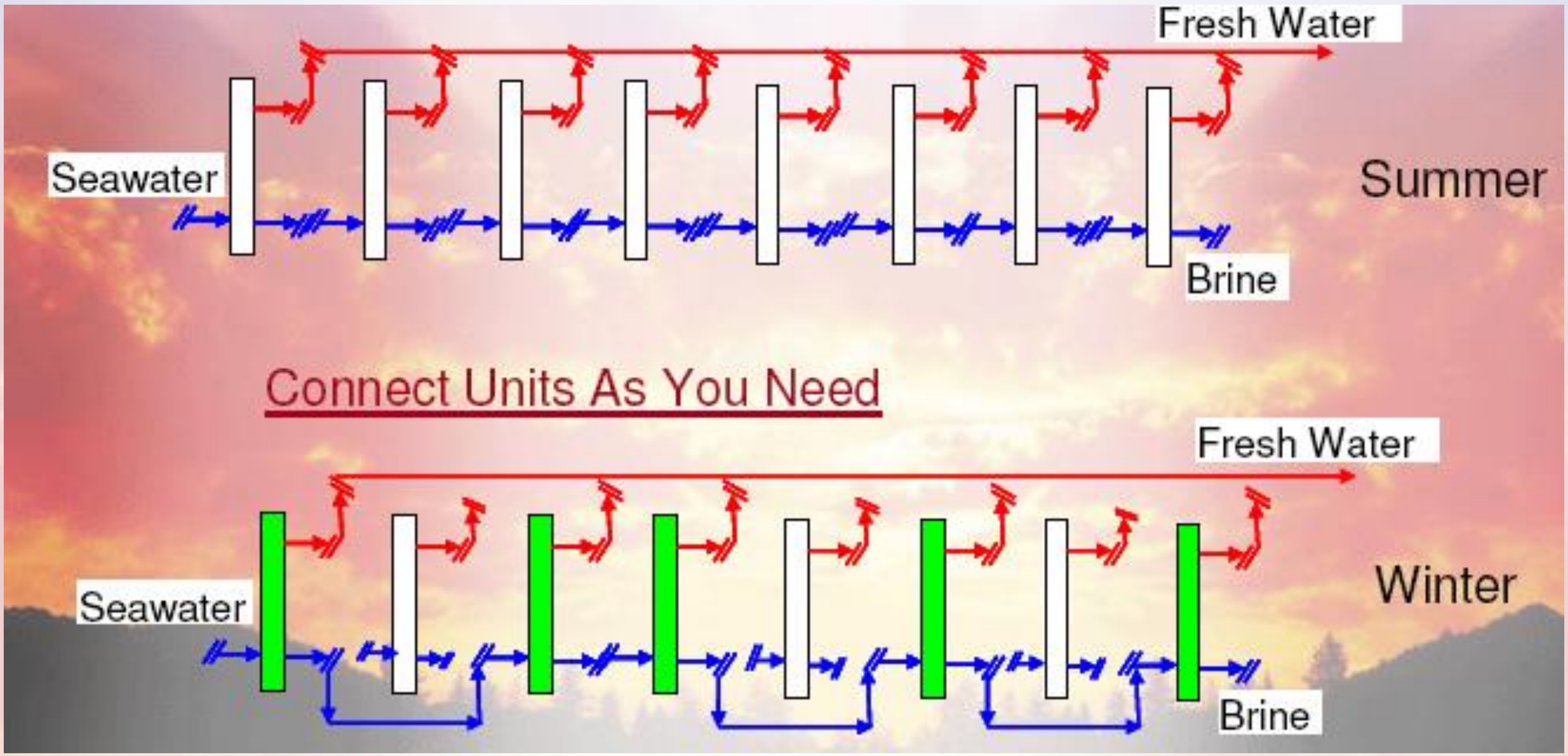
Low temperature operation will reduce the scaling & corrosion & amount of anti-scalant and thus will improve plant efficiency and will reduce environmental impact.



Tanvir & Mujtaba (*ESCAPE-2007; Desalination, 2008*); Hawaidi & Mujtaba *(2010)*

The variation of total monthly cost with total number of stages during a year





Fresh Water
Seawater
Summer
Brine
Connect Units As You Need
Fresh Water
Seawater
Winter
Brine

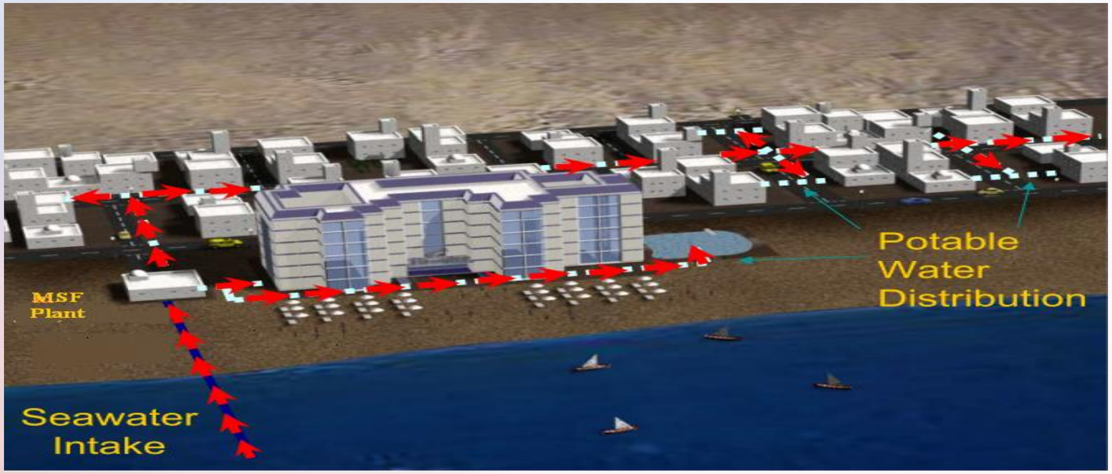
STATE OF THE ART: Dynamic Process Model

- Hussain et al. (simulation), 1993 (SPEEDUP)
- Maniar & Deshpande (control), *JPC*, 1995 (SPEEDUP)
- Thomas et al. (simulation), *comput chem eng*, 1998 (SPEEDUP)
- Mazzotti et al. (simulation), *Desalination*, 2000 (LSODA)
- Sowgath (simulation), *PhD Thesis*, 2007 (gPROMS)
- Hawaidi and Mujtaba (2011), Said et al. (2012), Optimisation with variable water demand

Extension of Helal et al (1986) model in all these dynamic models

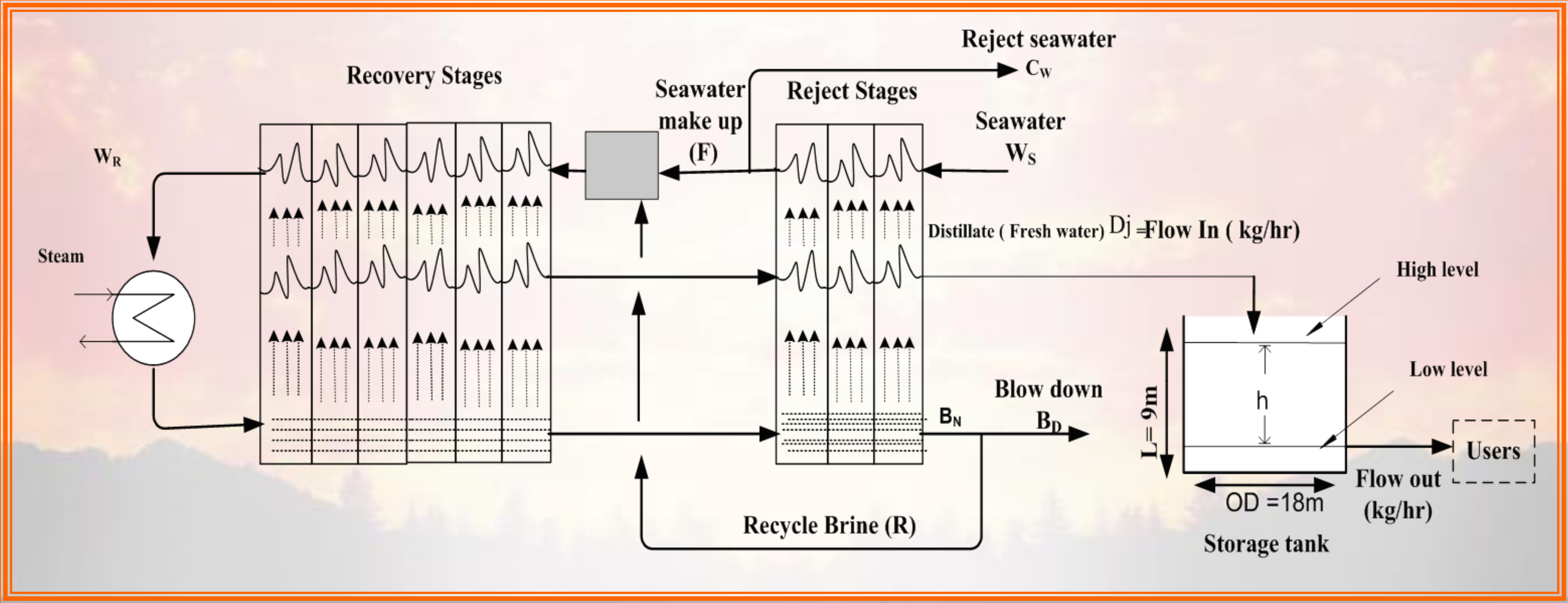
State variables: Stage Mass, Concentration, Temperature

Coping with Variable Freshwater Demand

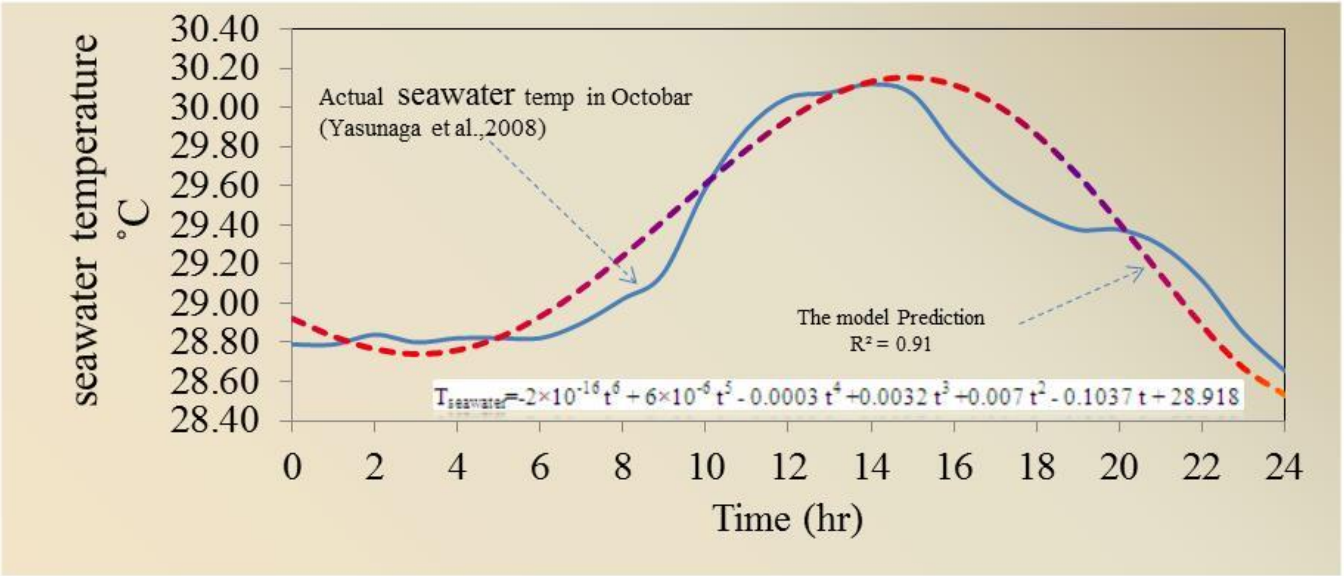


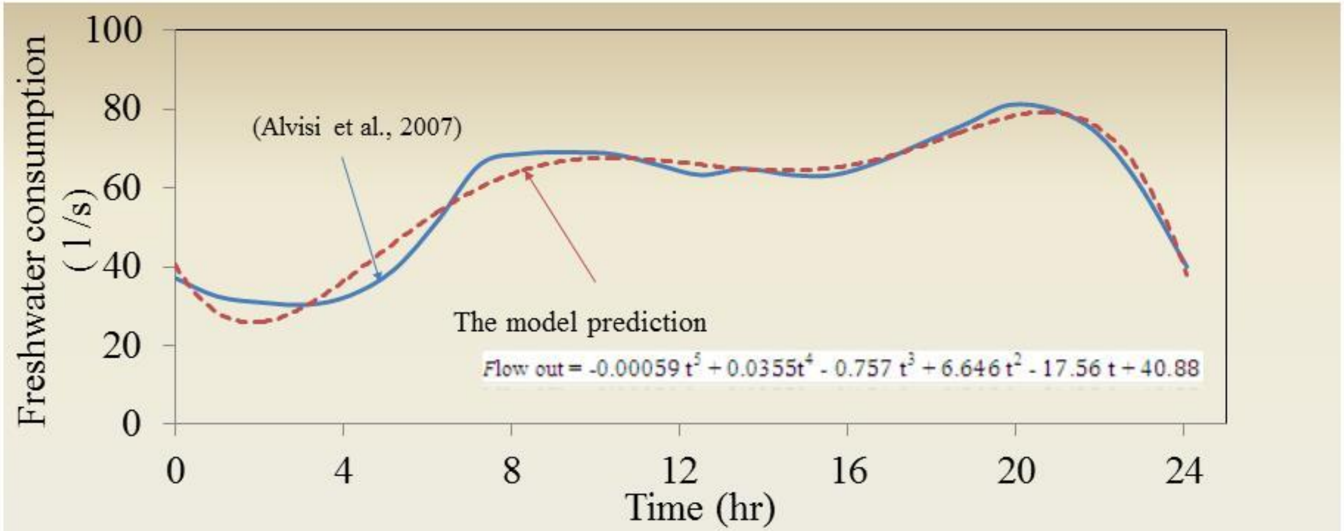
Hawidi and Mujtaba, 2011
Said et al., 2012

Coupled Dynamic and Steady State Model



Dynamic Seawater Temperature and Freshwater Consumption Profiles





Process Constraints

A: Tank level

Level violations

$$LV_1(t) = \begin{cases} (h(t) - h_{max})^2 & if\ h > h_{max} \\ 0 & if\ h < h_{max} \end{cases}$$

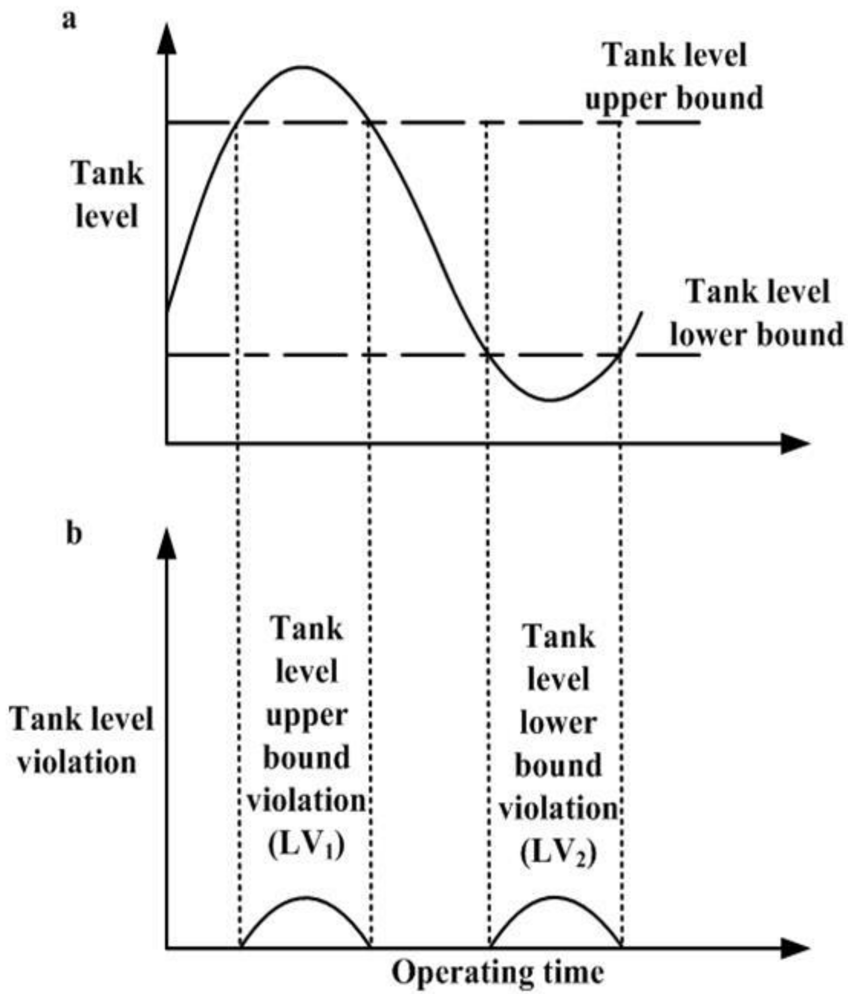
$$LV_2(t) = \begin{cases} (h(t) - h_{min})^2 & if\ h > h_{min} \\ 0 & if\ h < h_{min} \end{cases}$$

Total level violation (LV_T)

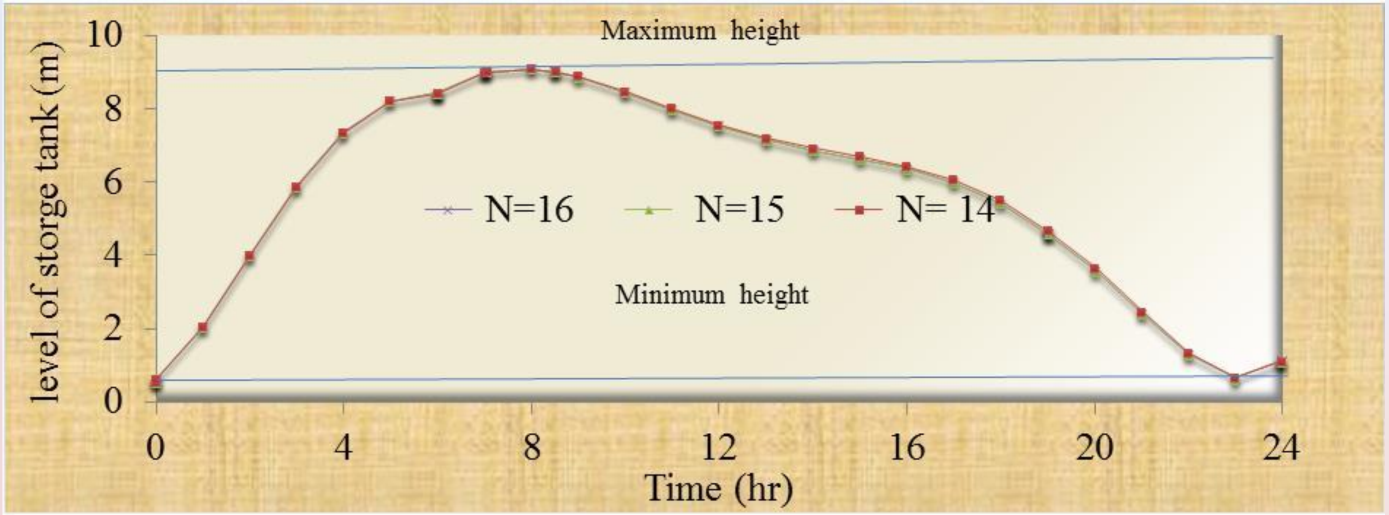
$$LV_T = \int_{t=0}^{t=t_p} LV_1(t) + LV_2(t)\ dt$$

or,

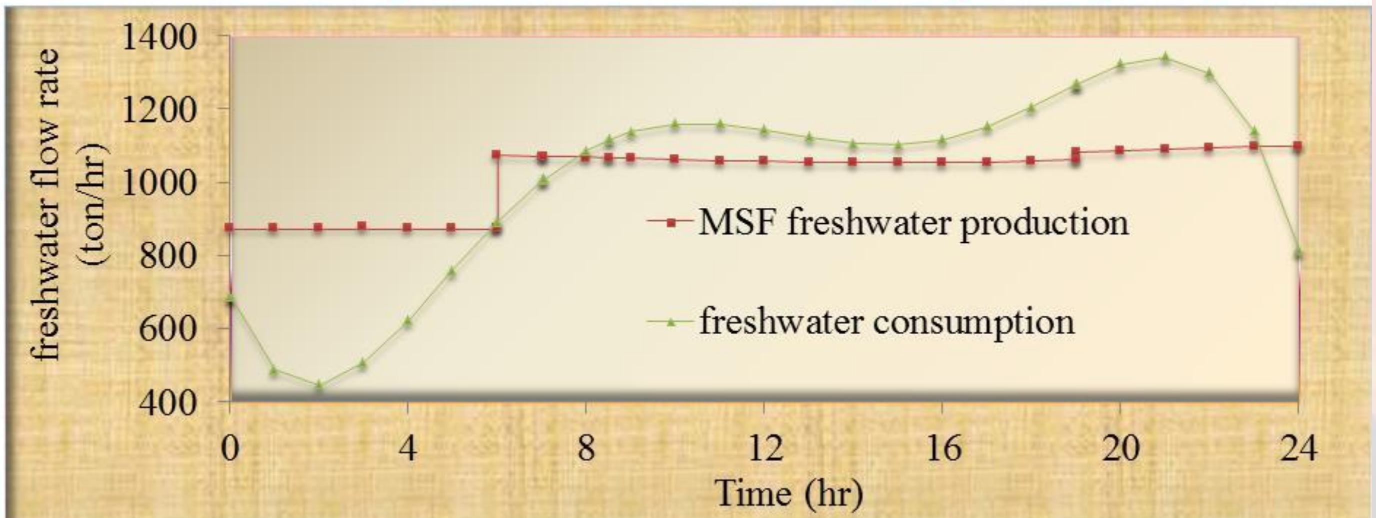
$$\frac{d\,LV_T}{dt} = LV_1(t) + LV_2(t)$$



Storage tank level profiles at different number of stages

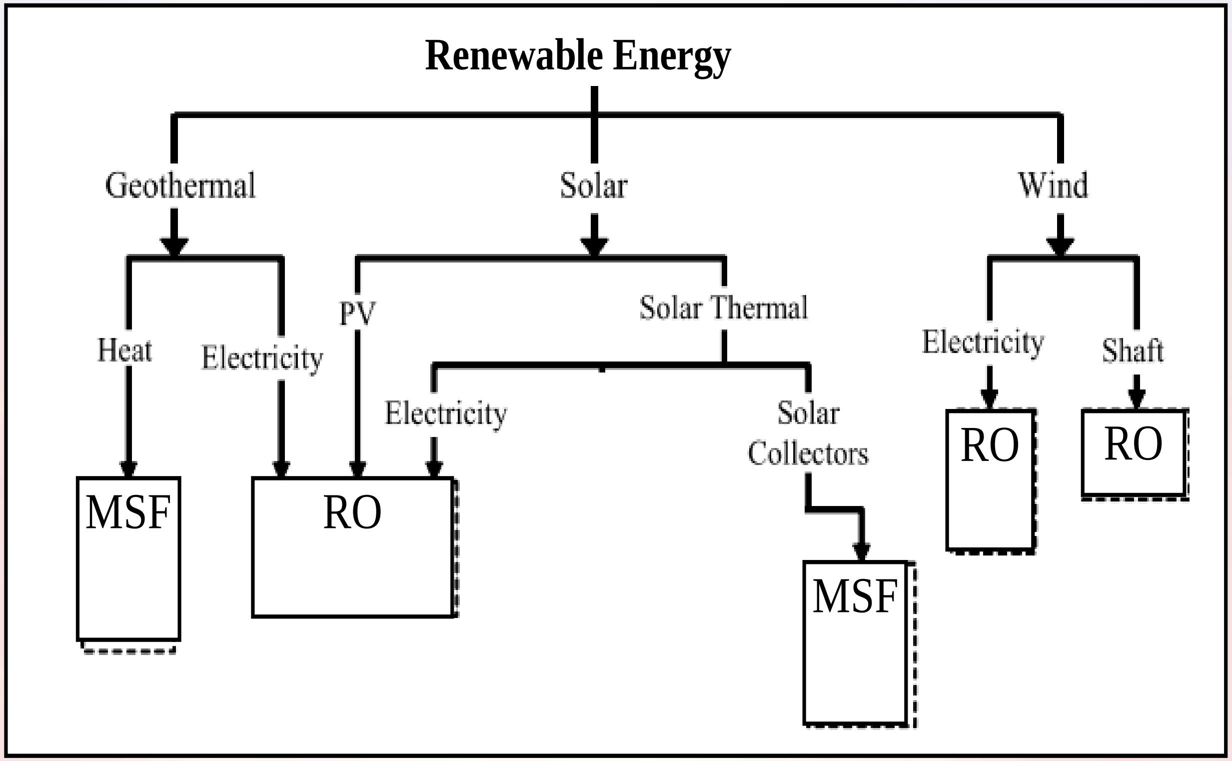


Freshwater production and consumption profile (N=16)



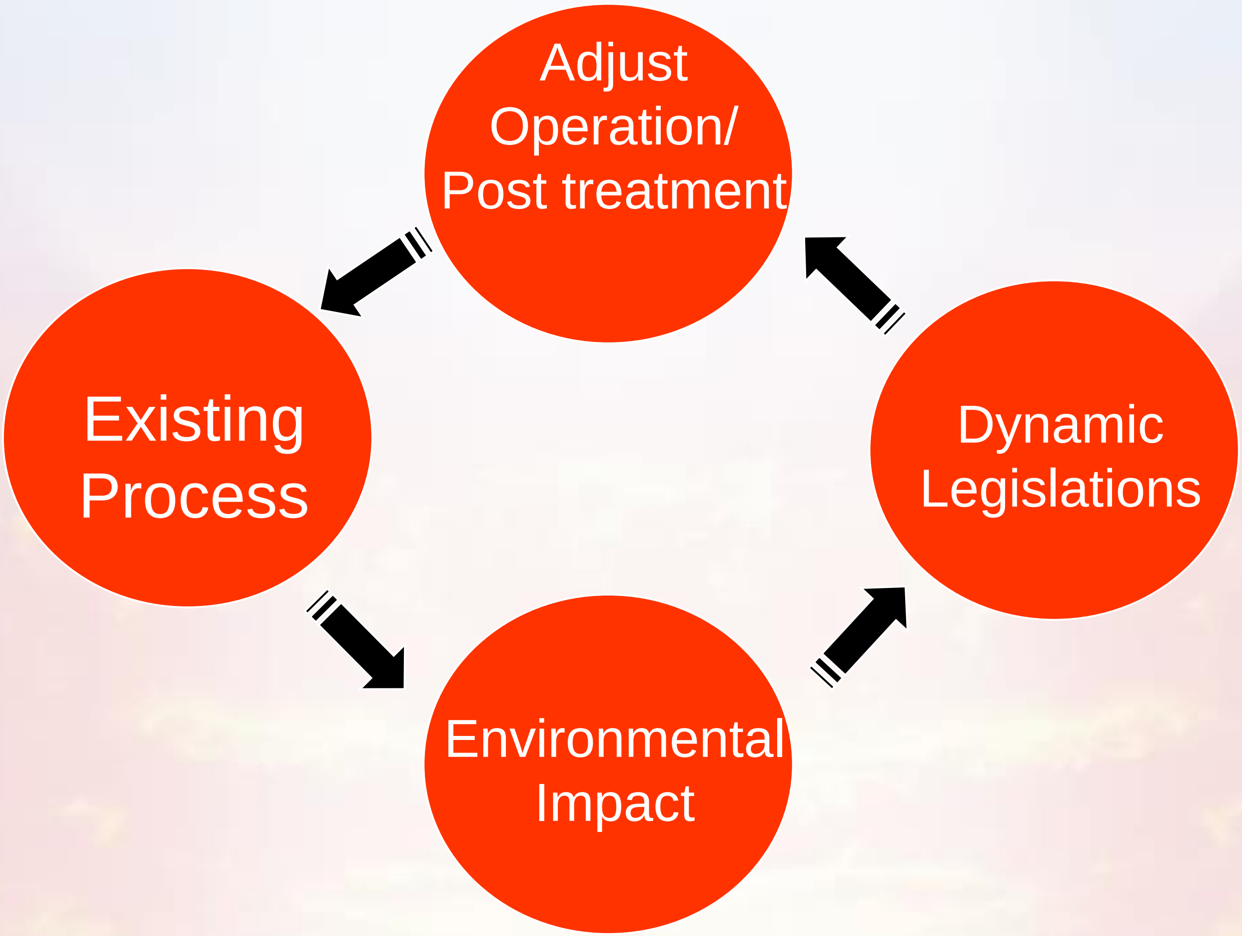
Use of Renewable Energy Desalination Process

Mathioulakis et al. (2007)



With renewable energy sources the cost in 2006 was10.32$/m3 (Tzen, 2006).

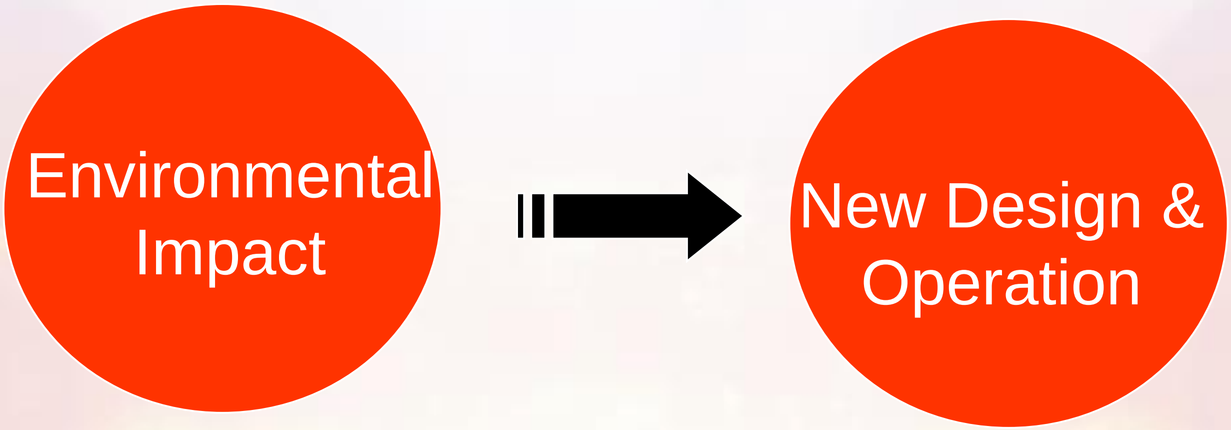
Environmental Impact



Sommariva, Hogg and Callister, *Desalination*, 2004

- **First paper** establishing relations between improvement in efficiency and environmental impact (paper without a single reference)

Environmental Impact



Some recent LCA based works of Vince, Aoustin, Breant and Marechal (2008 a,b) are worth noting in this respect.

By the year 2030, the global needs of water would be 6900 billion m^3/day compared to 4500 billion m^3/day required in 2009 (Water Resources Group, 2009).

Improvement in standard of living requires sustainable and steady water supplies (IChemE Technical Roadmap, 2007).

Global thirst in the next 25 years will turn millions into water refugees [The Independent, 23 March 2001, London].

Water refugees are likely to become commonplace leading to hydrological poverty. Millions of villagers in India, China and Mexico may have to move because of a lack of water [February 14, International Herald Tribune, 2004].

WHAT CAN WE DO??

WHAT CAN WE DO??

We need to ensure
sustainable and
steady water supplies

Opportunities for the PSE Community

Mass Balance
Energy Balance
Physical Properties
Fluid Flow
System Heat Loss

Process Model

(Steady State/ Dynamic)

Kinetic Model (Fouling/Scaling)
Fluid Flow (non condensable)
Corrosion Model (Material selection)
Fluid Mixing
Environmental Impact Model
System Heat Loss
Renewable Energy System

Taylor Made Algorithm (limited opportunities for detailed performance evaluation)

SIMULATION

(Steady State/ Dynamic)

SPEEDUP, ASPEN, gPROMS
(not widely used)
(unlimited opportunities)

Qualitative
Short-cut Model Based
Detailed Model Based
Repetitive simulation
NLP/MINLP based
Variable seawater temperature
Variable Demand, Wide Salinity
Structure, Energy Recovery

OPTIMISATION

Design & Operation

(Steady State/ Dynamic)

Dynamic (with Fouling & Scaling)
SS Optimisation
Irregular Demand (Day/Night)
Huge opportunities- material selection, Maintenance, scheduling/operation for Variable water demand (day/night)
Structure, Hybrid System, Energy Recovery

Considered in the Past

Model Based Approach

Future Opportunities

Finally,

MSF Model:

Helal, Medani, Soliman & Flower, *comput chem eng,* 1986

Cited only 73 times in the last 28 years!

Certainly, PSE/CAPE community has lot to offer!!

Thank you