What To Do With Produced Water When Its Reuse for Hydraulic Fracturing Is No Longer Feasible?

Omkar Lokare, Sakineh Tavakkoli, Vikas Khanna and Radisav Vidic

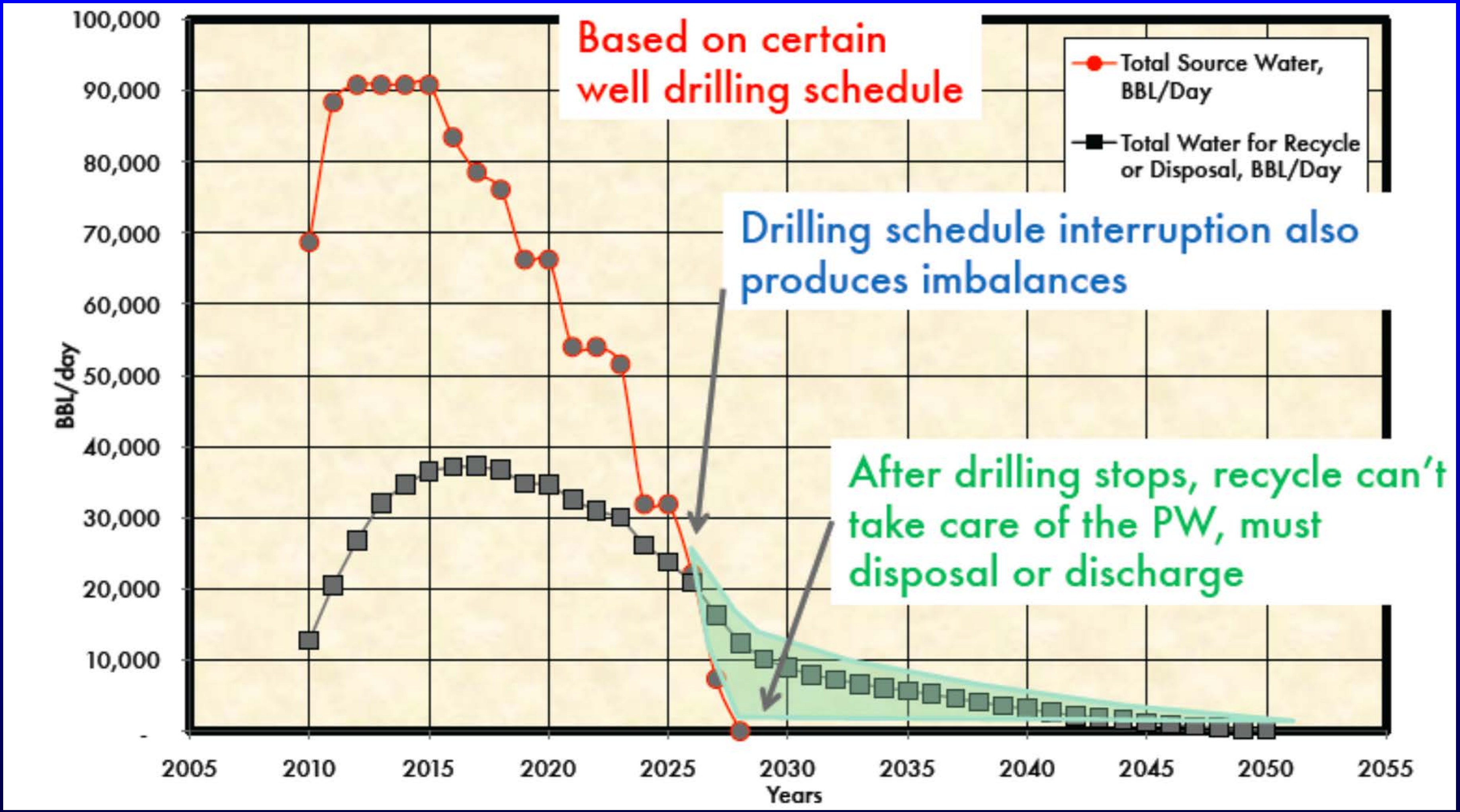
Department of Civil and Environmental Engineering

University of Pittsburgh

Treatment and Disposal Strategies

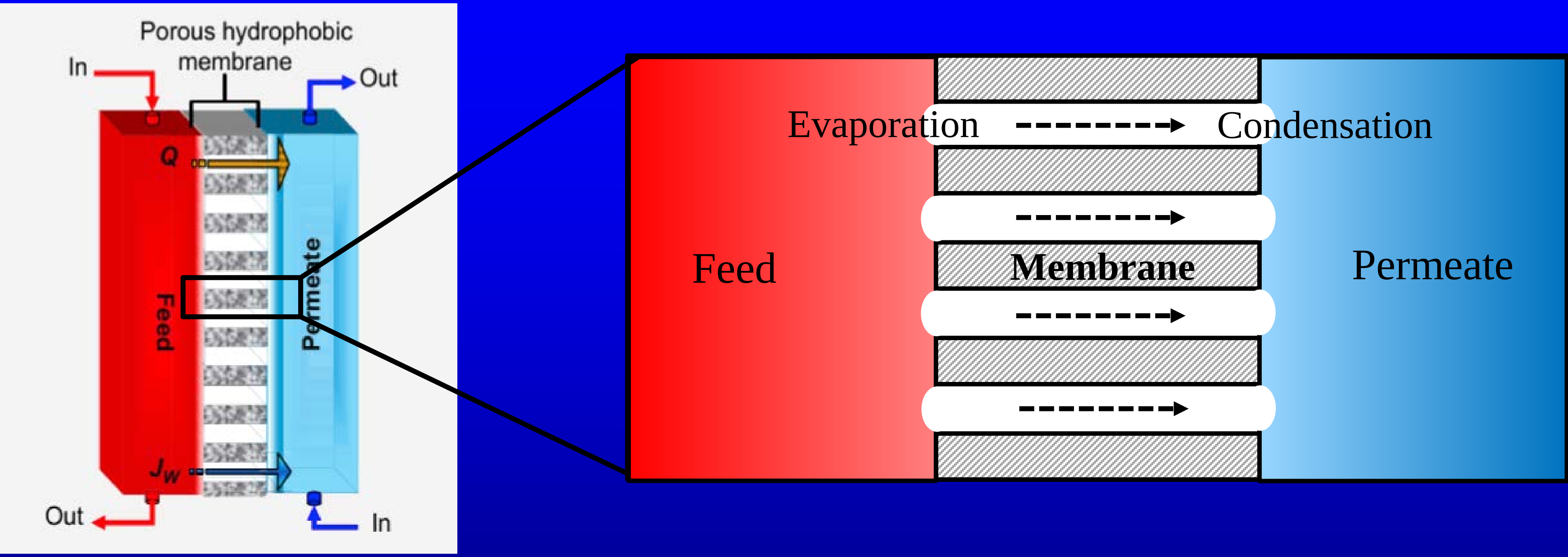
- Deep well injection
  - Linked with seismic activities
  - Viable as long as Class II injection wells are available
- Reverse Osmosis
  - Not feasible for wastewater with TDS> 40,000 mg/l
- Evaporation/Crystallization
  - Above 90% water recovery
  - High energy intensity and cost
- Recycling water for subsequent fracking
  - TDS interferences with hydraulic fracturing chemicals (e.g., friction reducers)
  - Water hardness and bacteria are a concern
  - Works only as long as we have new wells to fracture

Total Water Balance Within a Gas Field



(Kujivenhoven et al., 2011)

Direct Contact Membrane Distillation (DCMD)



- Vapor pressure driven process
- Hydrophobic membranes
- Pore size – 0.2 to 1 µm
- Membranes material – PTFE, PVDF, PP, AC
- Permeate flux is proportional to vapor pressure difference

Direct Contact Membrane Distillation (DCMD)

- Advantages
  - Operates at low temperature (<100^{o}C)
  - Low quality heat energy can be used
  - Ambient pressures
  - Not highly affected by salinity
  - Produces high quality water

- Disadvantages
  - Conduction heat losses
  - Energy consumption (up to 3.5 MWh/m^3)[1]

[1] A. Criscuoli, M.C. Carnevale, E. Drioli, Evaluation of energy requirements in membrane distillation, Chemical Engineering and Processing: Process Intensification, 47 (2008) 1098-1105

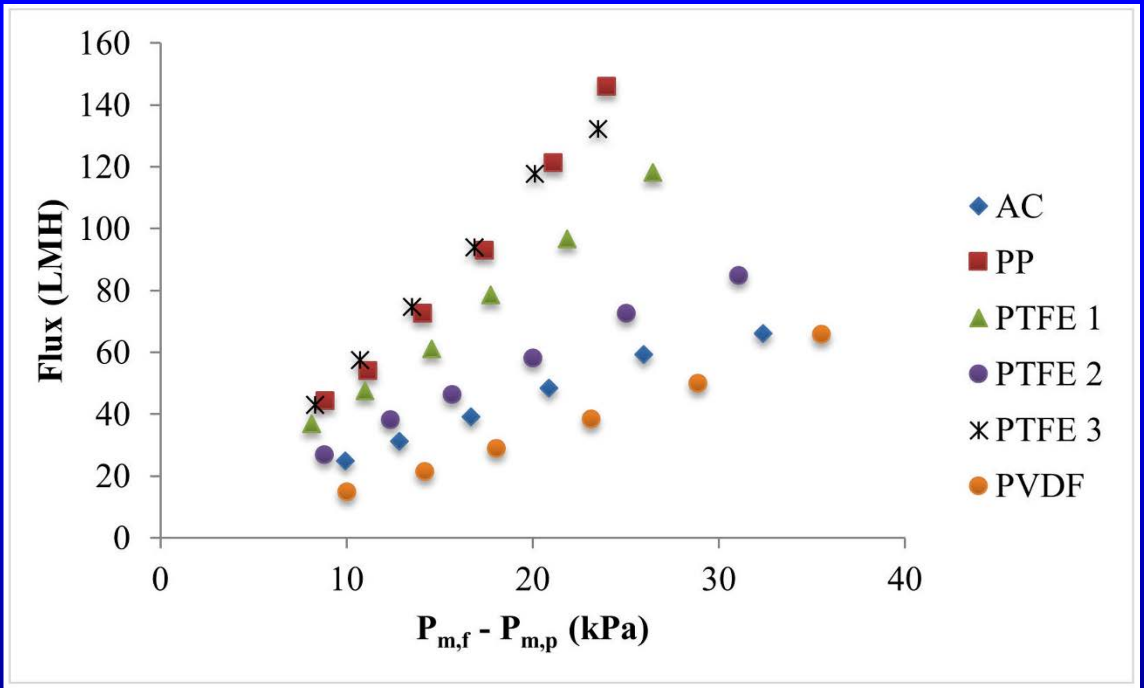
Experimental Setup

(a) Schematic diagram of experimental setup, (b) Picture of the DCMD module

Membranes Properties

Membrane	Mean pore radius (μm)	Thickness (μm)		Contact angle (active layer)	Membrane Porosity (%)		Thermal Conductivity (W/m.K)
		Total	Active layer		Bulk	Active Layer	
AC	0.23	215	-	135	30	-	0.105
PP	0.38	135	-	136	79	-	-
PTFE 1	0.21	112	20	142	42	92	0.294
PTFE 2	0.25	210	22	147	37	-	-
PTFE 3	0.24	148	60	149	60	94	0.242
PVDF	0.19	145	-	107	68	-	-

Performance of different membranes



Flux (LMH) vs Vapor pressure difference (kPa)

Membrane	MD coefficient (LMH/kPa)
AC	2.2
PP	5.6
PTFE 1	4.4
PTFE 2	2.8
PTFE 3	5.6
PVDF	1.7

Operating conditions:

- Feed and permeate velocity= 0.6 m/s
- Feed - pure water
- Permeate temperature=30°C

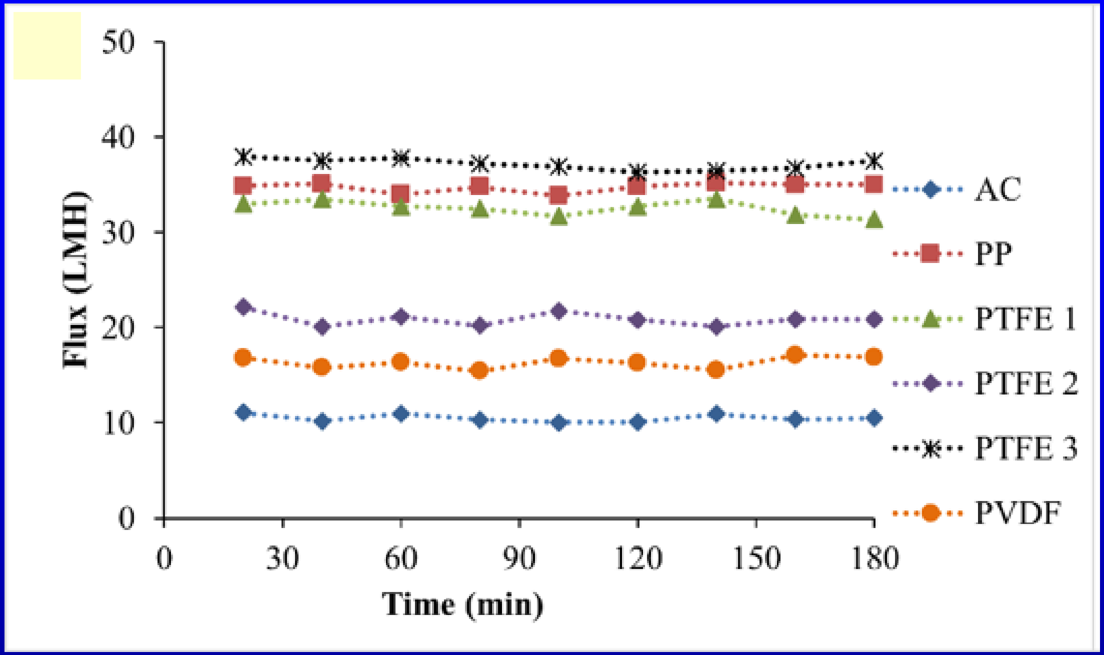
Flux unit – LMH (l/m²/hr)

Produced water characterization

Component (mg/l)	Site 1	Site 2
Cl^-	188,728	63,588
Na^+	81,442	26,427
NH_4^+	1,002	279
K^+	786	258
Mg^{+2}	2,664	675
Ca^{+2}	32,901	6,523
Sr^{+2}	11,910	1,620
Ba^{+2}	6,256	3,743
Fe total	30	10
TDS	308,334	92,800
TOC	0	11
*Ra226	17,980 ± 1,100	753 ± 60

* Ra 226 activity is shown in pCi/l

DCMD - Constant concentration - Site 1



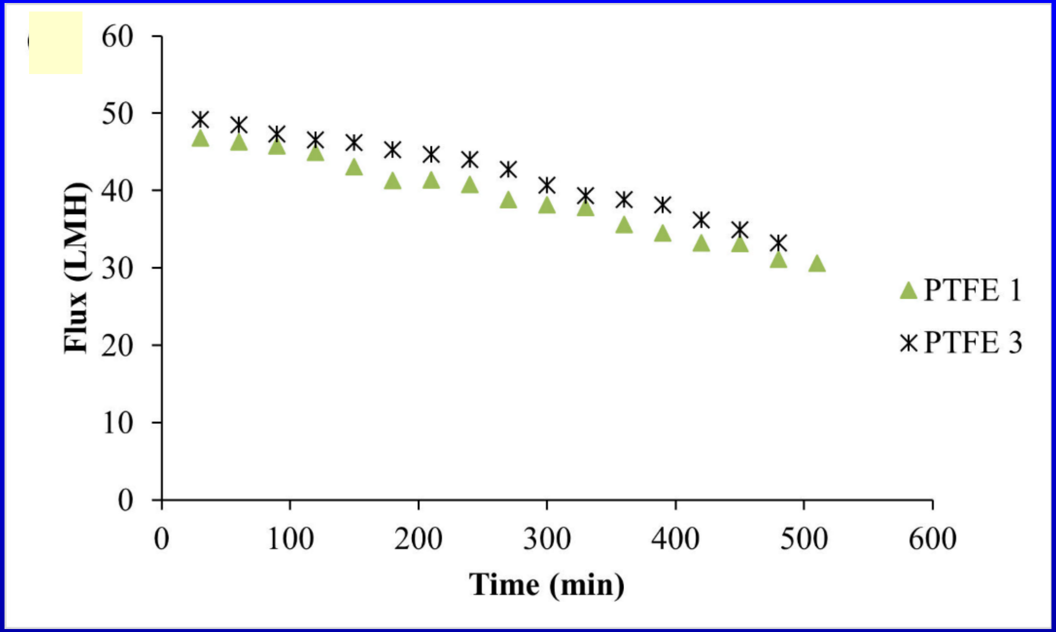
- Constant flux over time
- Negligible scaling even at a high TDS

- Constant concentration
- TDS = 308,334 mg/l
- Feed temperature = 60 °C
- Permeate temperature = 30°C
- Feed and permeate velocity=0.6 m/s

Permeate Quality

Membrane	Cl^- (ppm)	Rejection %	Average Flux (LMH)
AC	2	99.9	10.5
PP	7	99.9	34.7
PTFE 1	0.5	99.9	32.5
PTFE 2	1	99.9	20.8
PTFE 3	2	99.9	37.5
PVDF	1	99.9	16.3

DCMD - Concentrating produced water – Site 2



- Feed was concentrated until TDS reached 30%

Permeate quality

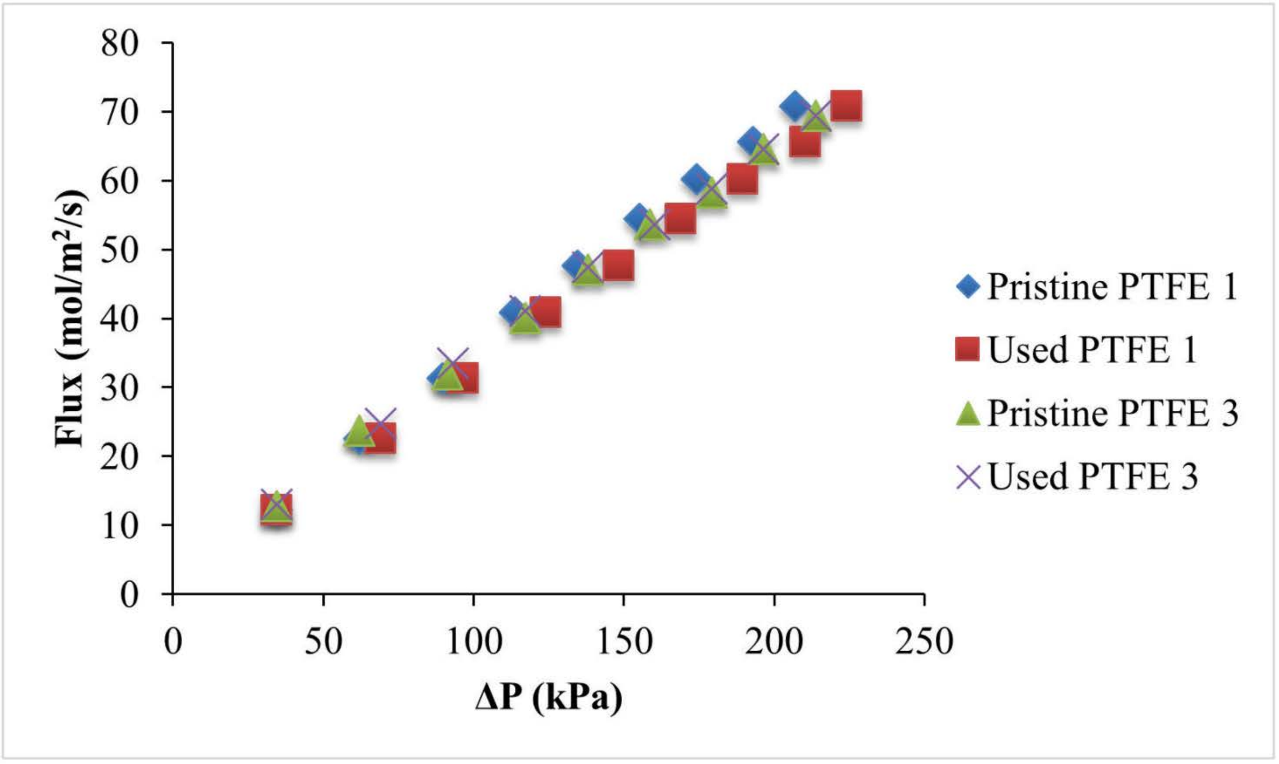
	PTFE 1	PTFE 3
Cl- (mg/l)	0.4 (99.9% rejection)	0.5 (99.9% rejection)
Ra 226 (pCi/l)	ND	ND
TOC (mg/l)	1 (90.9% rejection)	0.83 (92.4 % rejection)

Scale Formed on DCMD Membrane

- Scaling is not uniform on membrane surface
- Scale is about 1 micron thick after 8 hours of filtration

Testing of Used Membranes

Gas Permeation Test

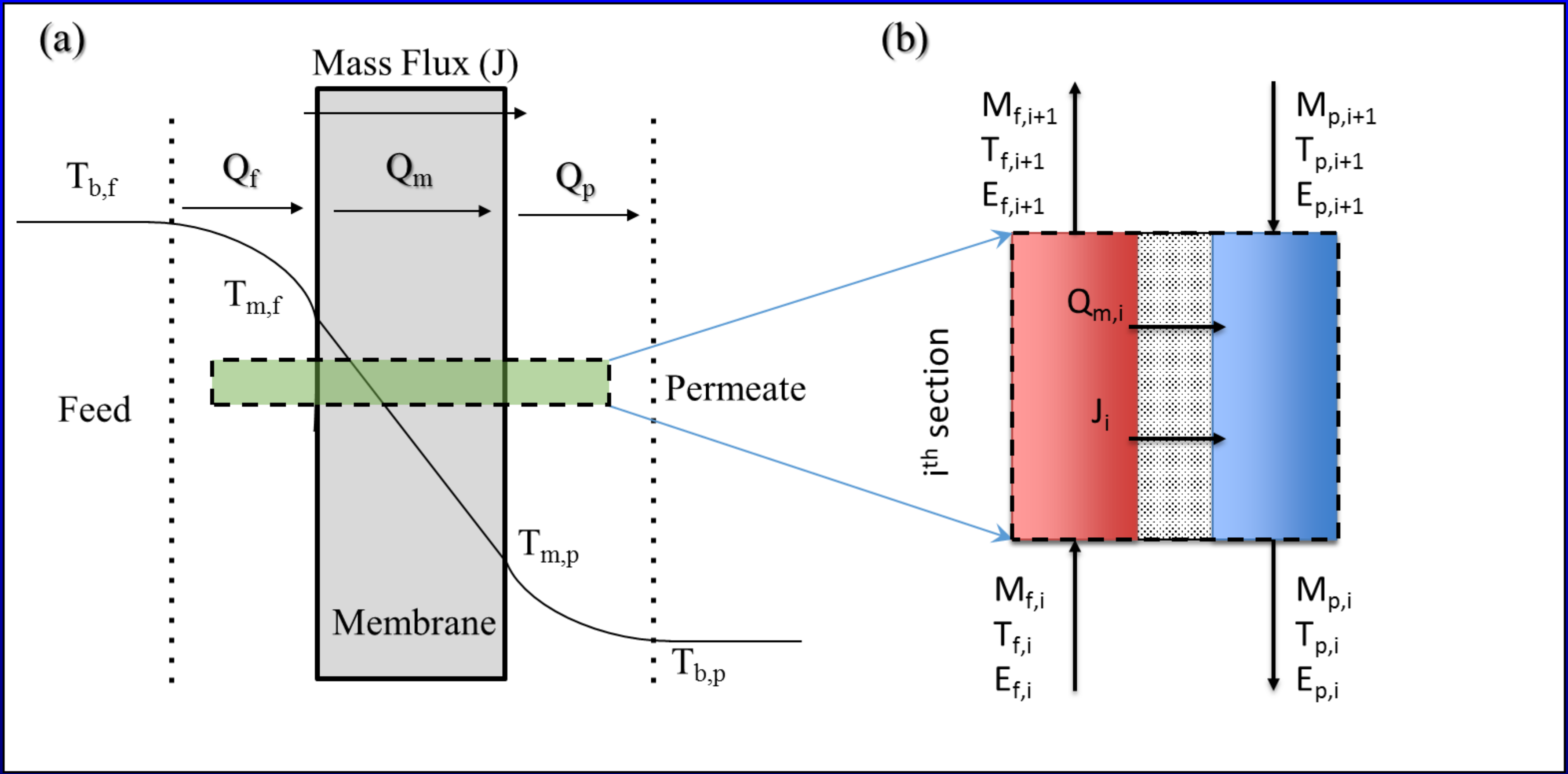


Pristine and used membranes exhibited almost identical gas permeability

Pure water flux with the used membranes was equal to that with pristine membranes

Systems Level Analysis

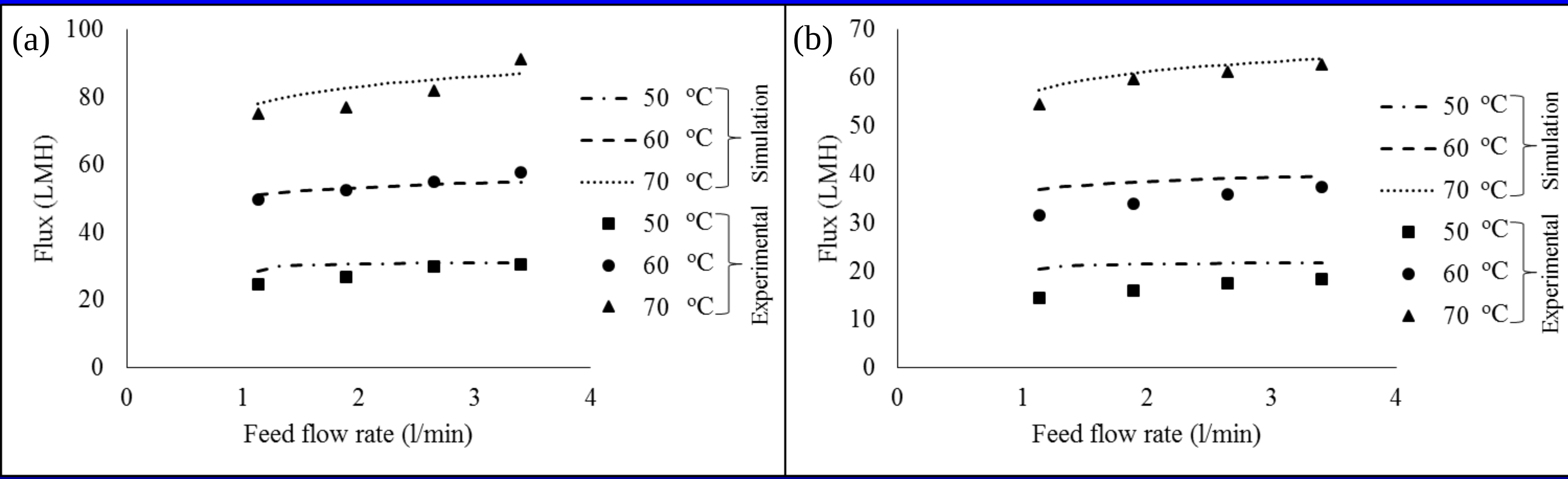
Stepwise Modelling



(a) Temperature profile across the membrane (b) Small section of the membrane

- Divide membrane into ‘n’ parts
- Solve for each part sequentially

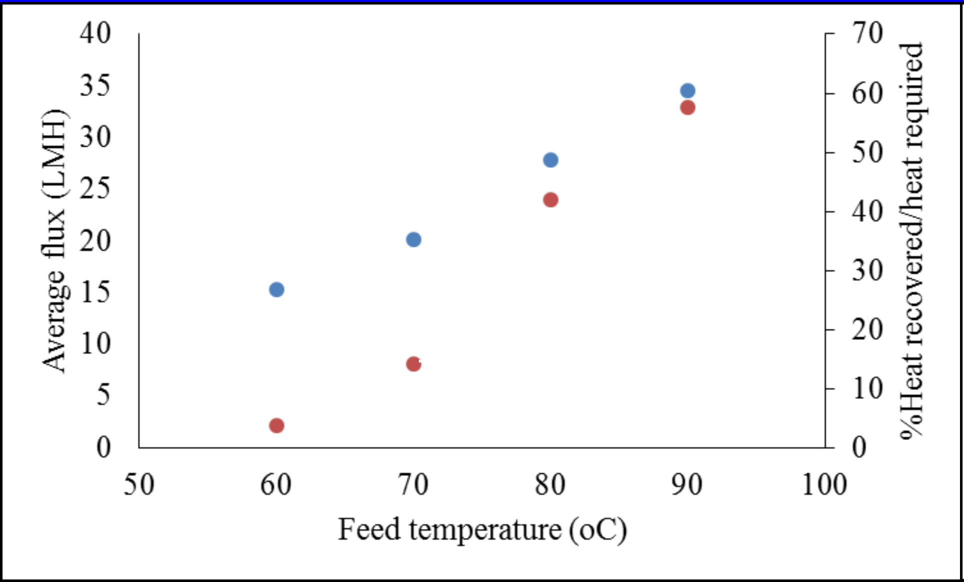
Model Calibration and Validation



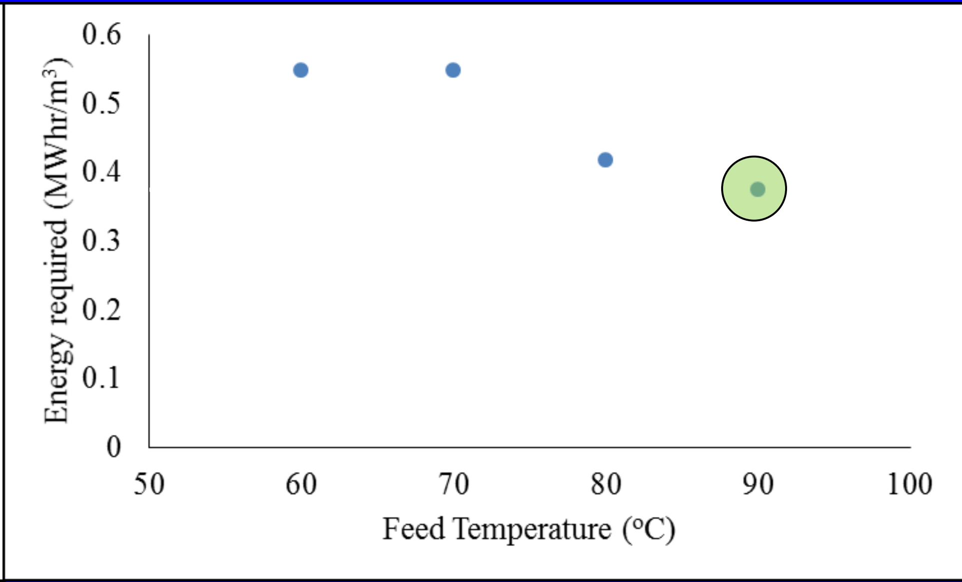
Flux vs flow rate at 50, 60 and 70 °C for (a) 93 g/l and (b) 308 g/l TDS produced water solutions

- Model was calibrated at 60 °C and 1.9 l/min

Optimizing System Performance



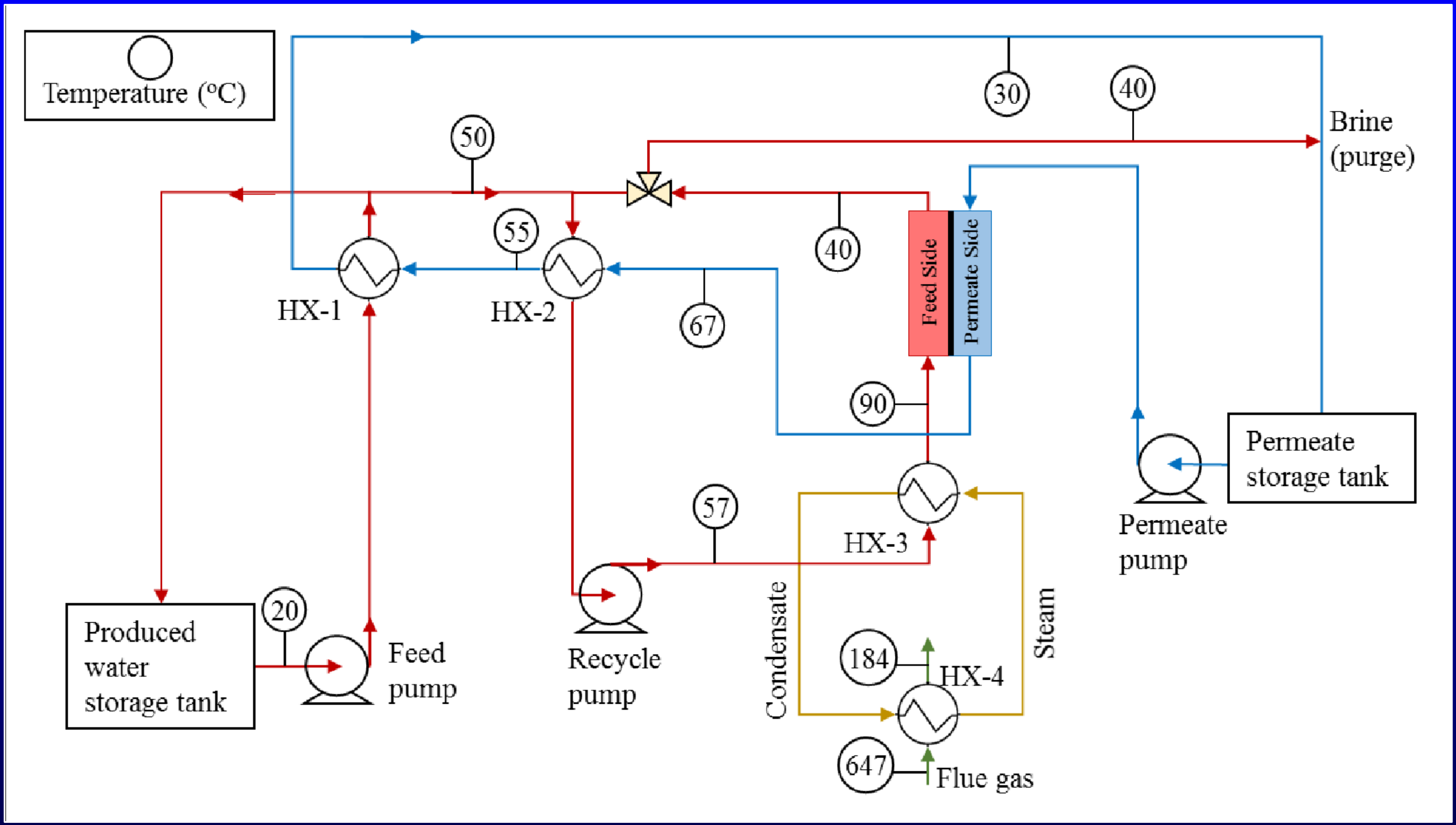
(a) Average flux and percent heat recovery vs Feed Temperature



(b) Energy required per m^3 of produced water vs Feed Temperature

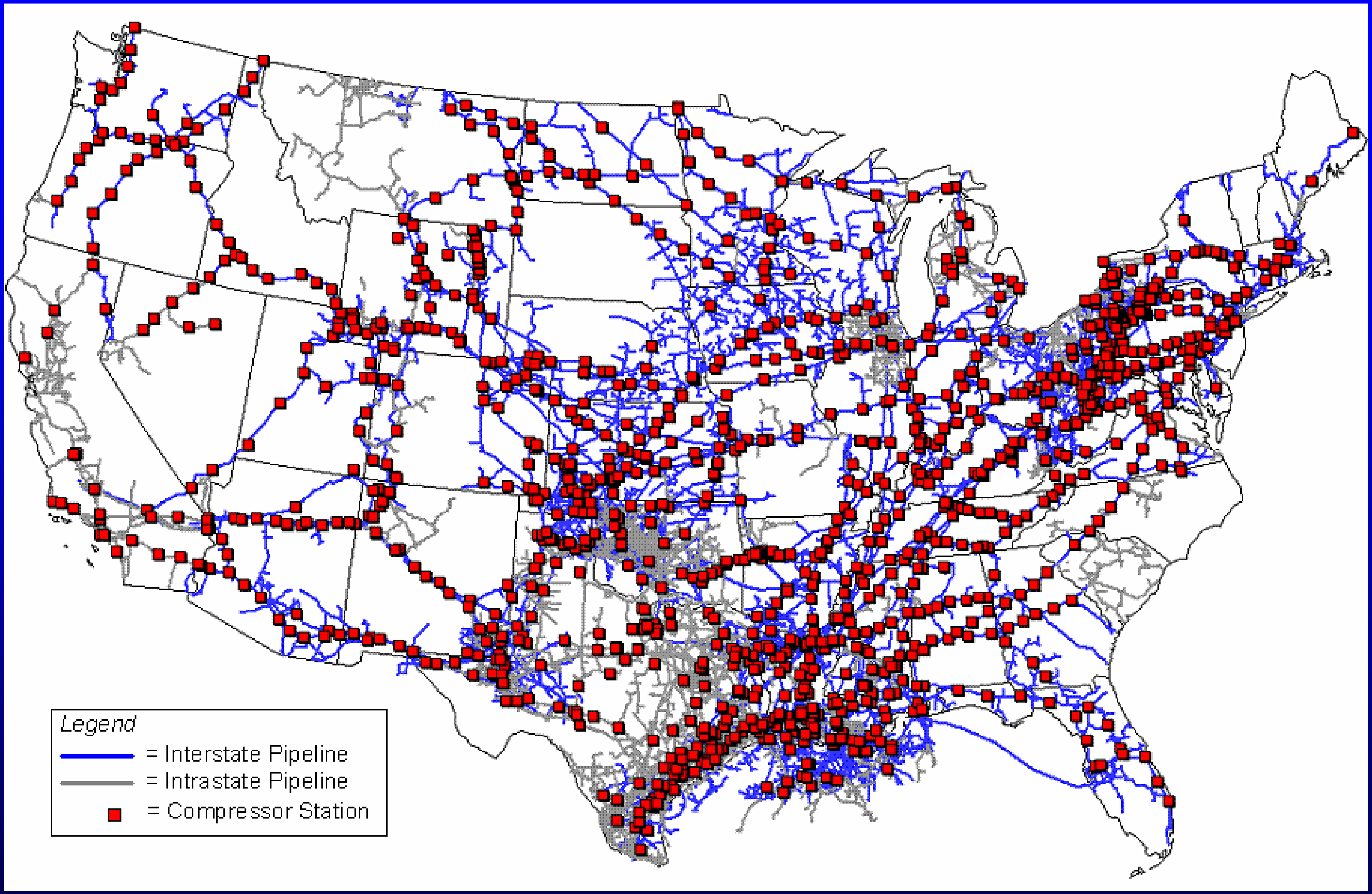
- Raising the feed temperature increases flux and heat recovery
- More energy is required at lower feed temperature

Systems Level Flow-sheet



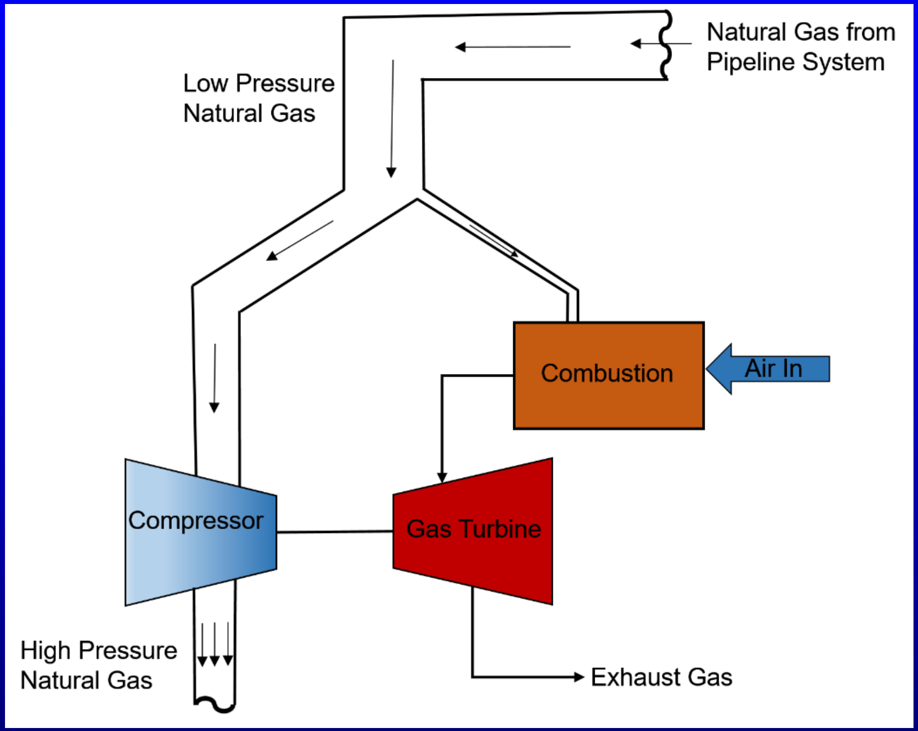
Process flow-sheet for water treatment using waste heat

Natural Gas Compressor Stations



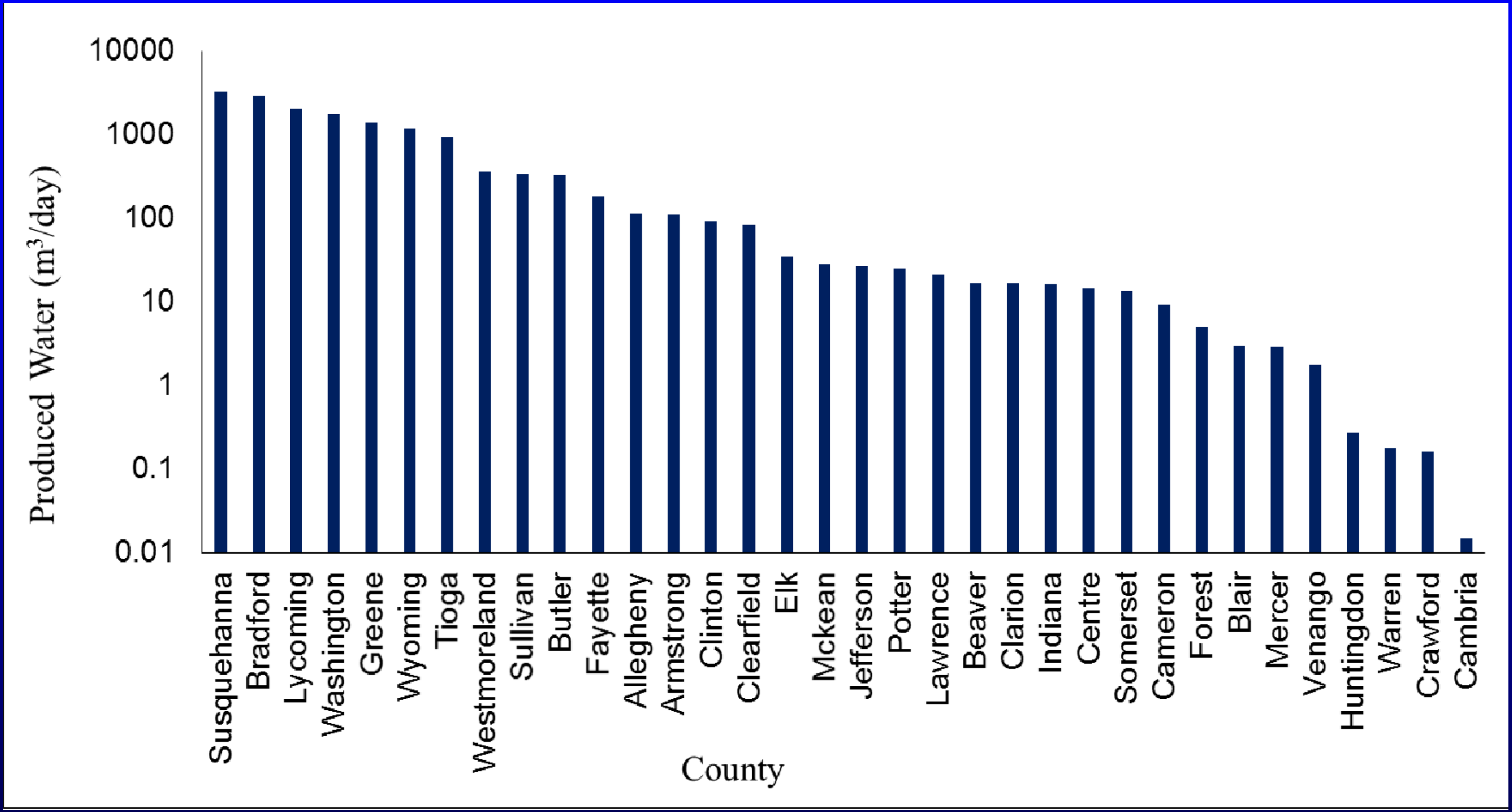
Source:US Energy Information Administration

Waste Heat Estimation



- Waste heat from natural gas compressor stations estimated to be 46 TJ/day in PA.

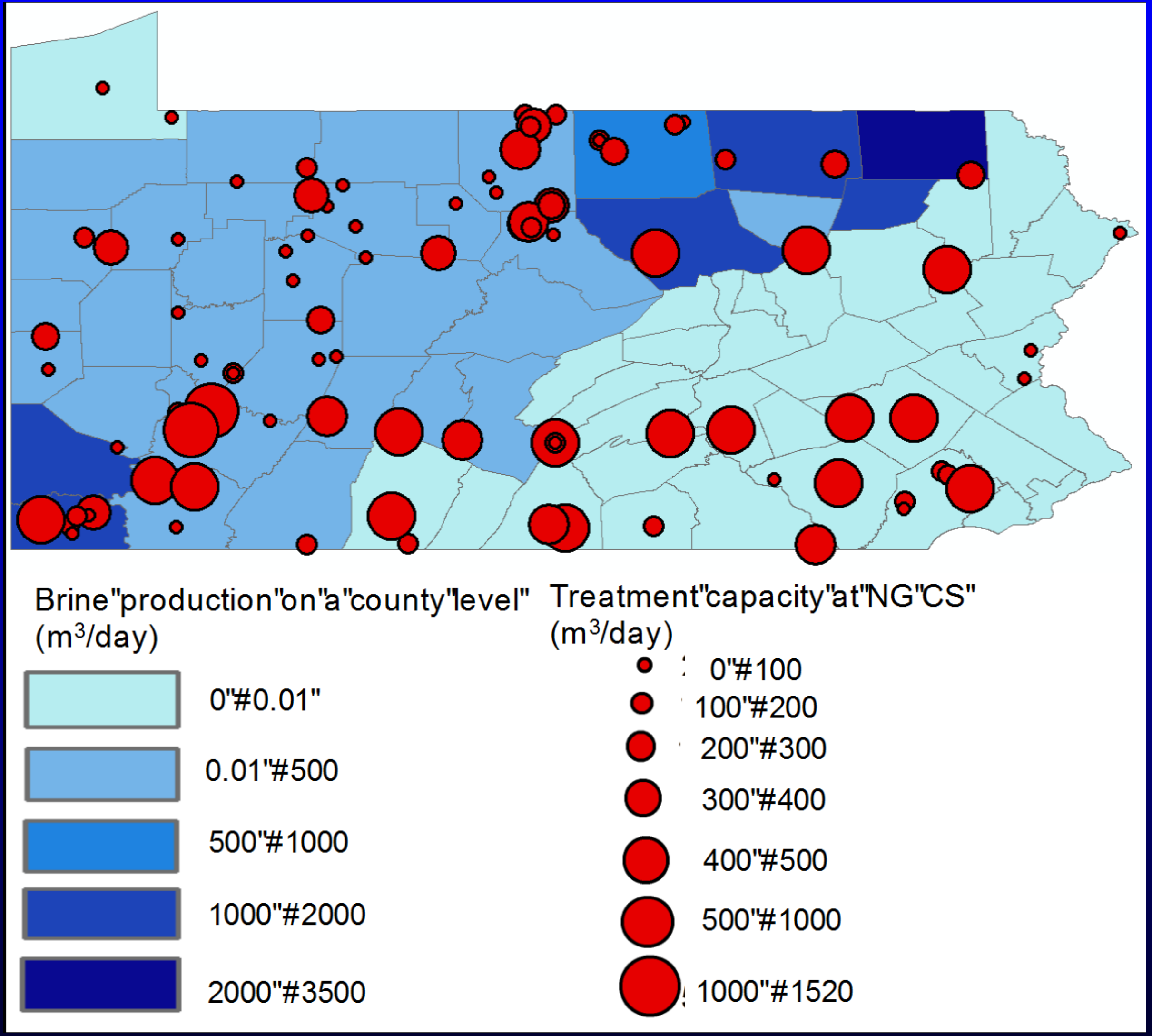
Quantification of Produced Water in PA

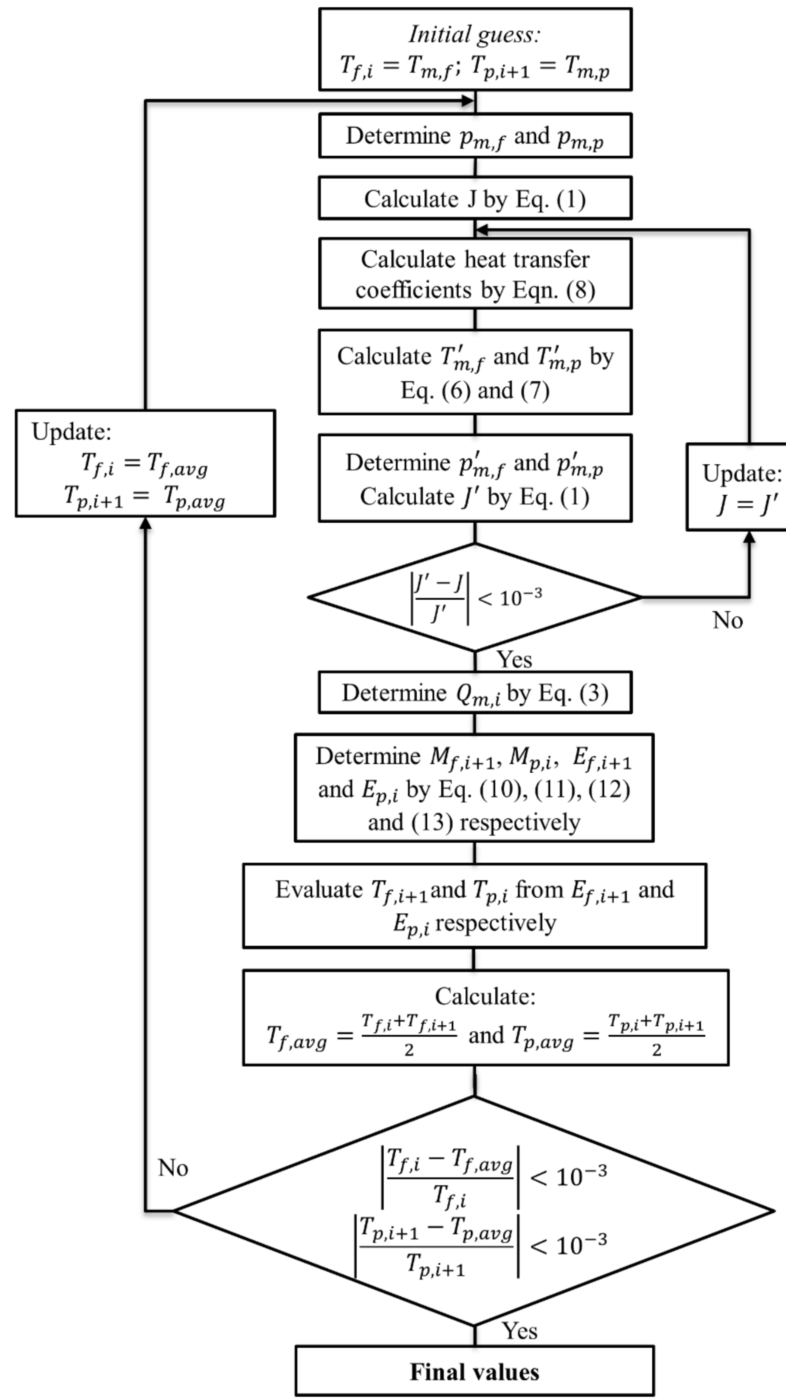


- Total of about 2.7 million m^3 produced in six months (2014)

How much produced water can be treated?

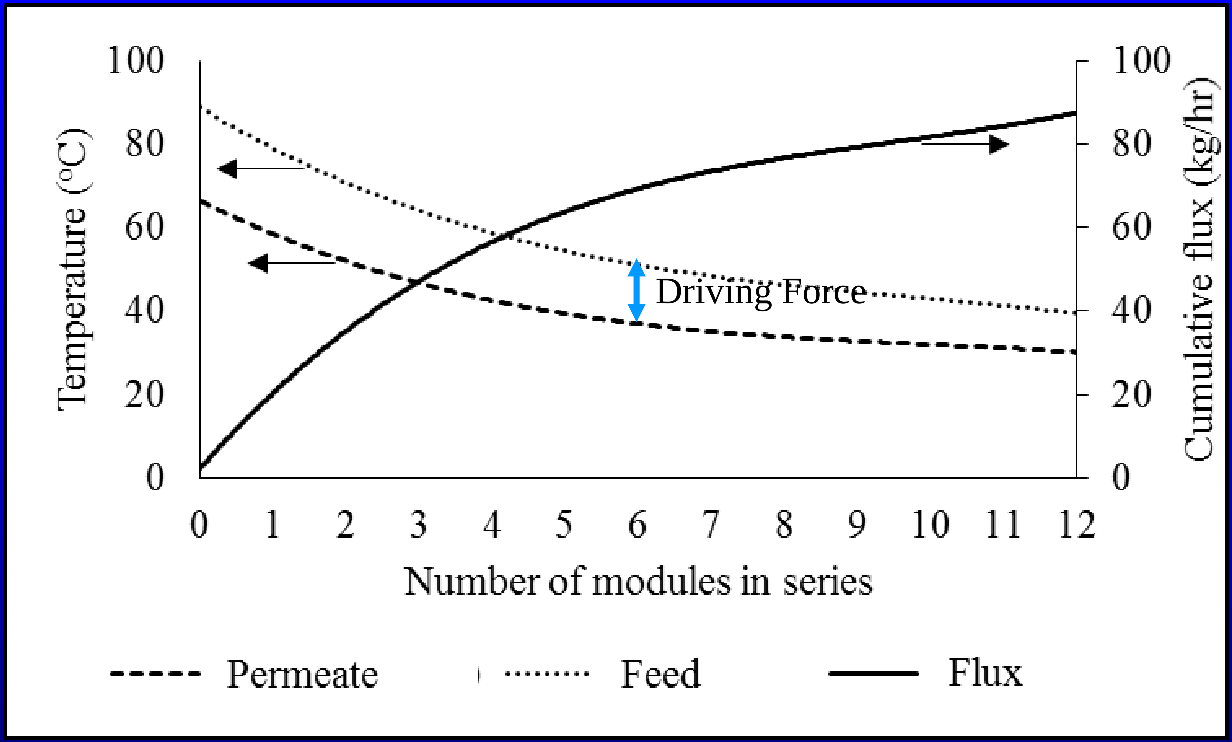
- 54% of waste heat from NGCS is required to concentrate produced water in PA to 30% salinity
- Practical constraints
  - Water transportation
  - NGCS load factor





Initial guess:
$T_{f,i} = T_{m,f}$; $T_{p,i+1} = T_{m,p}$
Determine $p_{m,f}$ and $p_{m,p}$
Calculate J by Eq. (1)
Calculate heat transfer coefficients by Eqn. (8)
Calculate $T'_{m,f}$ and $T'_{m,p}$ by Eq. (6) and (7)
Determine $p'_{m,f}$ and $p'_{m,p}$ Calculate J' by Eq. (1)
$\left|\frac{J'-J}{J'}\right| < 10^{-3}$
No
Update: $J = J'$
Yes
Determine $Q_{m,i}$ by Eq. (3)
Determine $M_{f,i+1}$, $M_{p,i}$, $E_{f,i+1}$ and $E_{p,i}$ by Eq. (10), (11), (12) and (13) respectively
Evaluate $T_{f,i+1}$ and $T_{p,i}$ from $E_{f,i+1}$ and $E_{p,i}$ respectively
Calculate:
$T_{f,avg} = \frac{T_{f,i}+T_{f,i+1}}{2}$ and $T_{p,avg} = \frac{T_{p,i}+T_{p,i+1}}{2}$
$\left|\frac{T_{f,i}-T_{f,avg}}{T_{f,i}}\right| < 10^{-3}$
$\left|\frac{T_{p,i+1}-T_{p,avg}}{T_{p,i+1}}\right| < 10^{-3}$
No
Update:
$T_{f,i} = T_{f,avg}$
$T_{p,i+1} = T_{p,avg}$
Yes
Final values

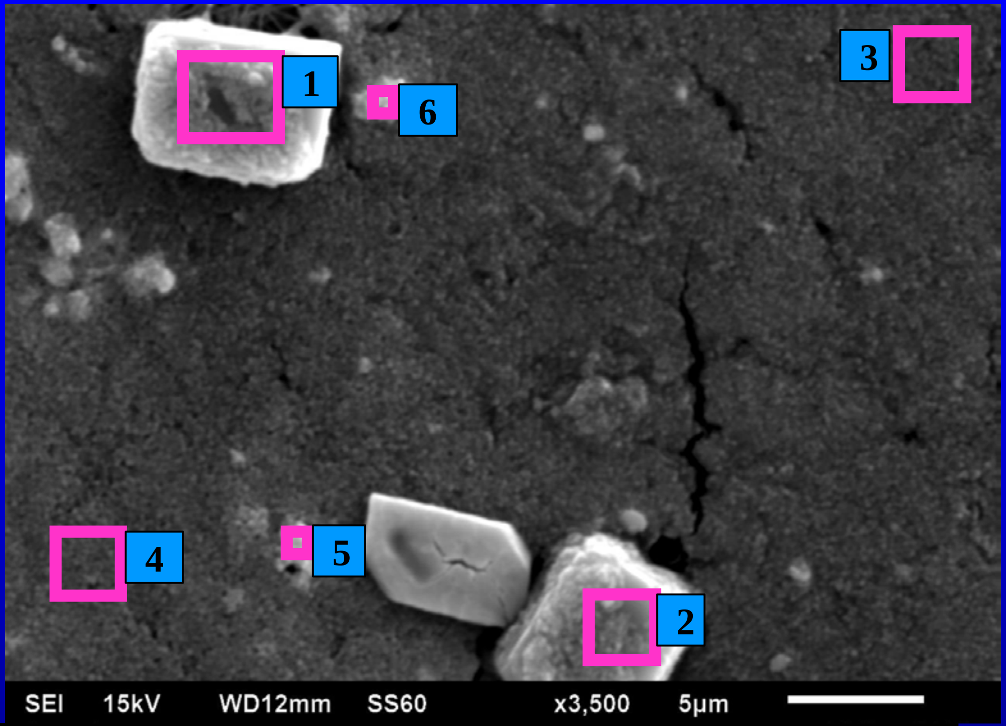
Simulation Results



Temperature and flux profiles for 12 modules in series

- Assuming 1 module has an area of 0.2 m^2
- Minimum temperature difference of 10 °C was selected
- 12 modules in series

Scale Formed on DCMD Membrane



Location	Weight %							
	O	Na	Mg	Cl	Ca	Fe	Sr	Ba
1	11	31	0	51	1	5	0	1
2	9	31	0	56	1	3	0	0
3	43	0	1	10	6	37	0	2
4	44	1	1	10	6	37	0	2
5	32	2	0	5	2	11	2	46
6	30	2	0	8	4	22	1	34

- Iron fouling may be a problem in the long run
- Pretreatment should be considered