Advances in Wastewater Treatment Technology Using Reverse Osmosis Membranes

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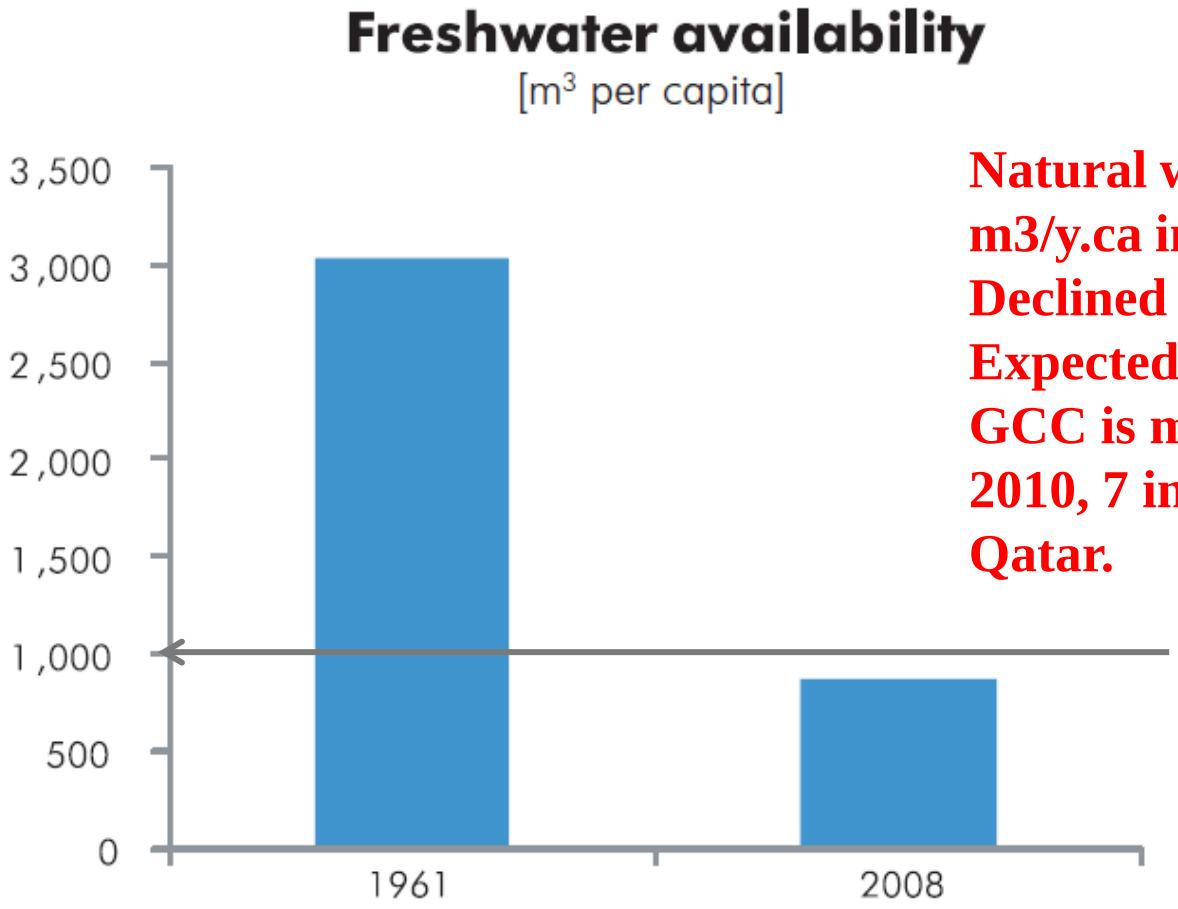
Outline

- Water Reuse
- Developments in Wastewater Treatment
- Description of the Largest Water Reclamation Plant
- Performance of the WR Plant
- Cost of Treatment
- Conclusions

Water Reuse

- Water reuse is considered as part of integrated water resources management
- It is essential to reuse treated wastewater effluents in arid and semi-arid regions of the world
- It is also required anywhere for global water sustainability
- New advances in wastewater treatment technology made it possible to obtain high quality water from wastewater for non-potable and potable uses.

Fresh Water



Natural water resources: was 3000 m3/y.ca in 1961.
Declined to 800 m^3/y.Ca in 2008.
Expected to be 500 m^3/(y.Ca) in 2015.
GCC is more severe, <100 m^3/y.Ca, In 2010, 7 in Kuwait, 20 in UAE, and 33 in Qatar.

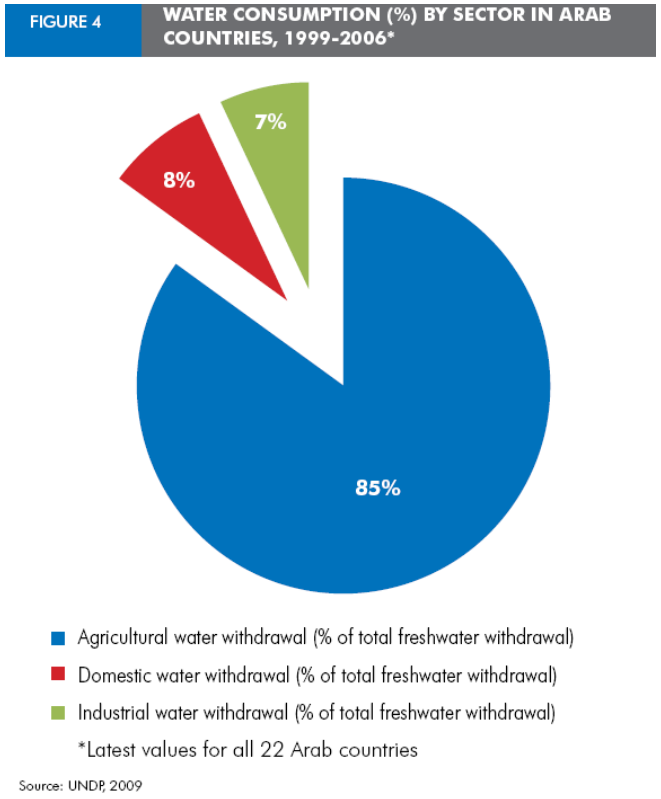
Renewable water resources and per capita share in the GCC

		Average share (m^3/y.Ca)		
Country/ Sub-Region	Natural Water Resources (M m^3)	2010	2030	2050
Bahrain	116	92	70	64
Kuwait	20	7	5	4
Oman	1400	503	389	374
Qatar	58	33	24	22
SA	2400	87	62	53
UAE	150	20	14	12
GCC	4144	95	68	59
Yemen	2100	87	51	34
GCC and Yemen	6244	92	61	47

GCC among the poorest in the world in Renewable water resources

WATER

- Allocating **1.5%** of GDP annually to investments in clean sanitation, water infrastructure, innovative water efficiency, and recycling technologies, amounts to **$28 billion** annually, and will create jobs in both rural and urban regions.
- Wastewater treated should increase from below **60%** today to a **90-100%.**
- The portion of treated wastewater which is reused should increase from **20%** today to **100%.**
- Innovative technologies for water desalination should be developed locally, incorporating the use of solar energy.



Wastewater Treatment

- Wastewater should be treated to protect the environment and safeguard public health
- It could be tailored to produce a treated effluent of any required quality
- In spite of complexity in raw wastewater quality, cost-effective treatment methods are available to produce good-quality effluents for various reuse applications

Increasing Levels of Treatment;
Increasing Acceptable Levels of Human Exposure

Primary Treatment:
Sedimentation

- No uses Recommended at this level

Secondary Treatment:
Biological Oxidation, Disinfection

- Surface irrigation of orchards and vineyards
- Non-food crop irrigation
- Restricted landscape impoundments
- Groundwater recharge of non potable aquifer**
- Wetlands, wildlife habitat, stream augmentation**
- Industrial cooling processes**

Tertiary Treatment:
Chemical Coagulation, Filtration, Disinfection

- Landscape and golf course irrigation
- Toilet flushing
- Vehicle washing
- Food crop irrigation
- Unrestricted recreational impoundment
- Indirect potable reuse **

Quaternary Treatment:
Membrane Processes, Disinfection

- Direct potable reuse
- Groundwater recharge of potable aquifer
- Surface water reservoir augmentation**

* Suggested uses are based on Guidelines for Water Reuse, developed by U.S. EPA.
** Recommended level of treatment is site-specific.

Fig. 1. Wastewater treatment levels, unit treatments, and water reuse options

Membrane Technology

Membrane filtration has increasingly been utilized as an effective measure to obtain higher quality water from wastewater and seawater. It is a process of separating materials based on their particle size and other compound properties by letting water through membranes using pressure and concentration. Membrane filtrations are classified according to the size of materials removed:

- Microfiltration (MF) membrane has pores of 0.1-1 μ m in diameter. It can remove particles and is effective against bacteria, cysts, and oocysts.
- Ultrafiltration (UF) membrane has smaller pores (0.01-0.1 μ m) and can remove particles and large molecules, including bacteria and viruses.
- Reverse Osmosis (RO) membrane can reject even smaller ionic solutes such as salts resulting in almost mineral-free water, based on sieving and electrochemical interaction between molecules and membrane (see Figure 5).
- Nanofiltration (NF) membrane is similar to RO and its operation pressure and salt rejection rate are low.

Osmosis and reverse osmosis flow

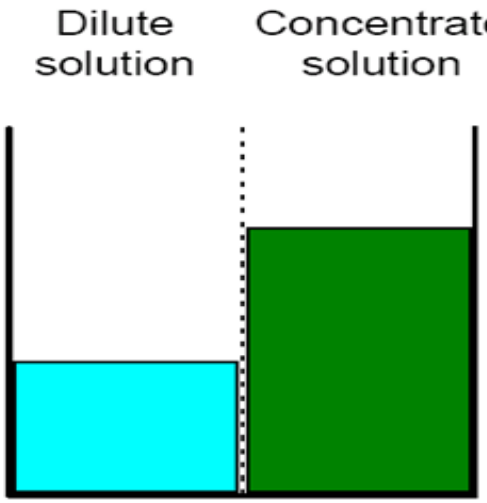


Figure 1a

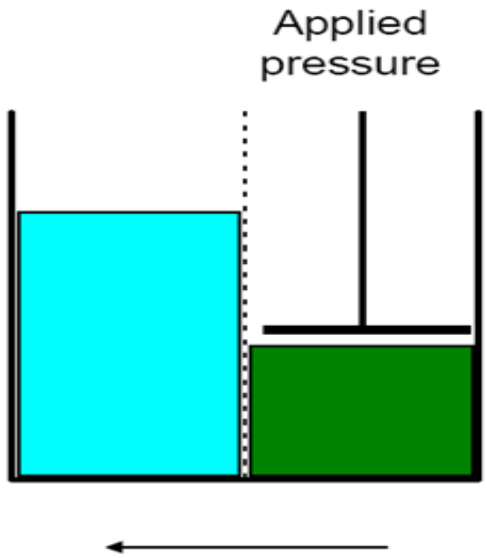
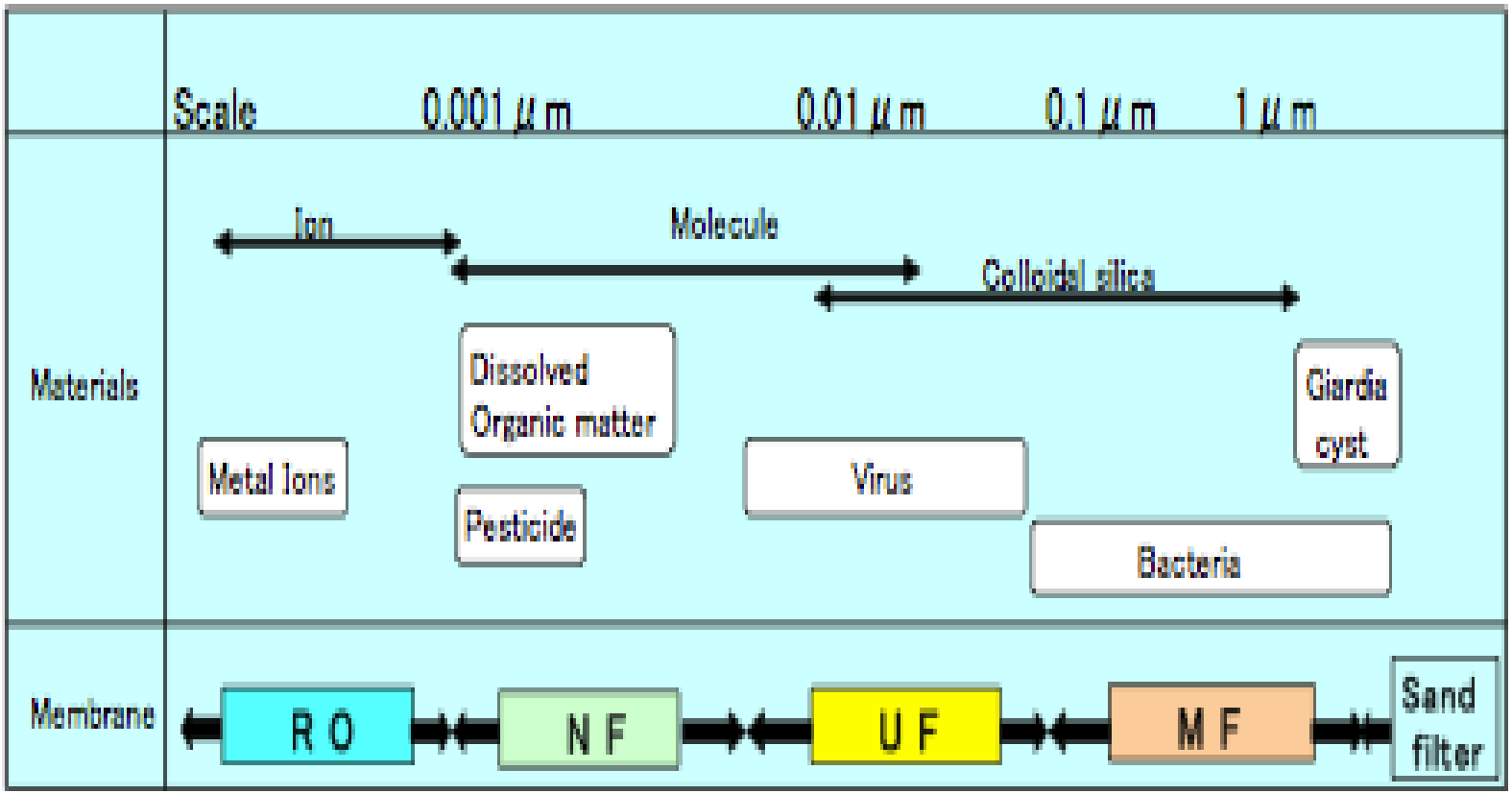
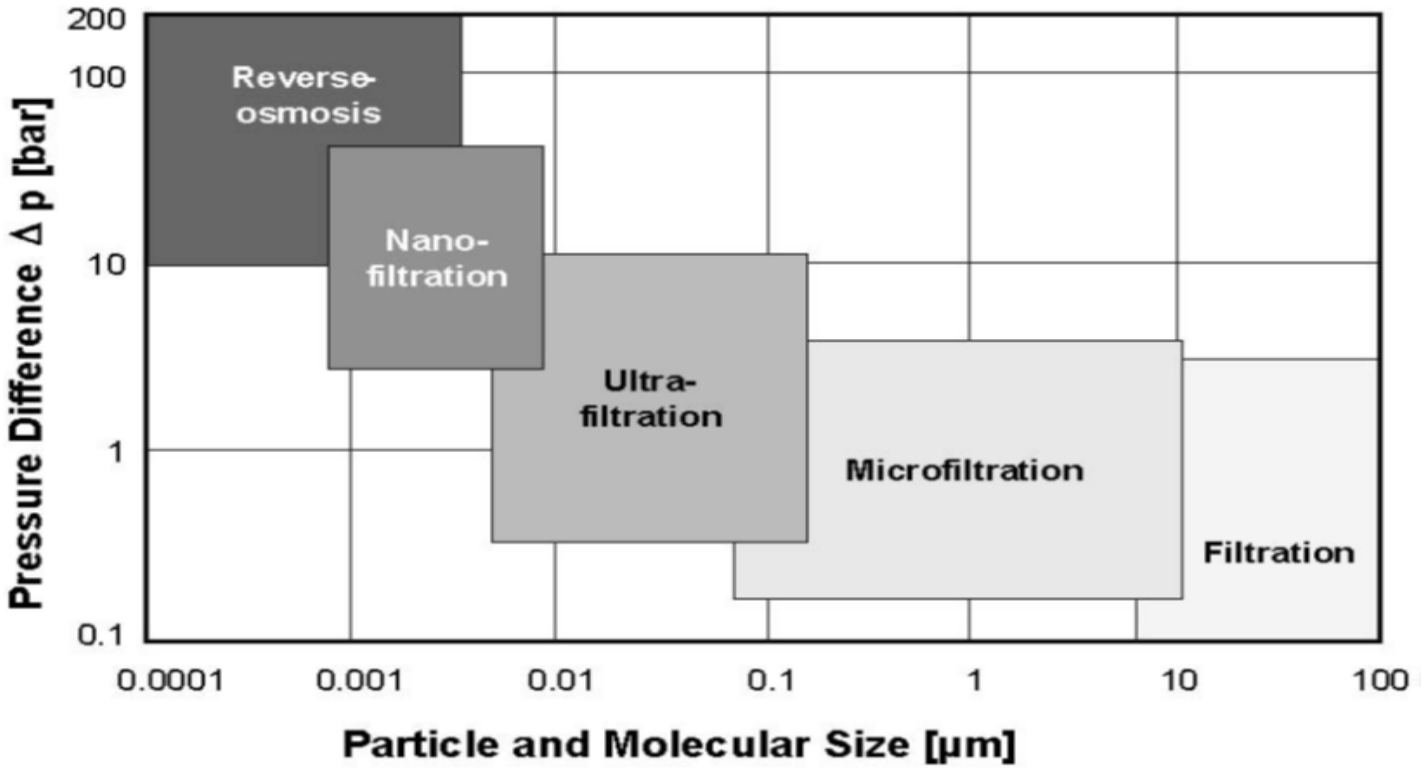


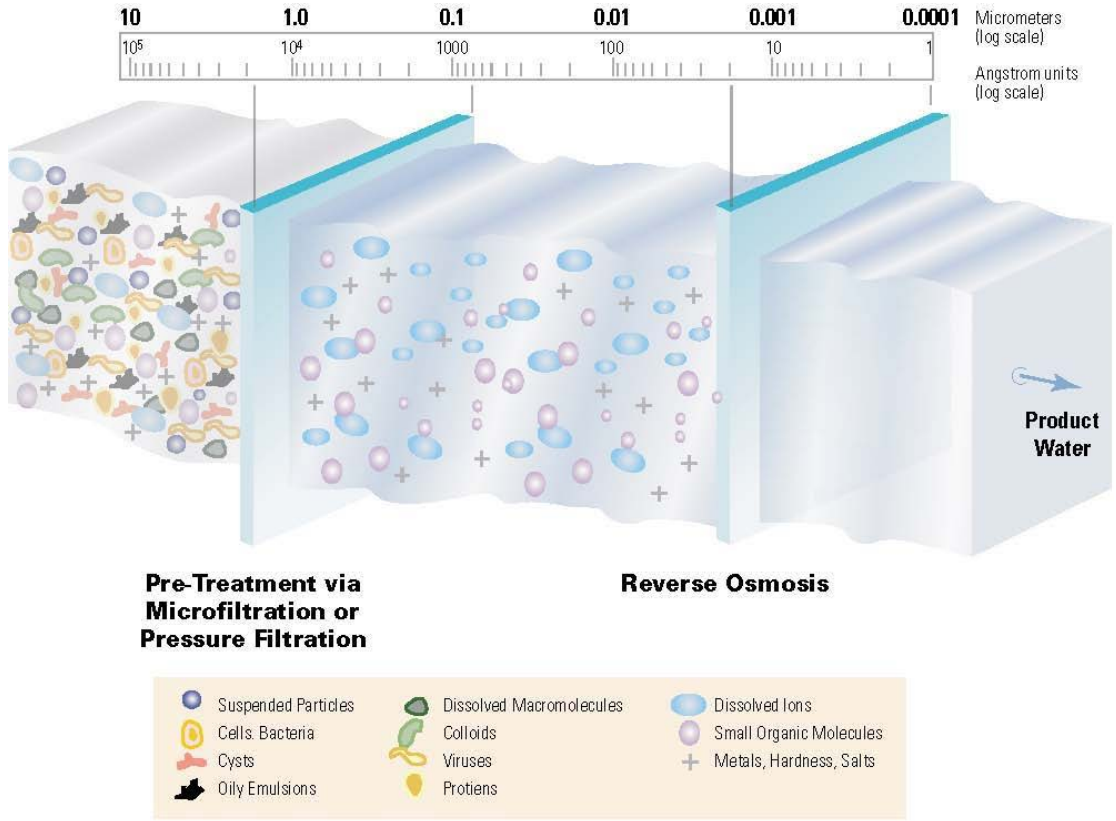
Figure 1b


Scale
0.001 μ m
0.01 μ m
0.1 μ m
1 μ m
Materials
Ion
Molecule
Colloidal silica
Dissolved Organic matter
Giardia cyst
Metal Ions
Pesticide
Virus
Bacteria
Membrane
R O
N F
U F
M F
Sand filter

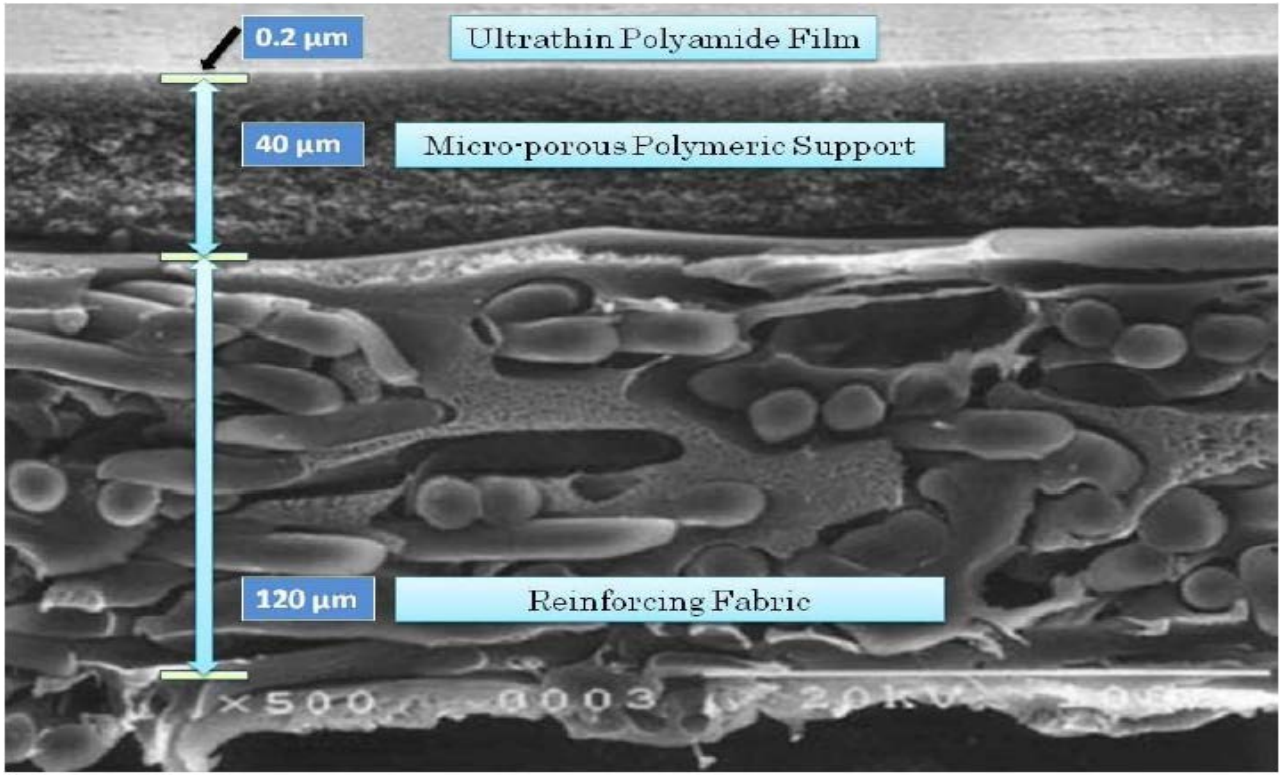
Separation capabilities of pressure driven membrane separation processes



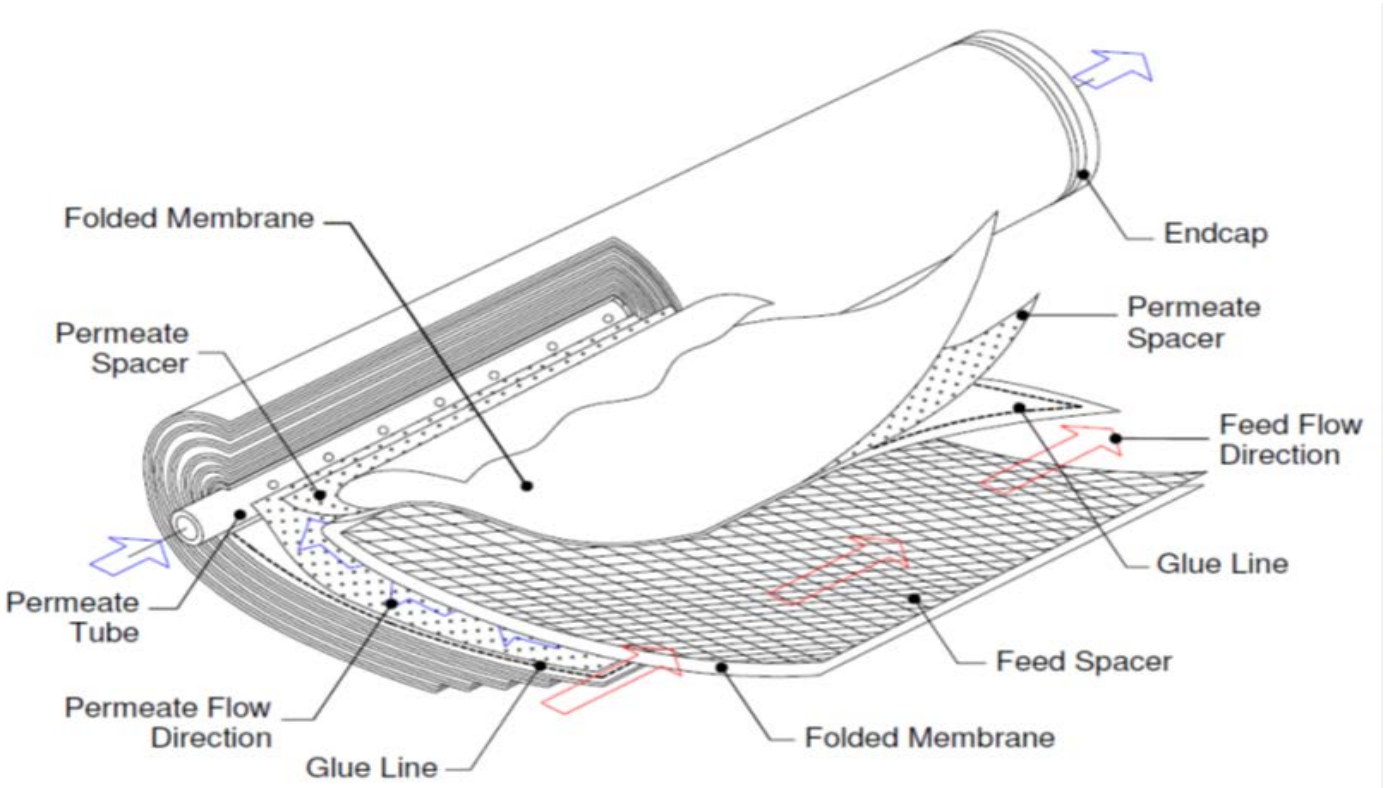
RO Membrane Removal and Pretreatment



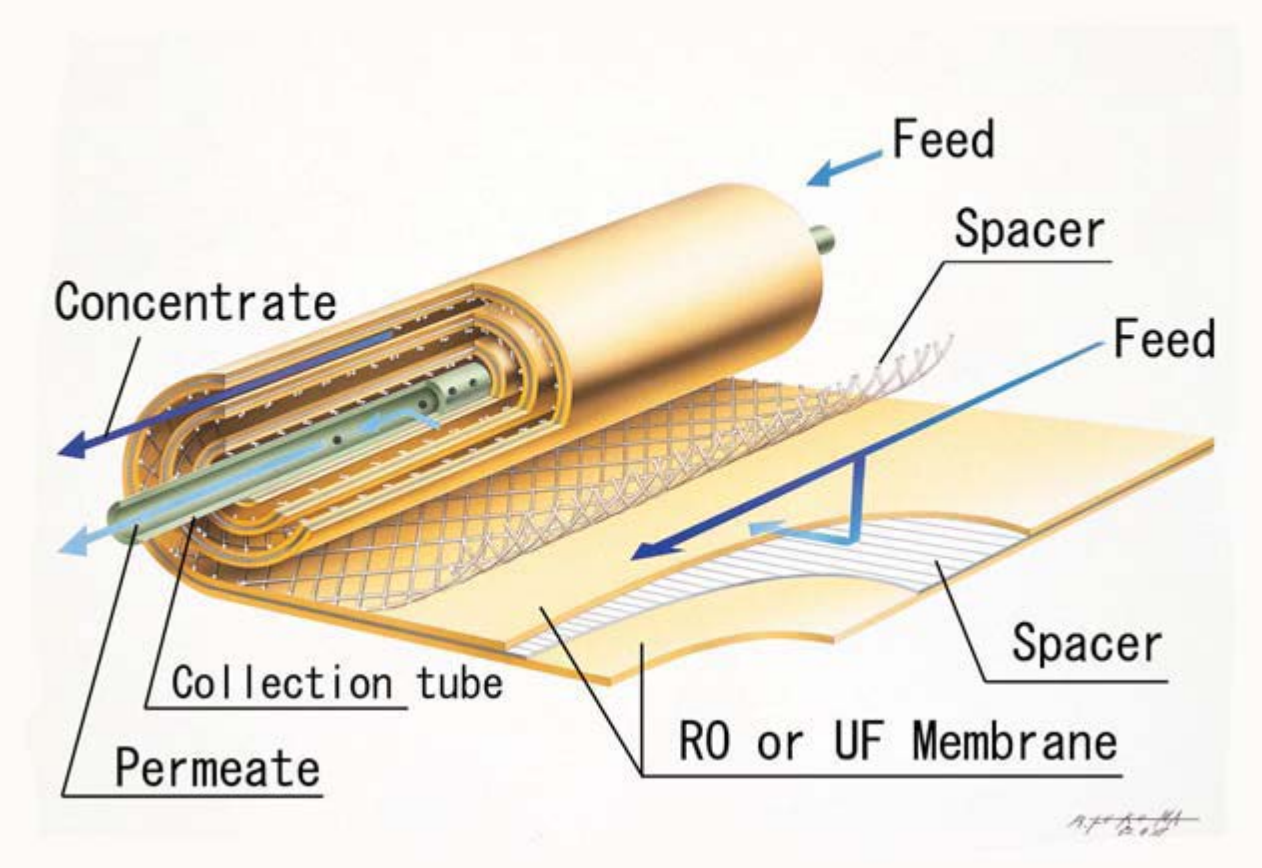
Structure of Typical RO Membrane



Spiral wound module



Reverse Osmosis Membrane Modules

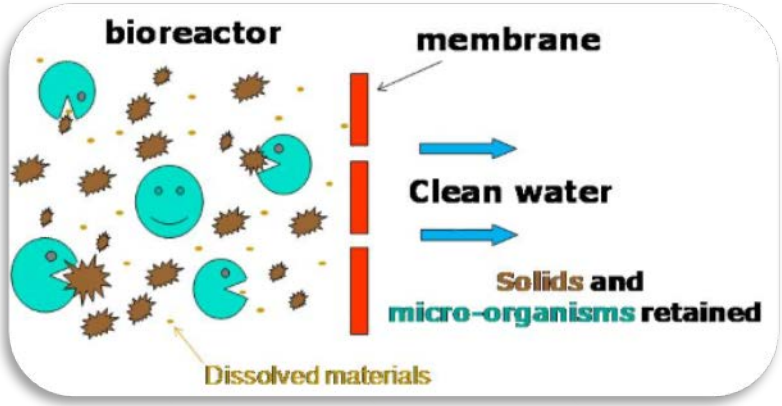


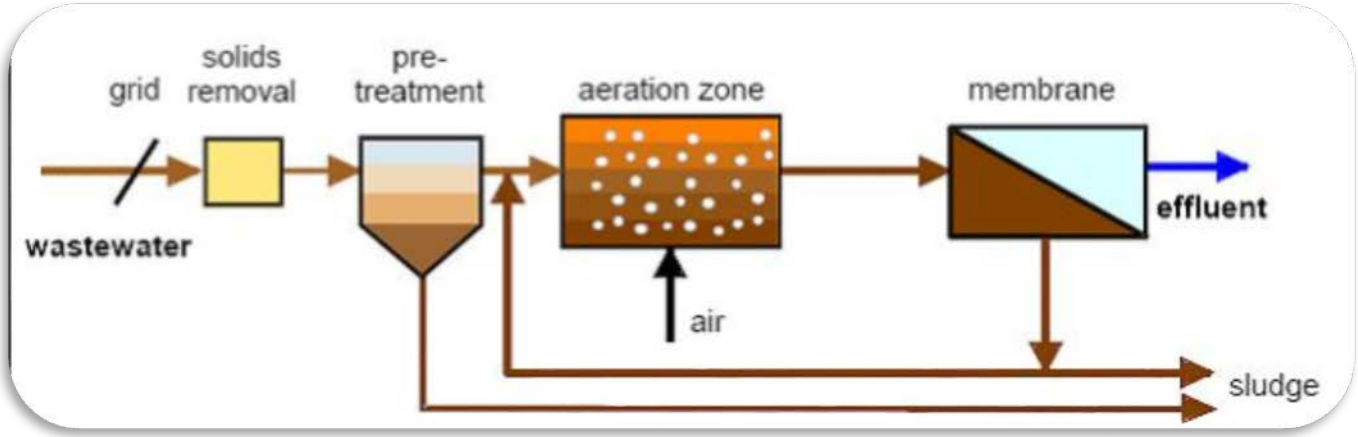
Applications of Reverse Osmosis in Wastewater Treatment

- **Secondary Treatment: Membrane Bioreactor (MBR)/Activated Sludge Process**
- **Tertiary /Advanced Treatment: UF/RO Reclamation System**

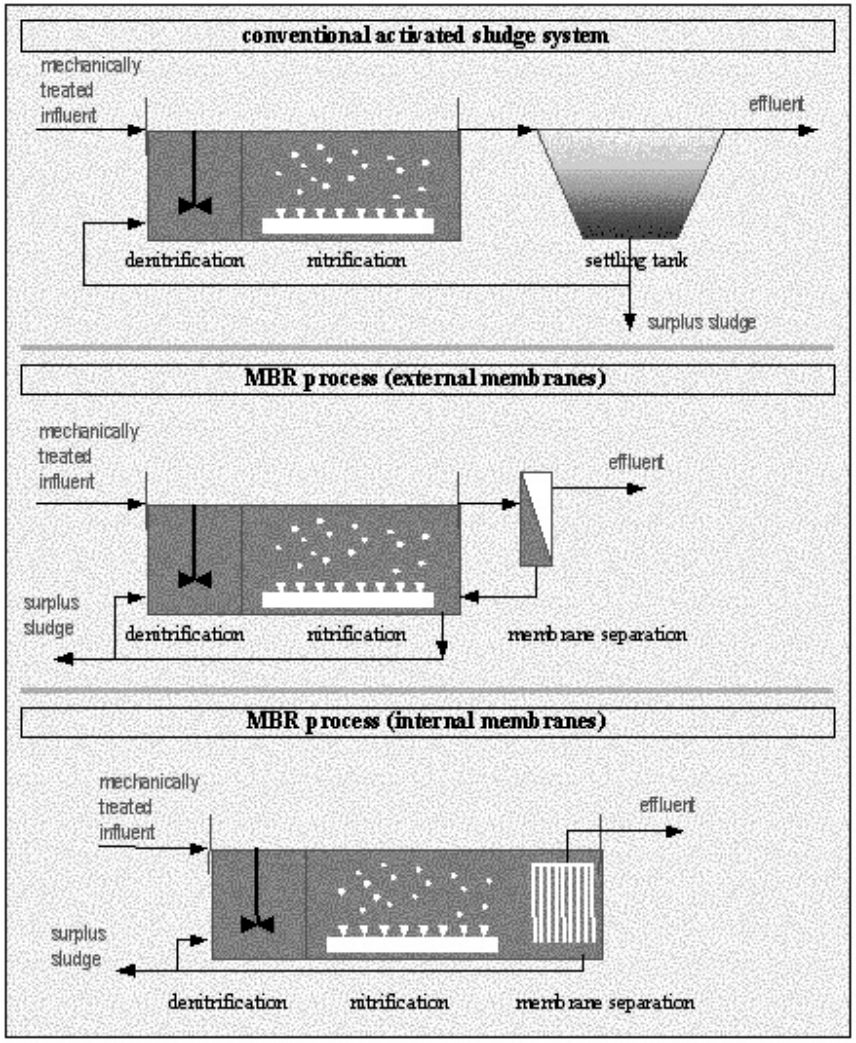
Membrane Bioreactor (MBR) Process

Simple schematic describing the MBR process





Activated Sludge and MBR Processes in Secondary Wastewater Treatment



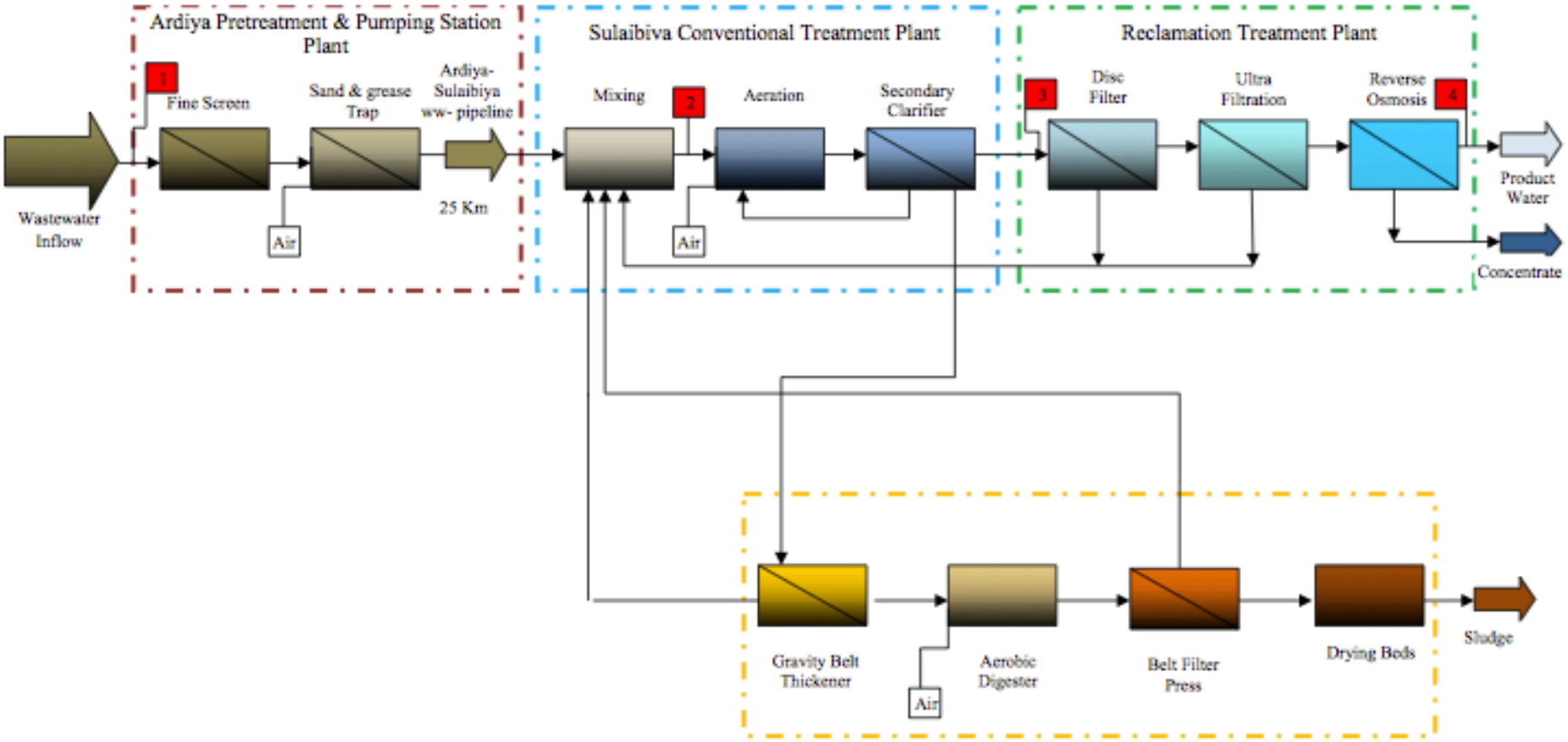
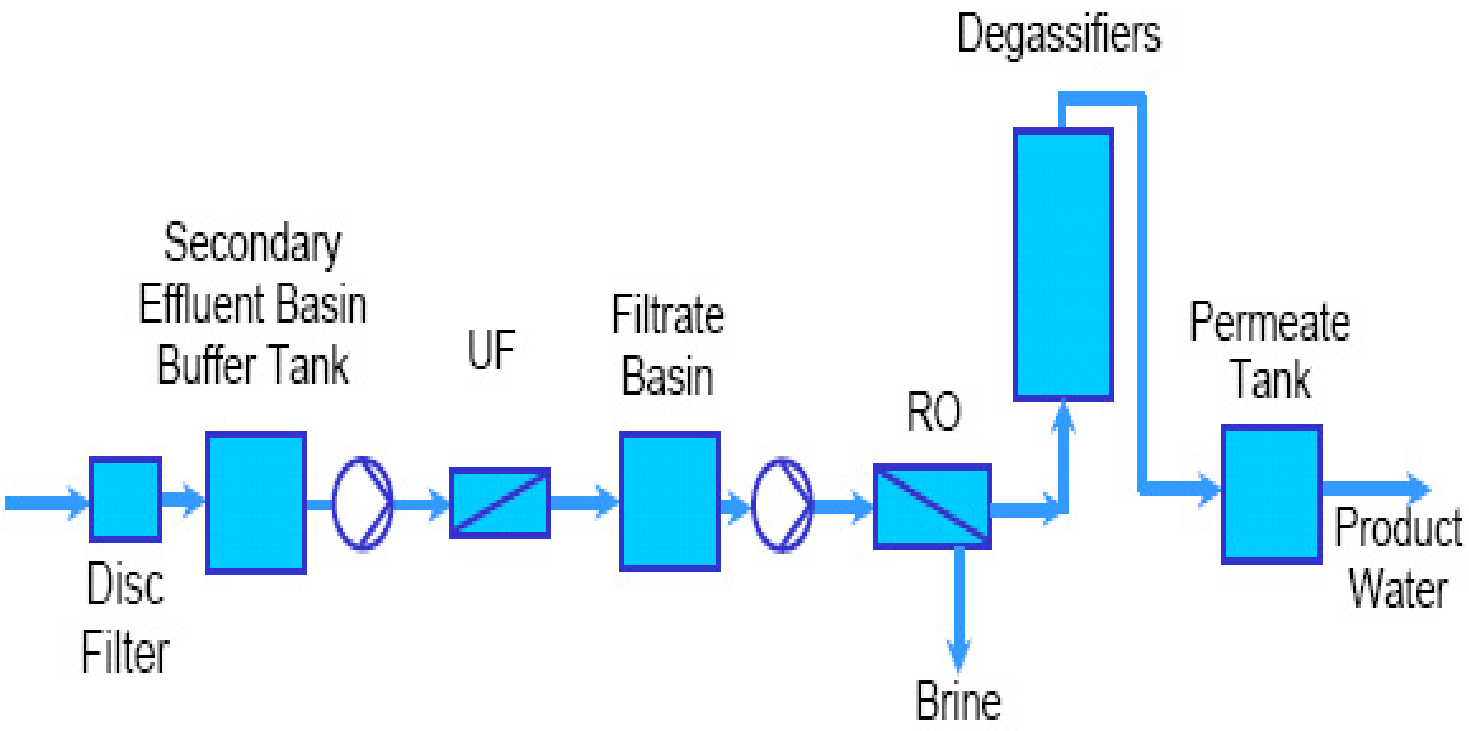


Fig. 3. Flow diagram of Ardiya – Sulaibiya wastewater treatment and reclamation plant

Scheme of Membrane Reclamation Plant



Common Wastewater Treatment and Reclamation Plants Using Membrane Processes Worldwide

No.	Plant, Country	Capacity m^3/day
1	Bedok, Singapore	32,000
2	Kranji, Singapore,	40,000
3	West Basin, California, USA	50,000
4	Ulu Pandan, Singapore	170,000
5	Orange County , California, USA	270,000
6	Sulaibiya, Kuwait	425,000

Table (2) Design Parameters of Sulaibiya Wastewater Treatment and Reclamation Plant.

No.	Parameters	Values
1	Total Feed Flow	425,000 m^3/day
2	Total Product Flow	352,750 m^3/day
3	Plant Recovery	83 %

Table 3. Characteristics of membrane systems employed at Sulaibiya water reclamation plant

Membrane System	**Membrane Type**	**Membrane Configuration**	**Membrane Arrangement**	**Membrane Area**
Ultrafiltration (UF)	Norit'sX Flow Cross Flow,The Netherland. (Model XIGA SXL-225). Polyvinyldene Fluoride	Capillary hydrophilic hollow fibers	Membranes packed in 20 x 152 cm membrane elements (35 m^2 /element), 4 membrane elements are placed inside a membrane housing. There are 68 skids, each with 32 membrane housings for a total of 8,704 membrane elements (4 x 32 x 68).	8,704 x 35 m^2 = 304,640 m^2
Reverse Osmosis (RO)	Torayof America. (Model TML 20-400). Polyamide composite.	Spiral wound	Membrane modules of 42 identical skids in a 4:2:1 array (train) of modules. Each module contains about 504 RO elements (72 pressure vessels x 7 RO element/ vessel) for a total of 21,168 membrane elements (7 x 72 x 42).	21,168x 37 m^2 = 783,216 m^2

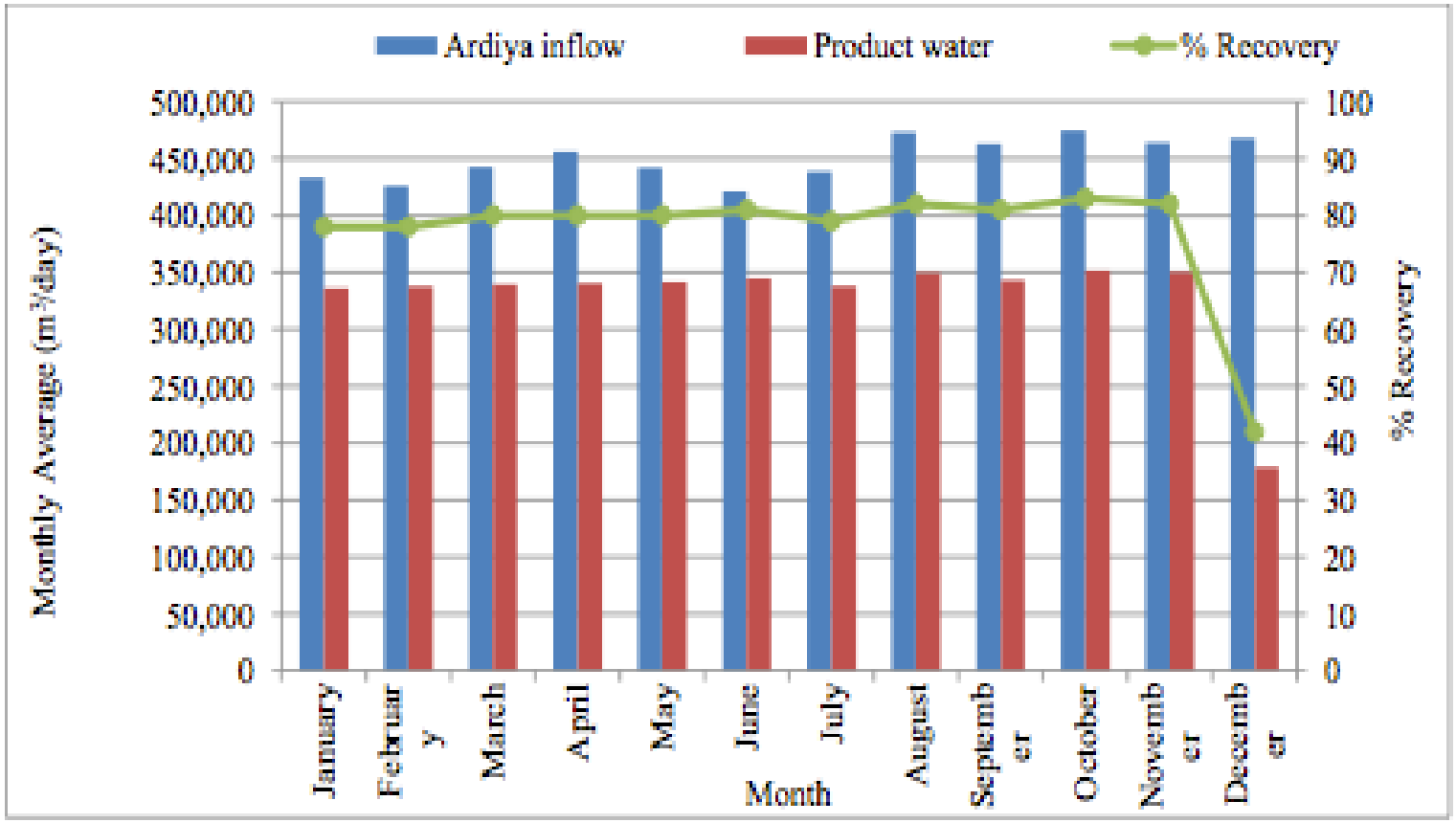


Fig.6. Monthly variations in % Recovery of influent flow in the reclamation stage

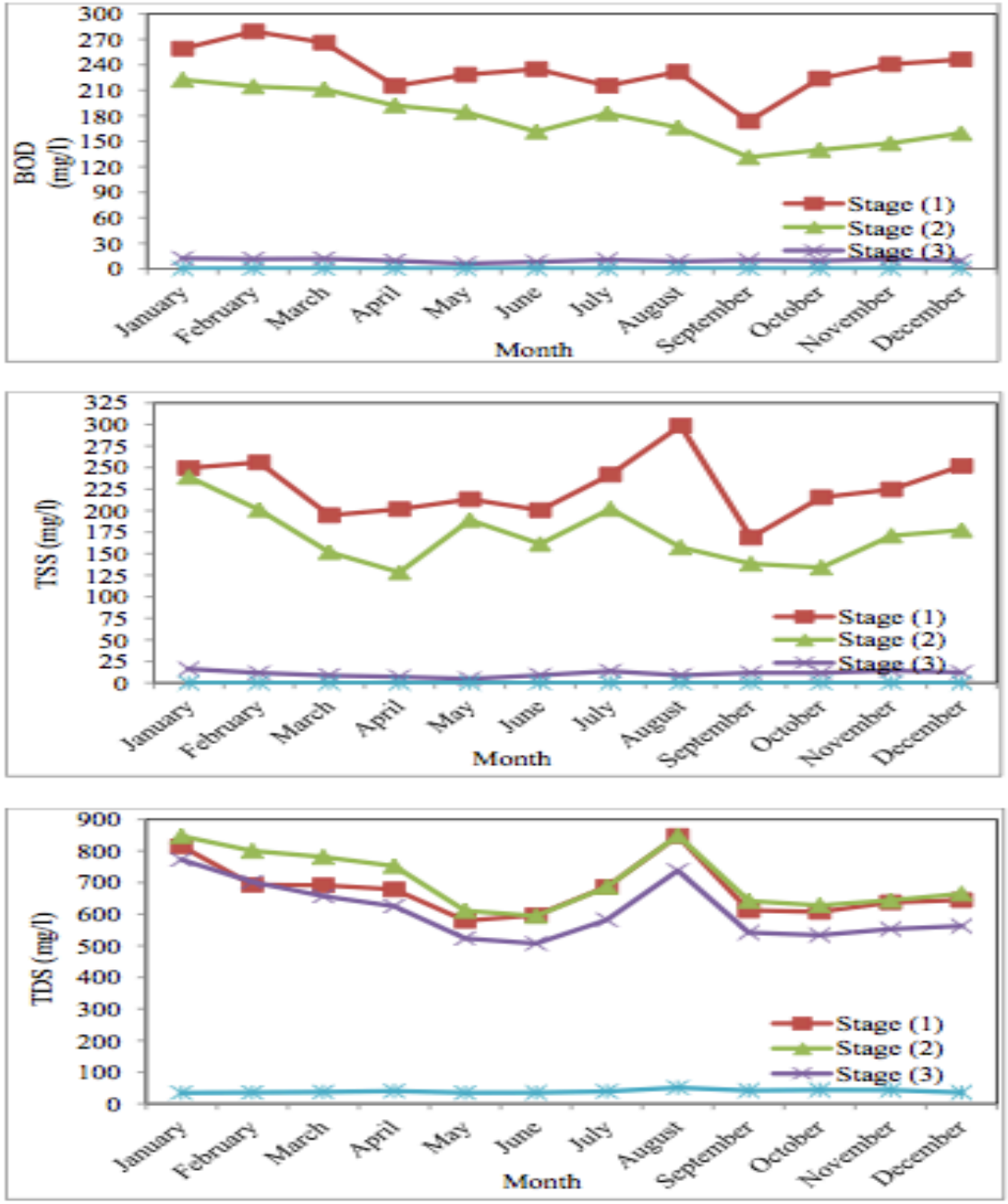
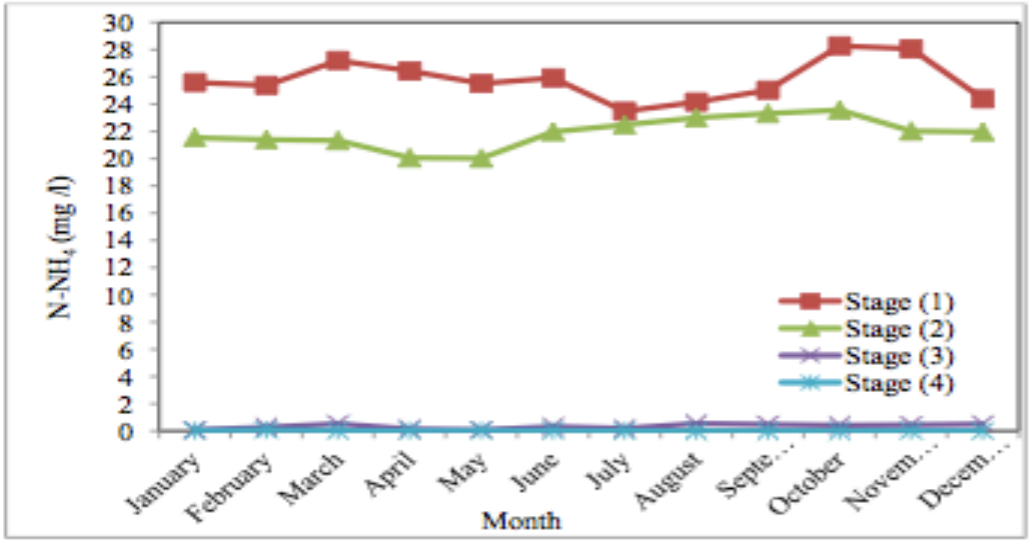


Fig.7. Monthly variations in different BOD and solids concentrations along the treatment stages



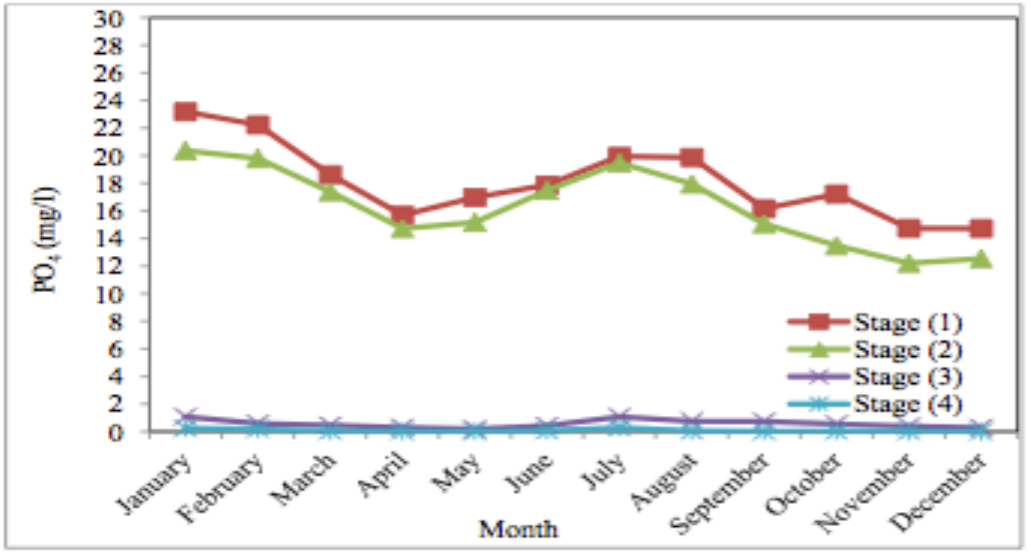
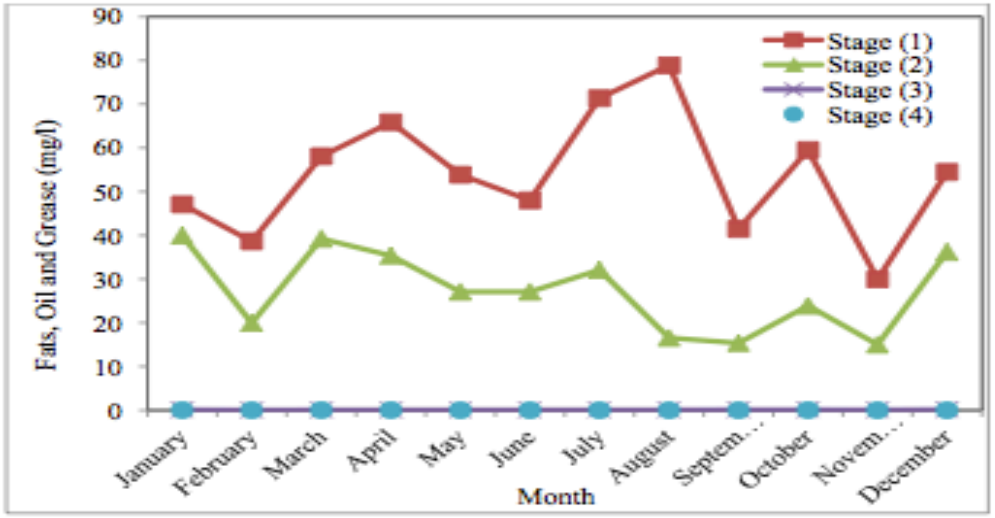


Fig. 8. Monthly variations in ammonia and phosphates along the treatment stage



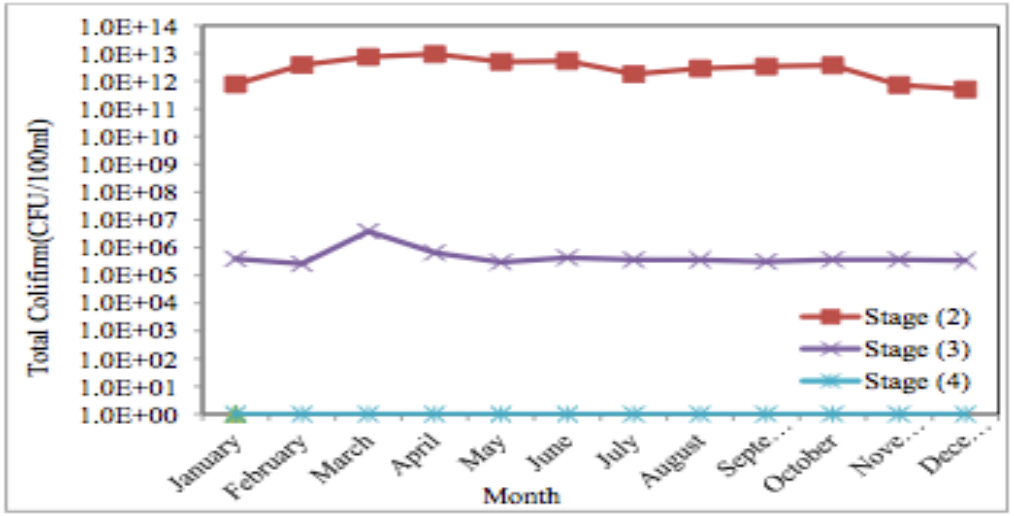


Fig. 9. Monthly variations in fats and total coliforms along the treatment stage

Table 5. Effluent water quality criteria as compared to potable water quality criteria

Parameter	Unit	Contractual Effluent Quality Standards from Sulaibiya	Actual Effluent from Sulaibiya (2012)	WHO Max Allowable Limits	Kuwait Standard for Un-bottled Potable Water (Max.)
pH	-	6-9	7.3	6.5-8.5	6.5-8.5
TDS	mg/l	<100	39	1200	1000
TSS	mg/l	<1	0.024		
VSS	mg/l	<1	0.019		
BOD	mg/l	<1	0.23		
Ammonia Nitrogen as N	mg/l	<1	0.03	35	1.5
Nitrate Nitrogen as N	mg/l	<1	0.7	10	
Total Phosphate	mg/l	2	0.08		
Sulfide	mg/l	<0.1	1.3E-04	0.1	0.05
Fats, Oil and Grease	mg/l	<0.05	0.015	0.01	
Total Organic Carbon	mg/l	<2	0.34		
Hardness as $CaCO_3$	mg/l	<10		500	500
Colour	T C U	<1	Clear		15
Total Coliform	MPN /100ml	<2.2	1		Free

Table 6. Statistical parameters of Suliabiya plant performance data in the year 2012

Parameters	Ardiya					Sulaibiya					Product Water				
	Min	Mean	Max	S.D	CV	Min	Mean	Max	S.D	CV	Min	Mean	Max	S.D	CV
Temp (^{o}C)	28.55	24.40	37.90	3.97	0.16	19.10	27.32	36.10	3.94	0.14	24.5	31.2	36.9	3.54	0.11
pH	7.01	6.89	7.40	0.12	0.02						6.3	7.3	7.8	0.18	0.02
Cond (µs/cm)	1150.53	1098.71	2190	272.49	0.25										
TSS(mg/l)	220.44	251.94	926	98.80	0.39	52	177	484	57.49	0.32	0.0	2.4E-2	5.0E-1	5.9E-2	2.49
VSS(mg/l)	170.82	186.77	794	72.53	0.39	42	144.8	436	48.39	0.33	0.0	1.9E-2	3.0E-1	4.9E-2	2.58
TDS (mg/l)	674.59	644.87	1286	159.51	0.25	514	708.3	1326	119.9	0.17	14	39.3	57.0	6.73	0.17
COD (mg/l)	410.17	471.83	972.75	106.91	0.23	190.03	318.7	618.88	69.15	0.22					
BOD (mg/l)	234.64	246.19	459	69.94	0.28	66.65	178.5	366.6	51.62	0.29	0.0	2.3E-1	1.4E+0	2.0E-1	0.88
FOG (mg/l)	54.08	54.49	187	26.87	0.49	3.10	27.39	95.92	12.89	0.47	0.0	1.5E-2	4.8E-2	1.2E-2	0.83
NH4-N (mg/l)	25.79	24.39	37.15	3.15	0.13	11.63	21.98	29.37	2.23	0.1	0.0	2.5E-2	2.8E-1	4.4E-2	1.74
N-Org (mg/l)	12.65	14.12	26.89	3.46	0.24	2.88	10.35	17.53	2.31	0.22					
NO_3 -N (mg/l)	0.51	0.48	2.10	0.21	0.43	0.1	0.46	1.30	0.16	0.34	3.0E-1	7.3E-1	1.0	1.2E-1	0.16
NO_2 (mg/l)	0.06	0.05	0.52	0.07	1.48	0.00	0.08	1.20	0.10	1.16					
P- total (mg/l)	5.92	4.80	16.34	1.88	0.39	1.75	5.33	13.60	1.47	0.28	0.0	8.4E-2	1.4	2.0E-1	2.34
PO_4 (mg/l)	18.03	14.72	44.03	5.57	0.38	5.37	16.38	41.70	4.51	0.28					
Alkalinity $CaCO_3$ (mg/l)	174.88	165.21	240.23	16.71	0.10	60	185	229.18	15.62	0.08					
Cl-(mg/l)	186.83	164.48	472.36	77.86	0.47										
SO_4(mg/l)	112.26	122.61	204	23.89	0.19										
H_2S (mg/l)	4.21	1.87	50.13	4.74	2.54						0.0	1.3E-4	9.0E-3	6.1E-4	4.76
TKN (mg/l)	38.65	39.57	54.57	4.55	0.11	19.49	32.64	41.93	2.69	0.08					
Settle (cm^3/l/hr)	2.77	2.83	14.7	1.67	0.59	0.30	3.56	12.20	1.31	0.37					
Hardness $CaCO_3$ (mg/l)											3.8E-1	2.9	4.1	4.5E-1	0.15
Total Coliform (colonies/100ml)	3.73E+12	5.03E+11	7.7E+13	6.27E+12	12.47						1.0	1.0	1.0	0.0	0.0
TOC (mg/l)											0.0	3.4E-1	1.1	1.7E-1	0.51

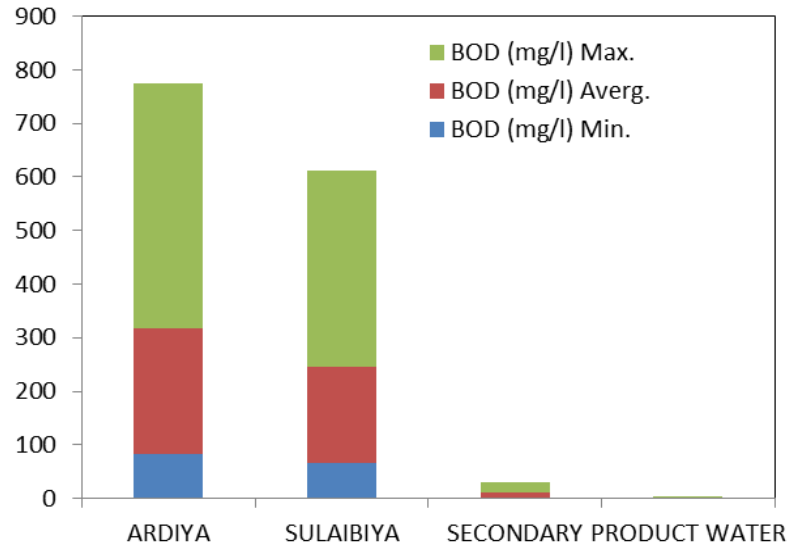
Chemical and Microbiological Quality of Wastewater Effluents along Treatment Stages

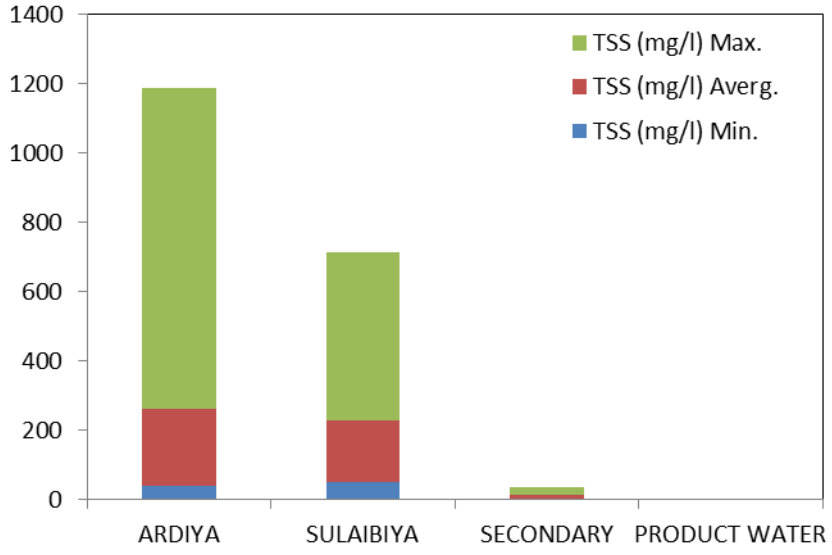
Parameter	Unit	Inflow to WWTP	Inflow to Water Reclamation Plant	RO Effluent for Reuse	Irrigation water Standards	Drinking water Standards
pH	—	6.5- 8	6.5- 7.5	6-8	6.5 – 8	6.8 – 7.5
Conductivity	µs/cm	1200- 3000	1100- 2200		1500	515
TSS	mg/L	100- 500	< 10	< 1	15	_
VSS	mg/L	70- 350	< 7.0	< 1	_	_
COD	mg/L	250- 750	< 40	15	100	_
BOD_5	mg/L	100- 400	< 10	< 1	20	_
Grease & Oil	mg/L	10- 50	NIL	< 0.05	5	_
TDS	mg/L	700- 1800	800- 1500	< 100	_	400
Chloride	mg/L	200- 400	200- 400		_	103
Ammonia	mg/L	15- 50	1- 5	< 1	15	_
Nitrite	mg/L	0.04- 0.7	0.1- 1.5	< 1	_	_
Total Count	colony/100mL	2.40E+09	1E+03	NIL	_	NIL
T.Coli	colony/100mL	3.20E+08	400	NIL	400	NIL
F.Coli	colony/100mL	4.10E+07	0 - 10	NIL	20	NIL
Salmonella	colony/100mL	4.50E+06	NIL	NIL	_	NIL
Streptococci	colony/100mL	1.40E+07	NIL	NIL	_	NIL
Fungi	colony/100mL	2.10E+05	2- 100	NIL	_	NIL

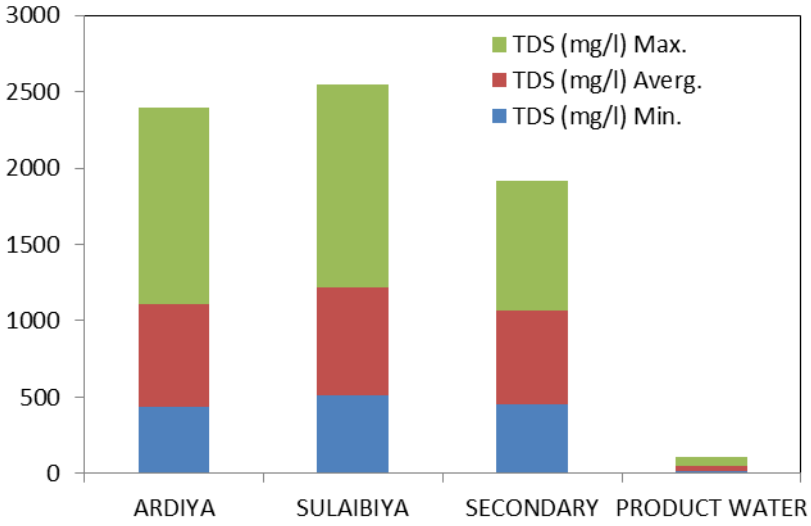
Effluent quality of secondary-treated and reclaimed product water as compared to water quality criteria

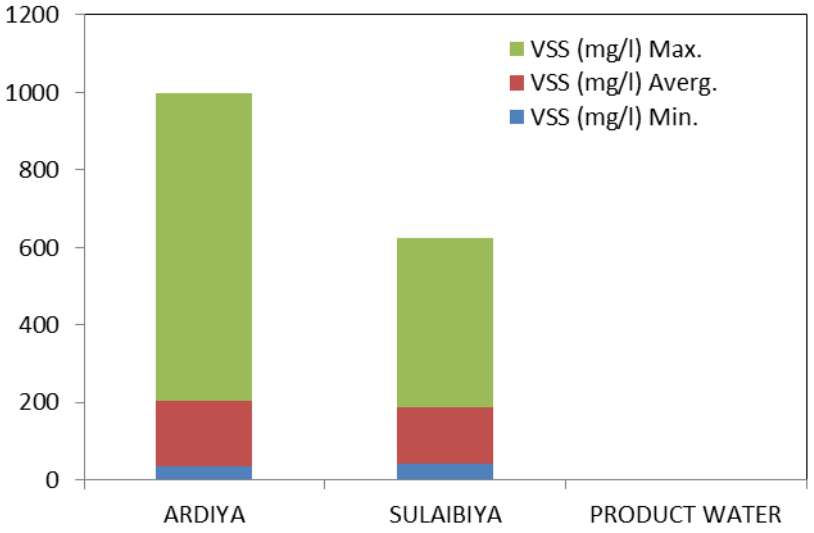
Parameter	Unit	Secondary Effluent	Reclaimed Product Water	Kuwait Standard for Irrigation Water (Max.)	Kuwait Standard for Un-bottled Potable Water (Max.)	WHO Allowable Limits for Drinking Water (Max.)
pH	-	7.3	7.3	6.5-8.5	6.5-8.5	6.5-8.5
BOD	mg/l	11	0.23	20	-	-
TSS	mg/l	7	0.024	15	-	-
TDS	mg/l	580	39.3	1500	1000	1200
NH_3-N	mg/l	0.53	0.025	15	1.5	1.5
NO_3-N	mg/l	1.1	0.73	35	-	10
PO_4	mg/l	1.2	0.04	30	-	-
Sulfide	mg/l	2	0.013	0.1	0.05	0.1
Chlorine	mg/l	0.25	0.11	0.5-1.0	0.2-0.5	-
Fats, Oil and Grease	mg/l	4.9	0.015	5	0.01	0.01
Turbidity	NTU	30	1		-	-
Hardness as $CaCO_3$	mg/l	360.8	2.9	500	500	500
Total Coliform	MPN /100ml	300	1	400	Free	1
Fecal Coliform	MPN /100ml	15	0	20	Free	Free

Variations in BOD, TSS, TDS and VSS concentrations along treatment stages

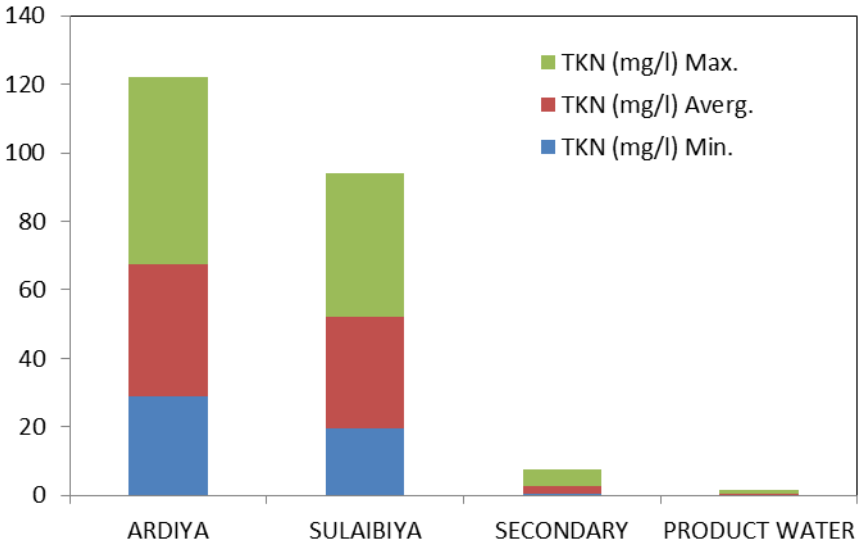


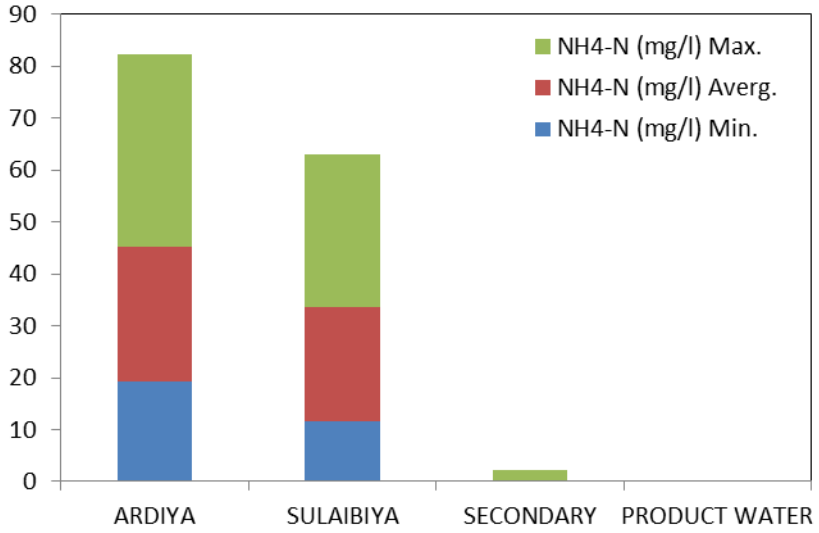


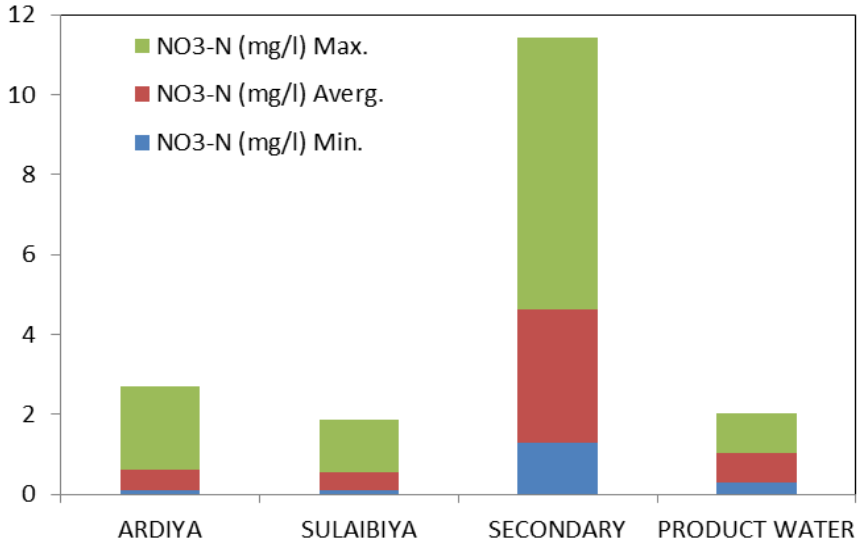


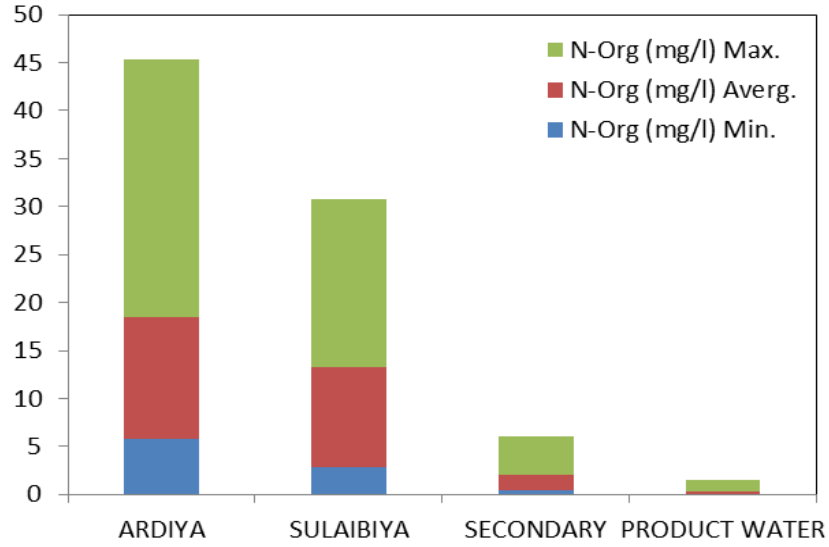


Variations in TKN, ammonia, nitrates, and organic nitrogen concentrations along treatment stages

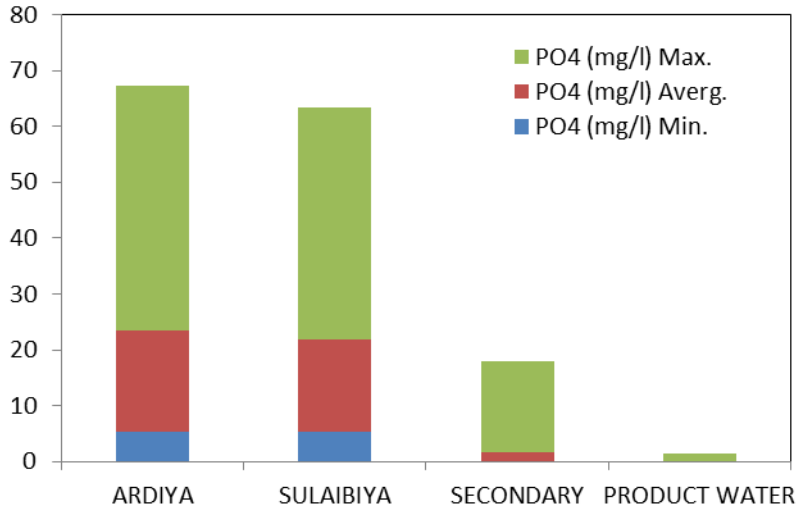


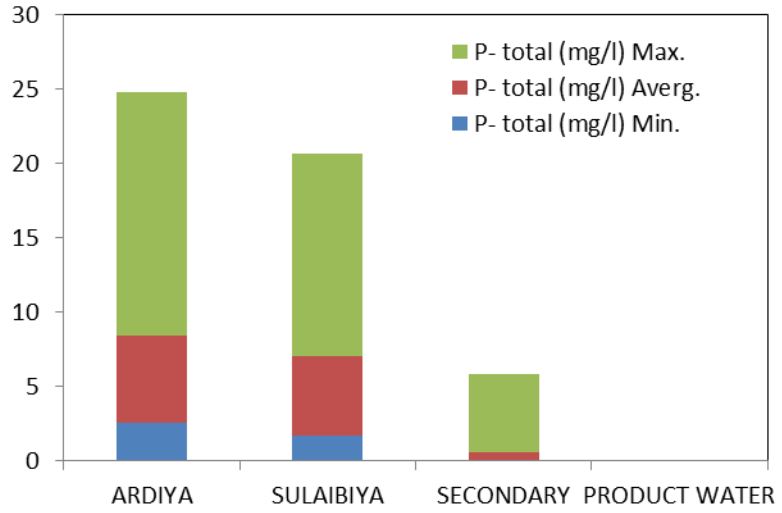


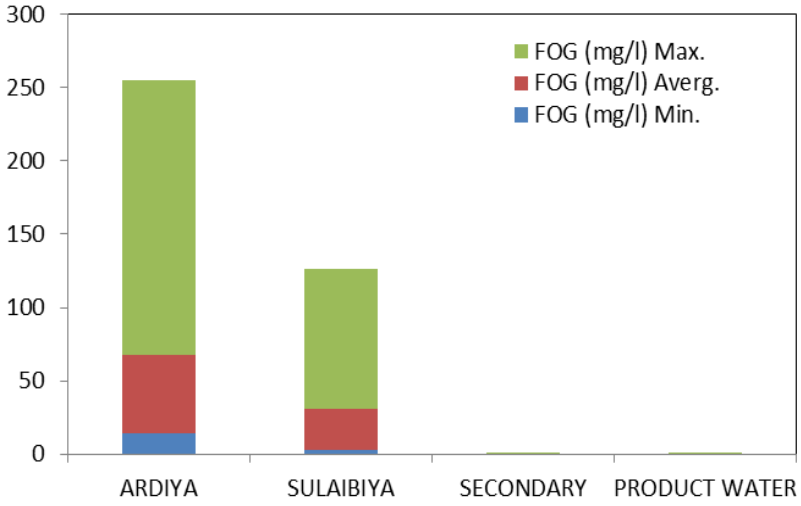


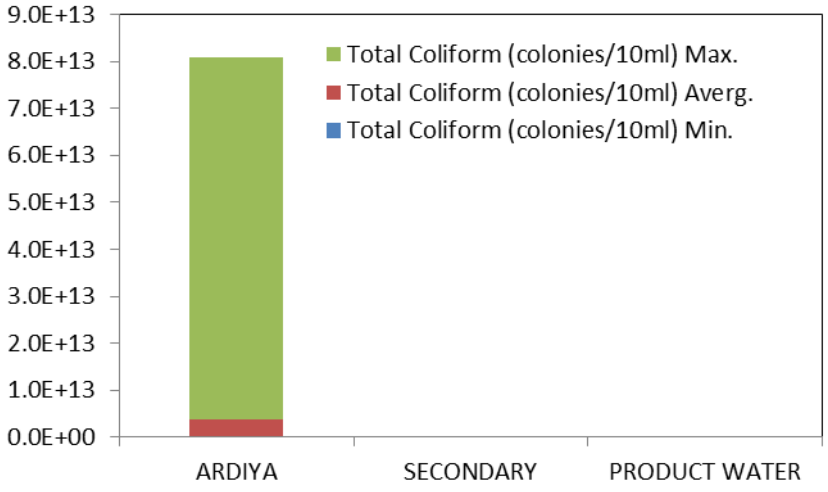


Variations in total phosphates, phosphorus, fats and coliform concentrations along treatment stages





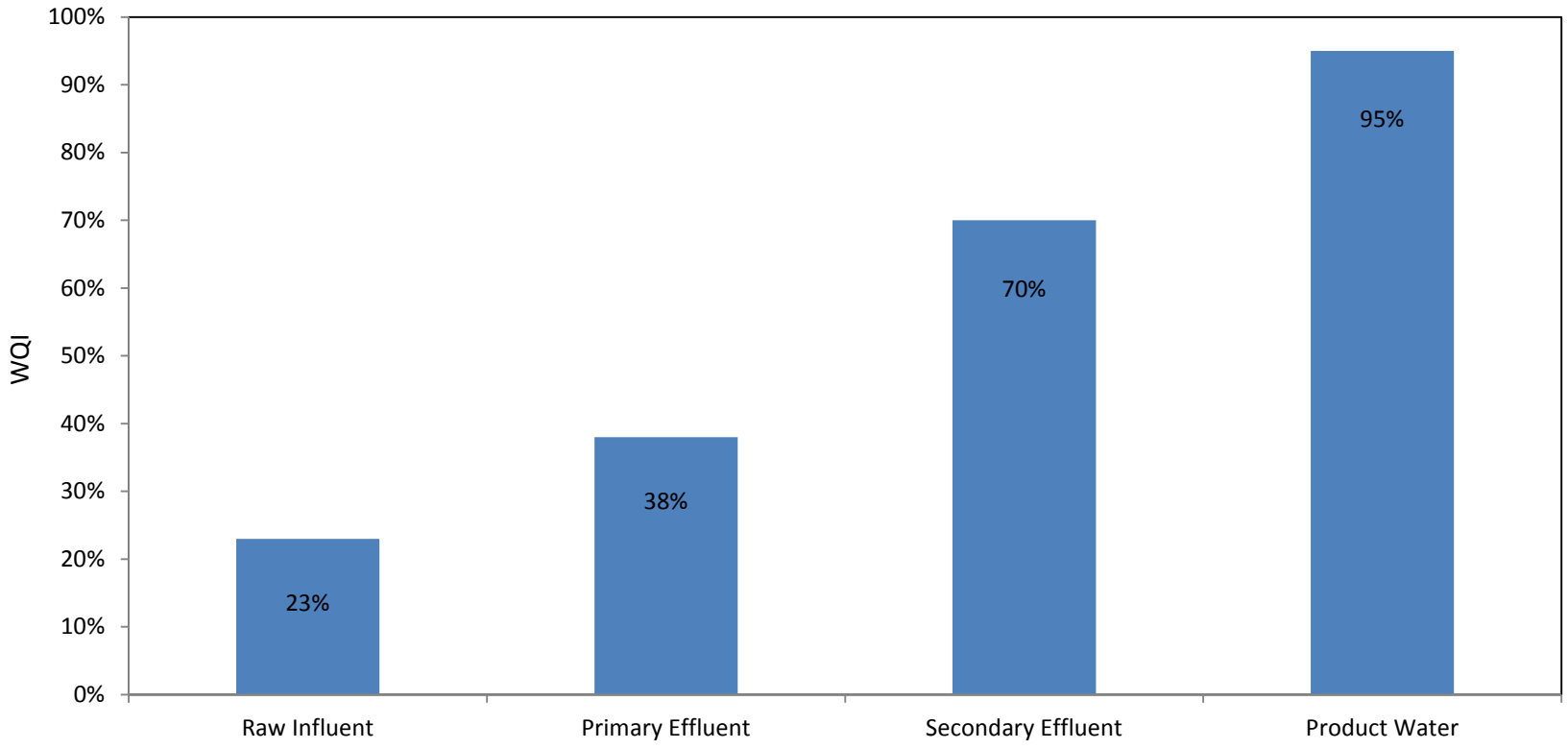




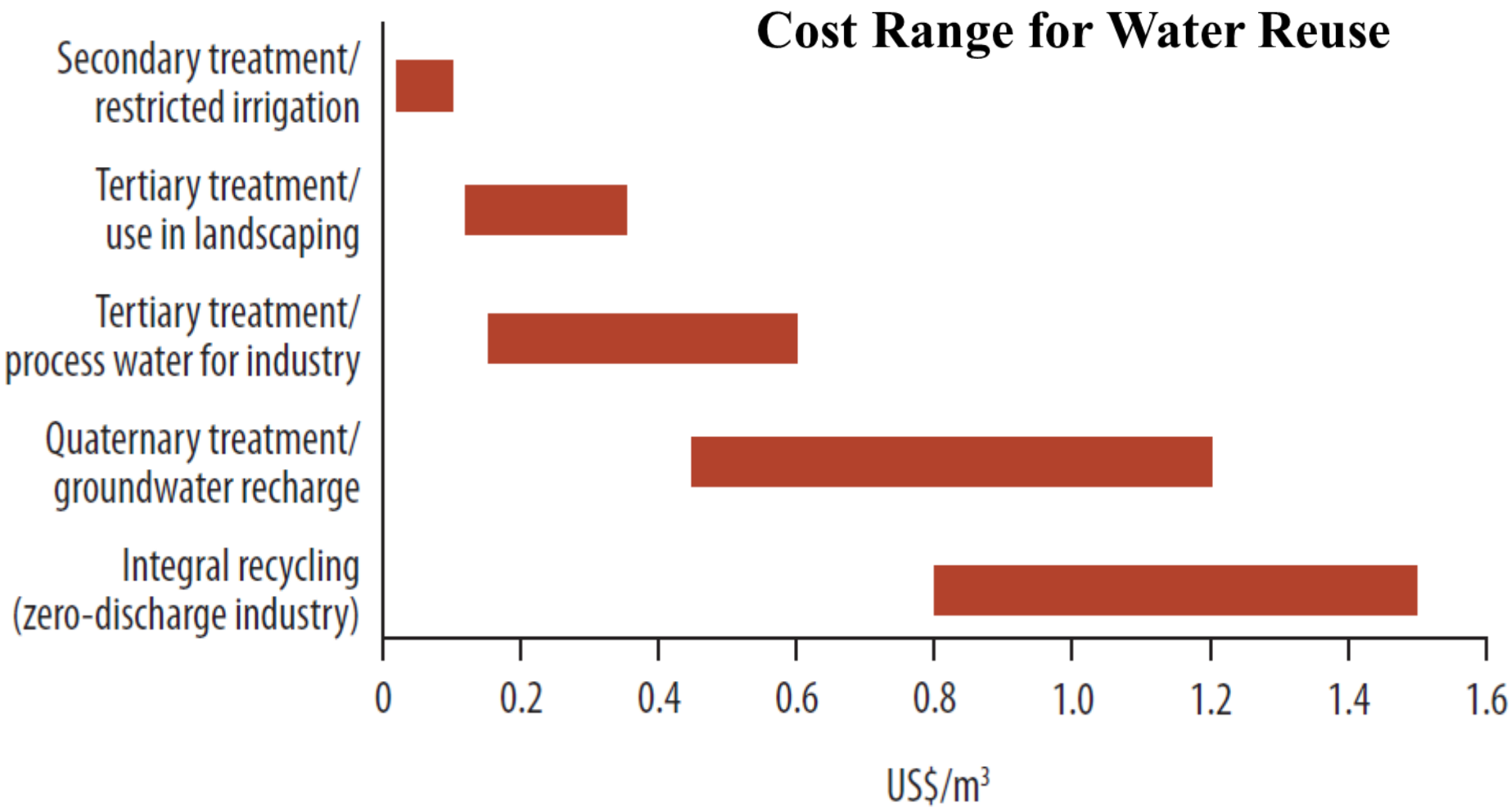
Rejection for Various Constituents of Wastewater by Reverse Osmosis

	Singapore - ESPA2+	CA, USA - ESPA2	CA2, USA - ESPA2	Singapore - LFC1	CA3, USA - ESPA2	CA4, USA - LFC1	CA4, USA - ESPA2	CA5, USA - ESPA2	Singapore MBR-RO ESPA2LD
Temp C	32	25	27.8	25	25	22	22	25	31
Flux	18.6 lmh	20 lmh	19.3 lmh	15.8 lmh	20 lmh	18 lmh	18 lmh	20.3 lmh	21 lmh
Recovery	80%	85%	85%	75%	80%	75%	75%	81.2%	75%
Ca	99.98%	99.99%	99.98%	99.89	99.98%	99.99%	99.95%	99.98%	99.90%
Mg		99.99%	99.99%	99.88	99.95%	99.99%	99.96%	99.99%	
Na	98.70%	99.36%	99.00%	98.46	99.16%	98.97%	99.26%	99.13%	
K		99.65%	99.30%	98.98	99.26%			99.21%	
NH4	98.35%	98.47%	97.20%	98.52	98.71%	97.63%	97.71%		
HCO3		98.27%	97.35%		95.61%	98.39%	97.96%	98.44%	
SO4	99.98%	99.74%	99.70%	99.93	99.93%	99.86%	99.82%	99.97%	
Cl	99.22%	99.59%	99.30%	98.79	99.37%	99.34%	99.62%	99.53%	
F				93.22	93.96%			85.13%	
NO3	97.58%	94.15%	95.10%	96.64	95.54%	94.32%	96.00%	93.45%	97.00%
B	26.25%			65.10					
SiO2	99.04%	99.71%	99.80%	98.21	99.17%	99.25%	99.55%	99.78%	98.60%
TOC	99.73%	99.70%	99.52%	99.64	97.93%	98.23%	98.28%	99.02%	99.70%
TDS		99.23%				99.23%	99.34%		98.90%
P				99.73	99.73%	99.99%	99.99%	99.46%	99.70%
TKN					98.35%				
Org N					96.67%				

Water Quality Index (WQI) at Different Treatment Levels



Municipal WW has to be treated anyway before disposed to sea or inland.
Additional treatment needed for its reuse in agriculture or any other application.
Water reuse benefits: freshwater conservation, GW protection.
Very limited amount of total withdrawal are treated in the GCC.



CONCLUSIONS

1. Technological advances in the field of municipal wastewater treatment, which includes application of membrane processes, have significantly improved the performance of treatment plants and the production of high quality effluent suitable for various reuse applications.

2. Water reclamation stage at Sulaibiya plant in Kuwait, using ultrafiltration and reverse osmosis membrane processes, showed high stability and minimal variability in response to seasonal variations in influent wastewater characteristics , water temperature and to about 15% increase in inflow over its design capacity.

3. The plant achieved up to 99% removal of pollutants along the treatment stages by removing traces of residual pollutants and lowering the TDS of plant effluent considerably. It also provided stability in overall plant performance. Product water quality showed minimal changes as raw wastewater composition changed and values were within the required water quality range for potable water.

4. Variability in product water quality was minimal as indicated by the coefficient of variation of each performance parameter.

5. The plant performance data presented in this paper provides basic references for establishing consistent regulatory water quality limits, determining regulatory compliance, controlling water reclamation processes, and evaluating process performance and reliability.