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An Introduction to Water Reuse in the Petroleum Industry

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Abstract

This paper is an introduction to water reuse in the petroleum industry. It presents a systematic approach on how to evaluate the potential of water for reuse. Virtually any water can be treated with off-the-shelf technologies and successfully reused for many different applications. However, not all water reuse makes sense based on economics, energy consumption or local need for the water. Other candidate waters sified as primary (gravity), sfor reuse include petrochemical wastewater, municipal wastewater, ground water and storm water. Water treatment technologies are clasecondary (biological) or tertiary (polishing step). Some of the reuse applications include agriculture, aquaculture, silviculture, industrial processes, recreation, wildlife and municipal nonpotable. As easily accessible water resources become scarce and the human population expands, the need for sustainable water reuse becomes paramount to both public and private sectors. The petroleum industry can effectively reuse water to benefit the local communities in which oil is produced and refined. Produced water that was once considered a throw-away by-product of crude oil production can become an asset in agriculture, aquaculture and silviculture.

Introduction

The maturation of the petroleum industry, world-wide water shortages and the expansion of human populations are converging to create an opportunity to beneficially reuse produced water (**Fig. 1**). The short history of the petroleum industry starts with kerosene being refined from crude oil to replace whale oil in lamps. Eventually, kerosene was replaced when Edison invented the light bulb. Churchill replaced coal with fuel oil in British navy ships. Refineries to process crude oil were built and new markets were developed for lube oils, gasoline and natural gas. Throughout this short 150-year history of the petroleum industry, produced water has been viewed as a useless by-product to be treated and disposed of in some fashion[1]. However, produced water can also be seen as an asset when the 135 million tonnes[2] of produced water currently being discharged onshore to surface waters around the world can be reused[3].

Consider the following:

- The surface of the earth is covered by 70% water. About 97% is saltwater and 3% is fresh water. Less than 1% is readily available[4] (**Figs. 2 and 3**). Most of the freshwater is used for irrigation[5,6].
- The world population is 6.6 billion as of September 2007. By 2050 the number is projected to be 9 billion[7].
- About 44% of world's population will live in water-stressed and water-scarce regions by 2050[8] (**Fig. 4**).
- The societal thirst for water varies greatly by country ranging from 27 to 200 L/day (7 to 53 gal/day). Engineers design water treatment systems based on 284 to 757 liters per person per day (75 to 200 gallons per person per day)[9, 10].
- People drink water; cook; bath; water lawns and gardens; wash vehicles; grow crops, livestock, fish and trees; and manufacture. The need for water reuse and conservation is here to stay. Water is important to sustaining both public and private sector endeavors.

Produced water from the extraction of petroleum deposits is not considered part of the world water balance. It is found water. Although the composition of produced water can vary greatly, it can be beneficially reused. Frequently, produced water can with only minimal treatment meet irrigation water quality standards. Reuse for agriculture is one application that helps to preserve groundwater for drinking. Produced water that once was considered a useless by-product may now become asset.

Water Reuse

When it comes to using new technology, there is often the tendency to want to stay in one's comfort zone and avoid the risk of the unknown. Unfortunately, water reuse is sometimes thought of as one of these new technologies when it actually is not. Water reuse is, for the most part, a collection of "off-the-shelf" existing technologies that have been repackaged to partially help fulfill industrial and municipal need for water. Through experience, the standards for municipal (grey) water reuse are well established.

Once human populations only existed where freshwater was readily accessible. When the water source dried up, populations moved on or died. Entire civilizations have disappeared due to a lack of water (e.g. Anasazi)[11]. With technology, humans can live just about anywhere (deserts to underwater to outer space). The Romans constructed aqueducts and the Mayans had extensive irrigation systems. Modern man can drill for ground water and can convert seawater into drinking water. The key is to use technology to create sustainable projects.

Water Reuse Evaluation

The concept of water reuse contains 3 basic components: identifying the water source, the type of treatment and the reuse application (**Fig. 5**). It isn't critical which of the three items you consider first. Evaluating potential water reuse applications is an iterative process where each component influences the other two.

Potential Water Sources

Almost any water is a candidate for water reuse:

- produced water,
- petrochemical/industrial wastewater,
- storm water,
- groundwater cleanup water,
- municipal wastewater,
- agricultural runoff and
- aquaculture (fish farm) wastewater.

Not all waters make good candidates for reuse due to economics (cost of treatment), energy consumption, and the social stigma associated with certain water, regulatory issues and/or perceived risk.

In the petroleum industry, the modern oilfield (or refinery) can be a city unto itself. It may have storehouses, food service, laundry service, security, streets, roads, medical facilities, power stations, machine shops, docks, airports, swimming pools, communication towers, recreational facilities, sleeping quarters, bus stops, storm water sewers, drinking water and wastewater treatment systems, and hydrocarbon processing and storage facilities. Petroleum operations have access to water similar to municipalities as well as produced water (upstream) and refinery wastewater (downstream). There are many possible water reuse opportunities.

Water Treatment

The engineering and science behind water treatment is reasonably well developed. Water treatment is classified as primary (gravity), secondary (biological) and tertiary (polishing) (**Fig. 6)**. In primary treatment, the lighter and heavier than water materials are separated by gravity. For example, oil floats. Solids drop to the bottom. In secondary treatment, microorganisms consume organic compounds and in the process release water, carbon dioxide and additional microorganisms. Tertiary treatment is a polishing step using physical, chemical and biological means to remove refractory compounds from the water.

There are several off-the-shelf water treatment technologies (**Table 1**) that one might use to meet a water reuse standard. Assembling the right sequence of primary, secondary and tertiary water treatments is part art and part science. Each industry approaches water treatment a little differently. Usually the focus is on one or two targeted constituents of the water to meet a reuse or discharge standard.

Many engineers start the water treatment design with a process flow diagram (PFD) (**Figs. 7, 8 & 9**). The design is based on form and function with specific treatment objectives in each step of the treatment process. In the upstream petroleum industry, one typically removes oil and solids first, followed by salt, if needed, and then water soluble organic (WSO) compounds. The remaining constituents in water are then polished by physical, chemical and/or biological means. The focus of the treatment is to prepare the crude oil for transport (shipping, pipeline) to a refinery. Then, the produced water is treated and disposed (injection or beneficial reuse).

Refinery wastewater has a more complex chemistry than produced water due to cracking of the crude oil. Oil/water separation is similar, but with a greater emphasis on desalting and dewatering to condition crude prior to the refining processes (e.g. cat cracking, hydrotreating, etc). Typical refining wastewater has higher WSO content than upstream produced water. Activated sludge (secondary or biological treatment) is commonly used to remove the WSO. Some form of polishing may also be needed to remove biorefractory compounds prior to discharge.

A treatment system for upstream or downstream water must be custom fit for the intended purpose. There is no universal treatment system that fits all water reuse applications. There are many design considerations. While the physical footprint, energy consumption and maintenance requirements can vary greatly, differing treatment systems can deliver the same water quality. For example, on an offshore rig, space is a premium and it strongly influences the water treatment system design. By contrast, space is much less of a premium for onshore facilities which provides additional degrees of freedom in the selection of a water treatment technology.

Water Reuse Applications and Standards

Some of the water reuse applications include:

- agriculture,
- aquaculture,
- silviculture,
- wildlife habitat,
- industrial water,
- groundwater recharge and
- recreation (**Table 2**).

Water reuse standards tend to be case specific to the application. There is no one single reference source that has all of the water reuse standards (**Table 3**). Each industry has its own collection of water standards, and the level of detail on the standard varies. There are literally millions of chemical compounds, and it is not feasible to have a standard for every compound. For practicality the reuse standards tend to be lumped into groups (e.g. TSS, TPH, salts, metals, pH, etc).

In the case of agriculture, a common water reuse application, salt is usually the focus, because most agriculture is based on sustaining a freshwater plant species. As such, irrigation water standards are based on potential salt and ion balance impacts to plants and soils[12] (**Table 4**). Plants are grouped by salt tolerance[12, 13]. If the salt concentration of the water is acceptable to the plant, most of the other water quality considerations can be economically treated.

Evaluation of Produced Water Reuse

Produced water may have one or several reuse options. A way to systematically determine if a particular reuse option is viable is suggested in the process flow diagram (PFD) in **Fig. 10**. The information gathering phase assembles data on the quantity of quality of produced water, reuse standards, applicable regulatory requirements, and local water needs. That information feeds into the design phase which considers treatment technologies, costs (capital and operating) and issues from an Environmental and Social Impact Assessment (ESIA). Environmental and social considerations can be equally as important as cost. In the evaluation phase other alternatives may be considered. To account for environmental benefits that may be difficult to quantify, a Net Environmental Benefit Analysis (NEBA) can by used. If the produced water cannot be beneficially reused, the usual default option is injection.

Information Gathering Phase

The quantity of water is usually framed in terms of annual water production based on probabilistic forecasts. The water quality testing parameters are functions of the potential water reuse. Typically, one starts with TPH, pH, TSS, TDS/EC, metals, NORM, and temperature and then adds supplemental testing specific to the reuse application. The suite of tests for irrigation water (**Table 5**) focuses on salts, ions and selected metals. Agricultural water reuse standards are set up to grow healthy plants and insure long-term soil productivity. Determination of community water needs may be as simple as a single contact to the local water district or it may require an extensive stakeholder analysis and multiple contacts.

Design Phase

Data from the information gathering phase feeds the design phase. The treatment technology selection is custom fit to meet a reuse standard and applicable regulatory requirements. Usually several technologies can be used to meet the reuse standard. Economics narrows down the technology selection. Both capital and operating expenses are considered. Whether a high or low technology treatment solution is selected, it needs to be sustainable. ESIA considerations help to make the water reuse sustainable. Frequently, the hard science (and engineering) needed to meet the water reuse standard is far easier to accomplish than the soft science of the ESIA. Where infrastructure is lacking, a water reuse project may require providing help with writing the regulations, setting up a water company through an NGO and teaching local farmers sustainable agriculture.

Evaluation Phase

In the evaluation phase, multiple water reuse alternatives and treatments are considered. A NEBA-like comparison of alternatives is sometimes helpful. Not all pluses and deltas fit neatly into spreadsheets for number crunching. While it is possible to make the reuse selection based solely on projected increases in crop productivity, there other socioeconomic, cultural, environmental, health, regulatory and reputation considerations. For example, supplying irrigation water can lead to increased crop yields, better diets, improved health and an increased standard of living. Capturing the true value of a water reuse project is critical to the final decision of whether to beneficially reuse the produced water or to inject it.

Chevron Water Reuse

Chevron has several ongoing water reuse projects in various stages ranging from feasibility studies to pilot testing to full-scale operations. Typically, a water reuse project starts with a feasibility study. If the evaluated project is worthy of further consideration, pilot testing may be done to collect kinetic and cost data to insure the treatment system is properly sized and to improve cost estimates. The final decision factors in the cost with the benefits. The Chevron reuse projects involve produced water, refinery wastewater, storm water and groundwater (**Table 6**). Based on water volume, agriculture is the most common reuse application for produced water. (The most common reuse of municipal wastewater is also as irrigation water[11]). In produced water pilot testing, fish, shrimp and crops have been grown and sustained. Some water is reused for wildlife habitat creating habitat for pollinators, waterfowl and upland species.

Conclusion

Water is life. The lack of available freshwater and an increasing world population will make water reuse and conservation key to the sustainability of public and private sectors. Cities must have water. So must industry and farmers. The petroleum industry is a position to create value out of what was once considered a useless by-product. Produced water (and other water) can be beneficially reused (agriculture, aquaculture, silviculture and wildlife habitat).

Future

Water reuse in the future may entail:

- policies to promote water reuse, water conservation and sustainability,
- tax incentives,
- water exchange banks,
- additional water reuse standards,
- changes in public attitudes related to water reuse, and
- links to biofuel production and carbon sequestration.

As water becomes scarcer governments and institutions are likely to pursue policies that promote water reuse, water conservation and sustainability. We may see tax incentives. Water exchange banks may help broker deals to match those with water with those who need water. As additional water is reused, it is expected that more complete water reuse standards will develop. Produced water may be reused to grow biofuel crops and sequester carbon.

Acknowledgments

To the farmers in my family who taught me to garden.

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Acronyms

API – Oil/Water Separator (API-like design)
ASTU – Activated Sludge Treatment Unit
CPI – Corrugated Plate Interceptor
CTW – Constructed Treatment Wetland
DAF – Dissolved Air Flotation
EC – Electrical Conductivity
ED – Electro Dialysis
ESIA – Environmental Social Impact Assessment
FO – Forward Osmosis
GAC – Granular Activated Carbon
IAF – Induced Air Flotation
MBR – Membrane Reactor
NEBA – Net Environmental Benefit Analysis
NF – Nano Filtration
NGO – Non-governmental Organization
NORM – Naturally Occurring Radioactive Material
PFD – Process Flow Diagram
PPI – Parallel Plate Interceptor
RBC – Rotating Biological Contactor
RO – Reverse Osmosis
SAR – Sodium Adsorption Ratio
SBR – Sequencing Batch Reactor
TDS – Total Dissolved Solids
TPH – Total Petroleum Hydrocarbons
TSS – Total Suspended Solids
UF – Ultra Filtration
UV – Ultra Violet
WSO – Water Soluble Organic Compounds

Figures and Tables

Fig. 1- Convergence of Petroleum Industry, Water Shortage and Human Population

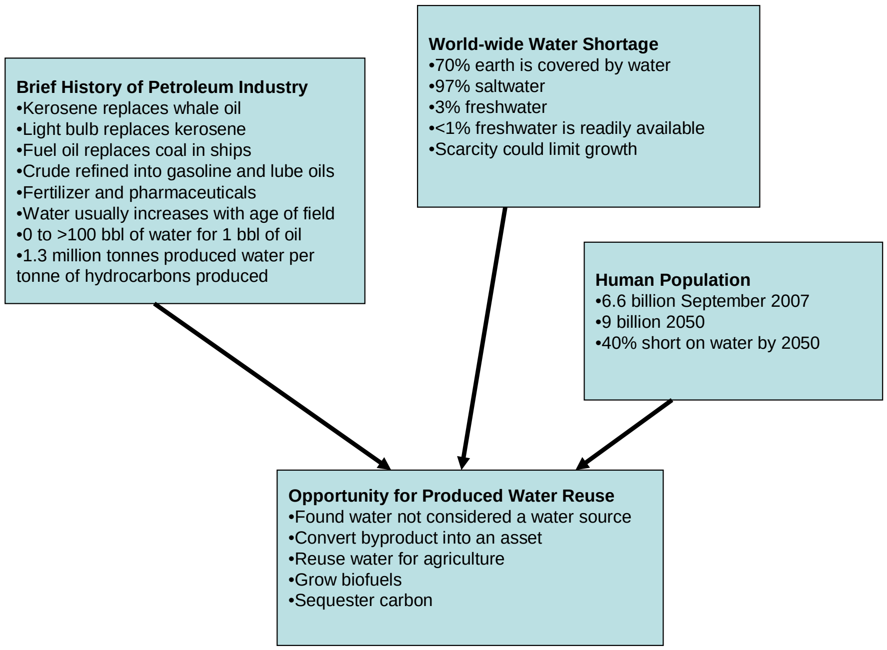

Fig. 2- Distribution of earth's water[5]. Easily accessible freshwater represents less than 0.01% of the earth's water

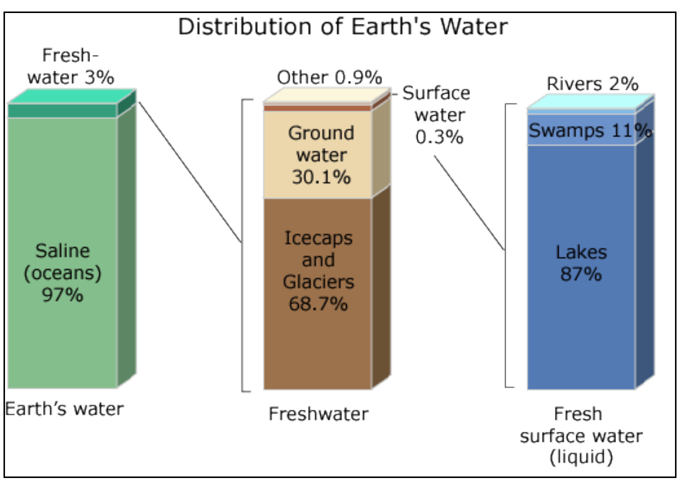

Fig. 3-Projection of Water Availability in 2025[4].

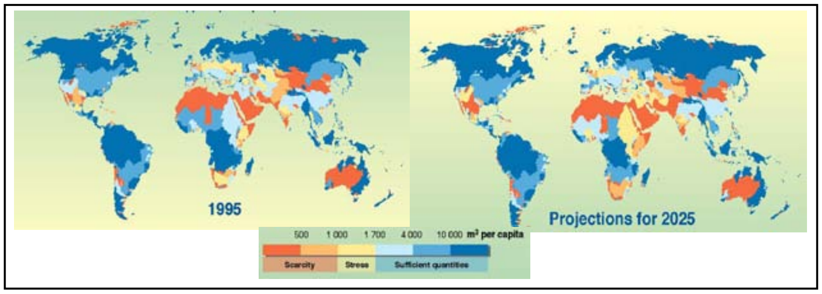

Fig. 4-Water Scarcity and Stress[6]

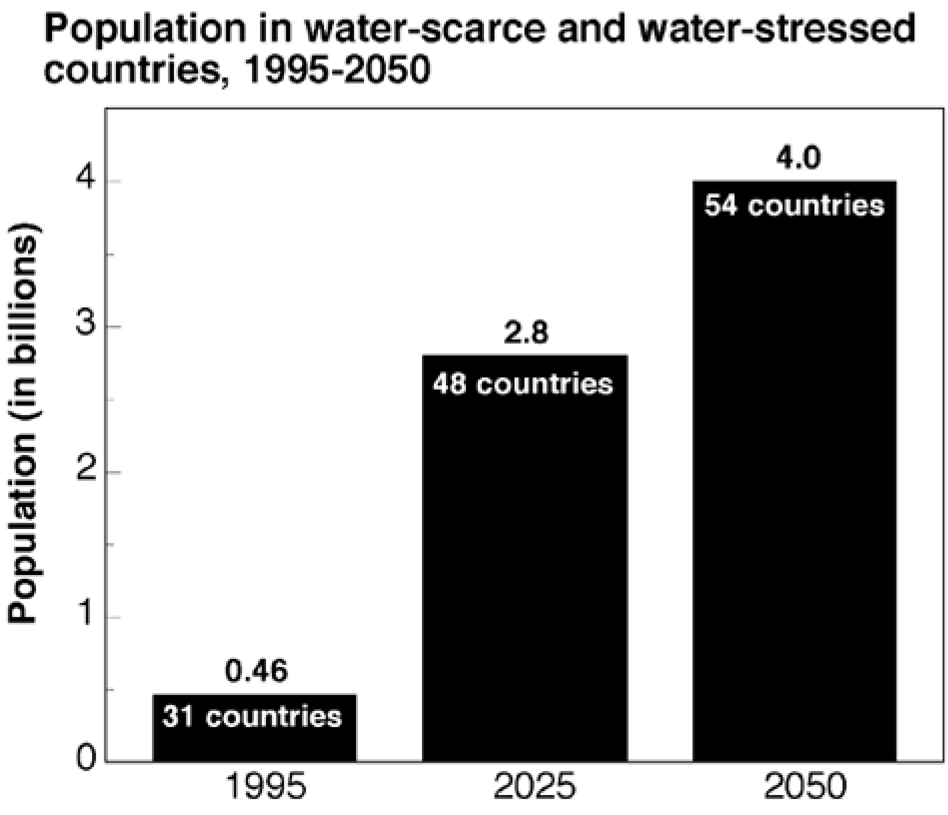

Fig.5-Water Reuse Basic PFD

Fig.6-Wastewater Treatment Classification

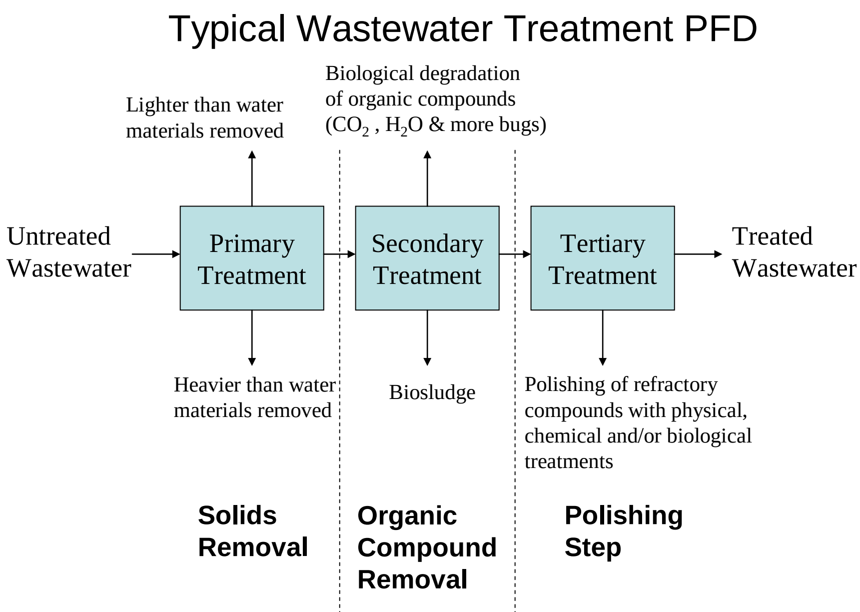

Fig.7-Produced Water Reuse Alternatives PFD

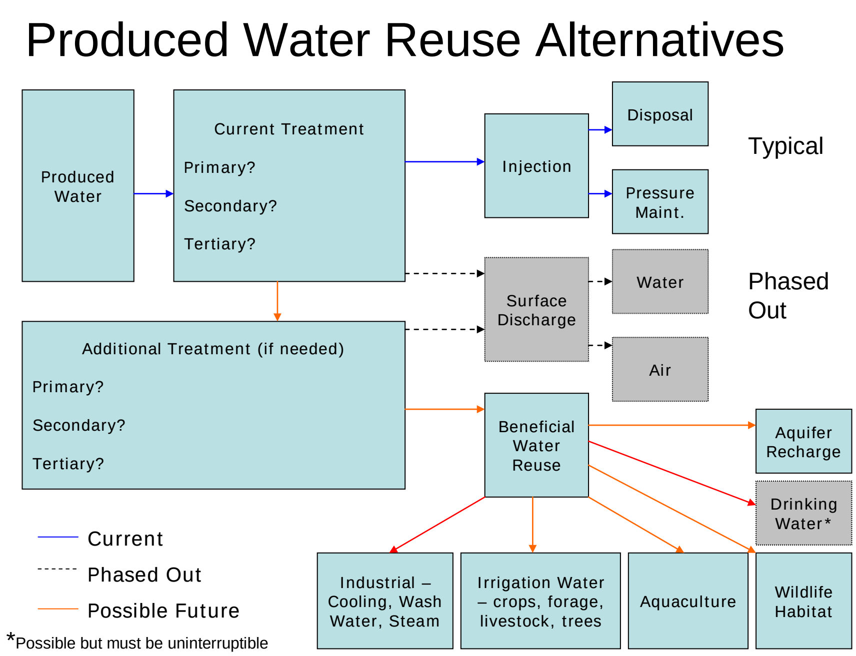

Fig.8-Produced Water Treatment Example PFD

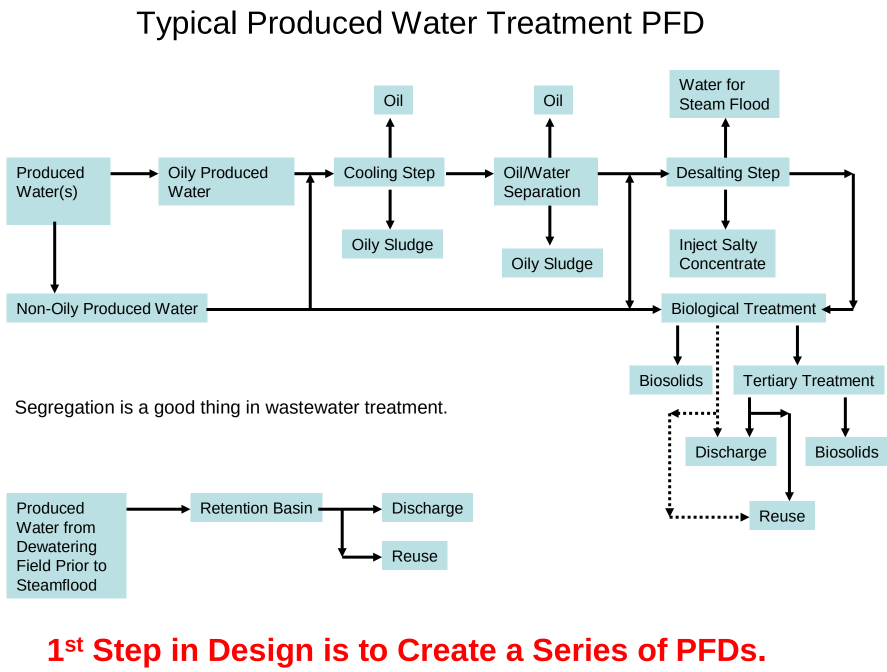

Fig.9-Refinery Wastewater Treatment Example PFD

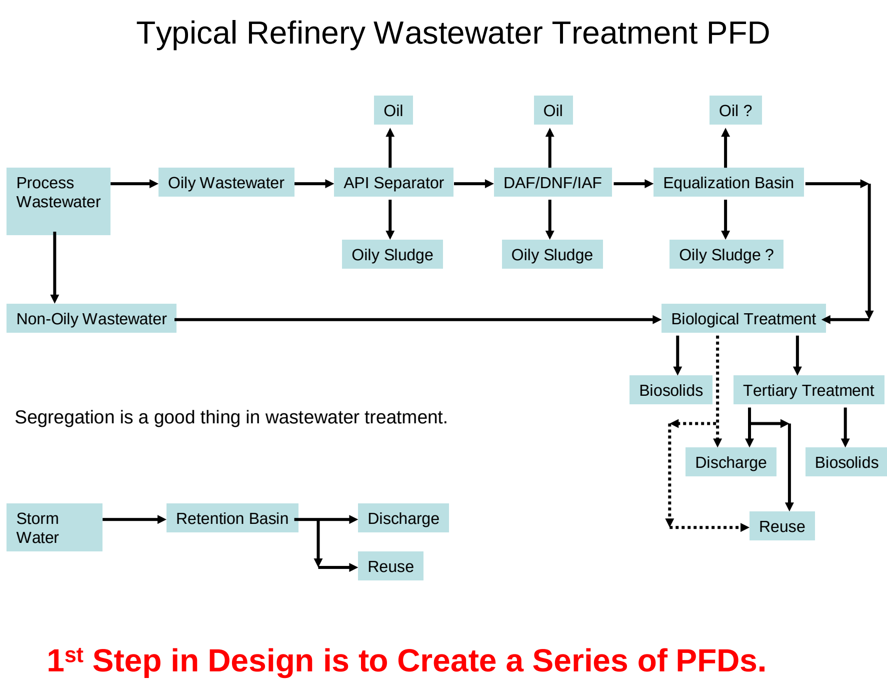

Fig. 10-Produced Water Evaluation PFD

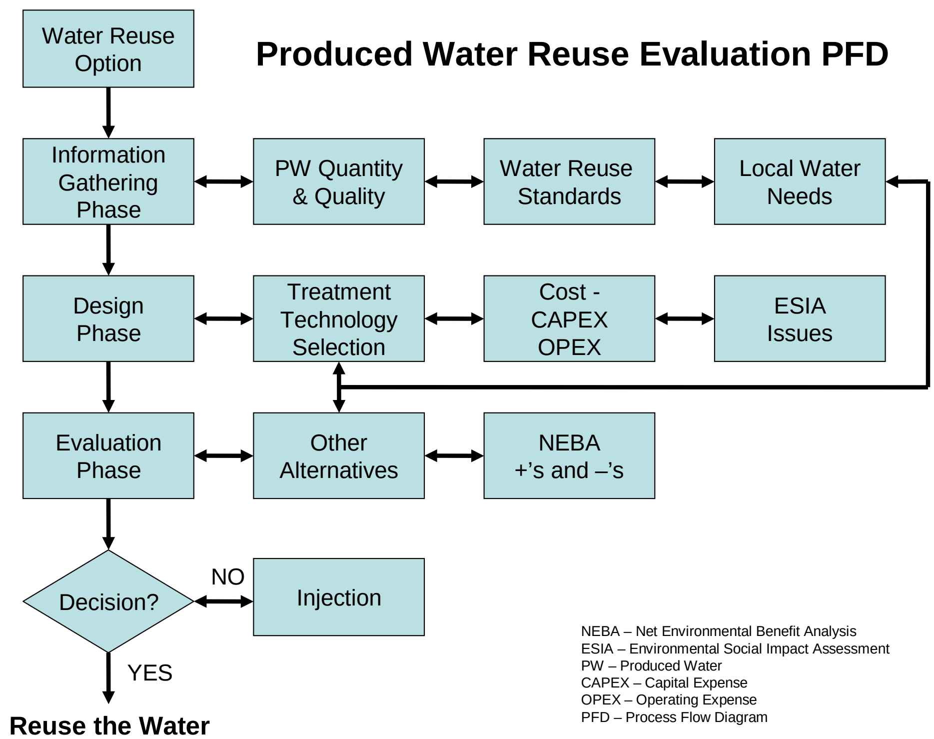

Table 1. Water Treatment Technologies

Water Treatment Grouped by Function		Comment
Primary Treatment - Oil/Water Separator - CPI - DAF - Clarifier - Treatment Wetland	 - API - PPI - IAF - Hydrocyclone	Gravity settling of solids heavy than water. Float oils lighter than water. Entrain oil with air/gas bubbles. Use density differences to remove solids and oils.
Secondary Treatment - ASTU - Facultative Lagoon - Aerated Lagoon - Treatment Wetland - Trickling Filter	 - SBR - RBC - Anaerobic Filter - MBR - GAC	Biological treatment uses micro-organisms to consume organic compounds in an ambient temperature combustion reaction. Some of the treatments are energy intensive with small physical footprints. Others are not energy intensive but have large physical footprints.
Tertiary Treatment - Activated Carbon - Chlorination - Chemicals (FeCl, O3, H2O2)	 - Filtration - UV	Polishing treatments remove the refractory compounds by physical, chemical and biological means.
Salts (desalting) - RO - ED - Freezing	 - FO - NF - UF	Salt removal is typically to meet irrigation water standards (EC/TDS/salinity). Some of the membrane technologies require pre-treatment (solids removal) to avoid membrane fouling.

Table 2. Potential Water Reuse[12]

Category	Typical Application
Agriculture	Crop irrigation Commercial nurseries
Livestock	Cattle Sheep Pigs Chickens Waterfowl
Aquaculture	Fish Shrimp Frogs Bait
Silviculture	Tree farming
Landscape Irrigation	Residences Golf courses Parks Cemeteries Freeway medians Greenbelts School yards
Industrial Recycling and Reuse	Boiler feed water Fire protection Cooling tower Process water Manufacturing Vehicle washing Dust control
Groundwater Recharge	Groundwater replenishment (water banking) Salt water intrusion control Subsidence control
Recreation	Lakes, streams and ponds Snow making
Wildlife Habitat	Marsh restoration Habitat enhancement Fisheries
Nonpotable Urban Use	Fire protection Air conditioning Toilet flushing
Potable Use	Blending in water supply reservoirs Blending in groundwater Direct pipe to pipe water supply

Table 3. Brief Overview of Water Reuse Standards

Reference	Category/Comment
Health Guidelines for Use of Wastewater for Agriculture and Aquaculture by WHO (1989)	Focus on helminth removal
Guidelines for Water Reuse by USEPA (1992)	Focus on municipal water
Water Reuse[13] (2007)	Compilation of municipal and agricultural standards
Water Encyclopedia[14] (2007)	Compilation of water standards
USA State Regulations on Water Reuse	Most have USEPA like standards
Forestry Standards (several sources & university papers)	Trees tend to tolerate lower quality water than other plants
Fishery Standards (several sources & university papers)	Focus is the taste of fish in commercial fish farming operations
AB Canada	Comprehensive lists including treatment technologies

Table 4. Water Reuse Analytical Testing Parameters for Irrigation[12]

		Degree of Restriction on Use		
Irrigation parameter	units	None	Slight to Moderate	Severe
		Salinity		
EC	dS/m	<0.7	0.7-3.0	>3.0
TDS	mg/L	<450	450-2000	>2000
Sodicity				
SAR, 0-3		and EC ≥0.7	0.7-0.2	<0.2
3-6		≥1.2	1.2-0.3	<0.3
6-12		≥1.9	1.9-0.5	<0.5
12-20		≥2.9	2.9-1.3	<1.3
20-40		≥5.0	5.0-2.9	<2.9
Specific Ion Toxicity				
Sodium (Na)				
Surface irrigation	SAR	<3	3-9	>9
Sprinkler irrigation	mg/L	<70	>70	
Chloride (Cl)				
Surface irrigation	mg/L	<140	140-350	>350
Sprinkler irrigation	mg/L	<100	>100	
Boron (B)	mg/L	<0.7	0.7-3.0	>3.0
Miscellaneous effects				
Nitrogen (total N)	mg/L	<5	5-30	>30
Bicarbonate (HCO_3) (overhead sprinkling only)	mg/L	<90	90-600	>500
pH	s.u.		Normal range 6.5-8.4	
Residual chlorine (overhead sprinkling only)	mg/L	<1.0	1.0-5.0	>5.0

Table 5. Typical Irrigation Water Test Parameters

Constituent
Alkalinity (as CaCO3 to pH 4.5)
Ammonium
Barium
Bicarbonate
Boron
Calcium
Carbonate
Chloride
Conductivity, Electrical
Free Carbon Dioxide
Hydroxide
Iron
Magnesium
Nitrate
Potassium
Residue, Filterable
Silicon
Sodium
Specific Gravity
Strontium
Sulfate
Temperature
pH

Table 6. Chevron Water Reuse Examples

Case	Setup	Reuse	Comment
California Produced Water[3]	Oil/Water Separation, Walnut Shell Filter, Cooling Pond	Agriculture	Chemical and mechanical treatment. Small footprint. Reused water grows >40 crops.
California Produced Water	Oil/Water Separation, Cooling, RO, CTW	Agriculture	RO for salt removal to meet irrigation water standards. Reused water recharges irrigation aquifer.
California Produced Water Demonstration Wetland	Oil/Water Separation, Walnut Shell Filter, Cooling Pond, Treatment Wetlands	Agriculture	Test program capturing data from multiple cells, plant species, planting densities and construction costs.
Ohio Closed Refinery Storm & Ground Water	Oil/Water Separation, GAC, Pond, CTW	Wildlife	Wetland is winning wildlife awards (pollinator and waterfowl). WHC certified wildlife management plan.
Mid-west Refinery Wastewater	Oil/Water Separation, ASTU, Facultative Lagoon, CTW	Wildlife	Gravity fed CTW. Pump once. Let gravity do the rest. Large wetland is attracting wildlife use. IOGCC award. WHC certified.
Wyoming DOE CRADAs Pilot Studies	Oil/Water Separation, Cooling, Facultative Lagoon, CTW	Wildlife Agriculture Aquaculture	Series of pilot CTW studies. Reused water irrigates a normally dry stream creating grazing habitat for mule deer and elk.
Far East Produced Water Feasibility Study	Oil/Water Separation, Cooling Pond, CTW	Agriculture Aquaculture Silviculture	Several applications possible. Lack of infrastructure makes water hand-off challenging.
Africa Produced Water Feasibility and Pilot Studies	Oil/water Separation, Cooling Pond, CTW	Agriculture Livestock	Several applications possible. Lack of infrastructure makes water hand-off challenging.