Alternative Use of Produced Water in Aquaculture and Hydroponic Systems at Naval Petroleum Reserve No. 3

Lorri Jackson, Critique, Inc., Rocky Mountain Oilfield Testing Center, Casper, WY, and Jim Myers, ChevronTexaco, Bellaire, TX.

Lorri Jackson, Environmental Project Coordinator, Rocky Mountain Oilfield Testing Center, Casper WY has been associated with the Navel Petroleum Reserve No. 3, Teapot Dome field, since 1994 and the Rocky Mountain Oilfield Testing Center since 1998. She has been involved in soil remediation projects, and develops bench tests and treatability tests for companies seeking approval from the regulatory agencies to use or distribute their product within a state for site remediation. Since 2000, most of her work has been associated with produced water management and passive water treatment technologies.

Jim Myers, P.E., Sr. Environmental Engineer, ChevronTexaco, Bellaire, TX, M.S. Chemical Engineering, B.S. Chemical Engineering, B.S. Zoology. 20+ years in the biological treatment of liquid and solids wastes from worldwide upstream and downstream petroleum operations. His awards include IOGCC environmental stewardship award for a refinery treatment wetland, Wildlife Habitat Council award for wildlife management, USFWS volunteer award for a waterfowl database. His professional work spans from environmental compliance and auditing, wildlife habitat and restoration, database creation

Abstract

Extraction of oil and gas generates large volumes of produced water. Only a small percentage of water is reused. Substantial volumes of water come from coal bed methane (CBM) development. Many of the regions where CBM is produced are arid or semi-arid and can benefit from water reuse for agriculture, livestock, and wildlife. If the water from CBM water can be efficiently and economically reused, it becomes an asset instead of a liability. The Rocky Mountain Oilfield Testing Center (RMOTC) installed an aquaculture and hydroponic center and is operating pilot treatment wetlands at Naval Petroleum Reserve No. 3 (NPR-3) to demonstrate the feasibility of raising agricultural crops in untreated produced water. This paper presents system design parameters and production results for fish (tilapia – *Oreochromis niloticus/aureus*) and plant (hybrid tomato – *Lycopersicon esculentum*) species raised in produced water. The paper also covers some of the technical and regulatory issues related to water reuse.

Introduction

Water reuse is not a new concept. The first western settlers captured storm water from roofs into rain barrels. The impact of water reuse technologies and best management practices on the future water resources of arid and semi-arid climates cannot be over estimated. Recently we have seen rapid coal bed methane (CBM) development in the western states (WY, MT, CO, NM, UT). The rate of development coupled with limited data with regard to volume and composition of associated water is of concern to all stakeholders. Most historical data were gathered based on production in the Black Warrior Basin in Alabama and the San Juan Basin in Colorado and New Mexico. Generally, water quality varies depending on the original depositional environment, depth of burial and type of coal. If the composition of the water is of sufficient quality then with minor or no treatment it could be used to supply water for irrigation, agriculture, wildlife or innovative enterprises such as aquaculture and hydroponics applications.

RMOTC operates a facility at NPR-3 where demonstrations of hydroponic and aquaculture systems are on-going. The Center has been in operation for approximately 24 months. During that time, tomatoes and tilapia were raised. The demonstrations tested the feasibility of raising aquaculture and hydroponic crops with reused oilfield produced water.

NPR-3 is a stripper oilfield, averaging slightly more than 500 BOPD and 40,000 BWPD. If NPR-3 produced water could be reused for agricultural crops, rangeland grasses and/or aquaculture, the vast quantity of water produced would become an asset instead of a liability. Similarly, CBM water like oilfield produced water could be reused in agriculture, aquaculture or for wildlife habitat.

Science Center

RMOTC sought alternative uses for the more than 40,000 barrels of water produced from oil production each day. Suggestions for uses of the water included using it as geothermal heat for buildings, or to raise fish and plants in a greenhouse (aquaponics). The water is of fair quality, although not potable water quality. Demonstrations of the feasibility for using the Tensleep water in an aquaponic system shows a high degree of practicability for reusing the natural resource, though profitability may be limited to local market demand.

It's important to note that the demonstrations described in this paper are not scientific or academic based experiments. Many parameters were not monitored simply due to the limited funding available to conduct experiments that are more detailed. RMOTC created the Center to conduct such demonstrations and to work with local schools on environmental education. The facility is available for a variety of tests, projects and further demonstrations.

RMOTC Science Center (Aquaculture/Greenhouse)

Aquaculture is a form of agriculture encompassing the propagation, cultivation and marketing of aquatic animals, plants and related supplies. Aquaculture is the fastest growing form of agriculture in the United States. Hydroponics is the cultivation of plants without the use of organic soil. Aquaponics is the combination of aquaculture and hydroponic systems.

There are numerous examples of recirculating aquaponic systems like the one in use at the RMOTC Science Center. In addition, there is a vast array of resources available to assist potential growers with set-up and operation of aquaponic systems. The best systems are low-cost and simple to operate.

Re-circulating systems are aquaculture systems in which most of the water is reused. They are space and resource efficient and provide the operator with substantial control over the aquatic environment. The three main components of the operation are fish, plants, and bacteria. Basic systems consist of a supply of water and electricity, personnel to feed the fish, fish to provide nutrients to the plants, and plants to return oxygen to the water and take up wastes. Bacteria are a critical element in the system. A healthy bacterial culture allows the system to support more fish and improve plant production.

Several species of fish such as hybrid striped bass, yellow perch, largemouth bass, tilapia, and catfish can be grown in aquaponic systems. RMOTC chose Nile tilapia to raise for several reasons. Tilapia ranks second worldwide in freshwater fish production and is found on restaurant menus throughout the world. They are a hardy, disease resistant, warm-water fish. They can tolerate low oxygen levels and poor water conditions. The feed conversion rate for tilapia is excellent. Reports vary from one to one and one-half pound of feed yields one pound of fish.

A variety of plants can be grown in the aquaponic system and plants can be grown from seed, seedlings, or cuttings. Lettuces and salad greens grow quite well but food crops such as tomatoes and mushrooms, or fresh herbs can be grown also. Hydroponic plants grow in one-half to one-third the time required as compared to traditional growing methods.

Materials for setting up an aquaponic system are low cost and include:

- Building.
- Tanks (round with sloped floors).
- Growing beds.
- Pumps.
- PVC piping and fittings.
- Water supply.
- Gravel.
- Fish, plants, and bacteria.

Basic operating costs include:

- Labor.
- Electricity.
- Fish food.
- Seeds and plants.

Finally, recirculating aquaponic systems are environmentally friendly since there is no effluent discharged from the system. Operators can expect to lose less than 10-20 percent of the water volume per month due to evaporation and plant uptake. Antibiotics and pesticides are not used since they would find their way back to the fish and plants, respectively. Instead, organically approved methods such as predatory wasps, ladybugs, and lacewings can be used to control whiteflies, aphids, and other pests and diseases.

Tilapia Demonstration

Nile tilapia (*Oreochromis niuloticus/aureus*), a member of the *Cichlid* family, is ideally suited for aquaculture. These are tropical fish, native to Africa. They are disease resistant, reproduce easily, feed efficiently, and tolerate poor water conditions. Depending on the species, tilapia can be successfully grown in freshwater, brackish water and/or seawater.

Since tilapia is quite adaptable to different water quality characteristics, a demonstration was conducted to determine how successfully the fish could be raised in produced discharge water associated with oil production. A control tank was set up using potable water to compare the results.

The source water used in this case is produced from the Tensleep formation. Nearly ninety percent of all the water produced at NPR-3 comes from this formation. The water is generally of fair quality. Water quality characteristics are listed in Table 1.

The demonstration began on January 2, 2001 and concluded on September 10, 2001. Tank A was fed with Tensleep formation water as source water. Tank B used potable water. Filtration, feed and cleaning remained the same for both tanks. Temperature in the tanks was kept at 85°F and nitrite levels were monitored to ensure levels did not create a toxic environment (>0.8 mg/L).

Three hundred and ninety-four (394) fry were added to each tank. A bucket filtration system was installed to help maintain nitrite levels. If nitrite levels exceeded 0.8 mg/L, feed was shut off for 24 hours. An automatic feeding system was put in place and filters for both tanks were backwashed daily.

Results

Tank A

Three hundred and ninety-four (394) Nile tilapia were added to Tank A and 286 were harvested. The mortality rate in this tank was 27%. The total weight of the fish in Tank A was 2,704.8 ounces or approximately 169 pounds. The average weight was 9.5 ounces. The largest fish removed from Tank A weighed one (1) pound. The smallest fish from this tank weighed 1.5 ounces.

Tank B

A total of 394 fish were removed from Tank B. The mortality rate could not be calculated due to discrepancies in the records. Although it was recorded that fish died in Tank B, and no additional fish were added, the same number of tilapia were harvested on September 10, 2001. It's possible the fish may have been breeding in Tank B. The total weight of the fish in Tank B was 2933.5 ounces or approximately 183 pounds. The average weight of each fish was 7.5 ounces. The largest fish weighed 12.9 ounces, with the smallest fish weighing 0.4 ounces.

Hydroponic Tomato Demonstration

This demonstration spanned 12 months from February 5, 2001, through February 12, 2002. The demonstration compared hydroponic hybrid tomatoes raised on potable water to those raised on Tensleep oilfield produced water. The plants received the same amount of fertilizer and same amount of water. Growth rates, quantity of fruit, size and flavor of the fruit were monitored. In addition, the tomatoes were tested for toxicity.

The tomato seeds were planted in rock wool cubes and placed on heaters. The cubes were fully saturated and maintained at a temperature of 80°F. Approximately three weeks later, the seedlings were separated into two sets of plants and transplanted into hydroponic buckets filled with perlite. Bubblers were added to each feed tank to increase the dissolved oxygen level of the feed water. Fertilizer consisted of 0.5 lb of hydro-gro, 0.25 lb of calcium nitrate, and 0.33 lb of magnesium sulfate. Seedlings received one-half dosage of this formula. As the plants matured, a full dosage of fertilizer was administered. The pH was monitored and adjusted by adding sulfuric acid to the feed water. The pH for the produced water plants was maintained at 6.0 standard units and 6.1 for the potable water plants.

Initial watering regimen was three times daily for five minutes. This rate produced too much runoff. Subsequently, the rate was adjusted to 3 times daily for three minutes. In March, the plants weren't using as much water due to cooler temperatures. The watering frequency and rate was adjusted again to once daily for 3 minutes. As the demonstration continued, water frequency and duration rates were adjusted based on the dryness of the media and ambient temperature.

The produced water plants began blooming on April 17 and three days later flowers were observed blooming on the potable water plants. Initially the produced water plants seemed to grow more rapidly than the potable plants. Eventually the potable water plants caught up and surpassed the produced water plants in height and fruit production.

Results

The test ended on February 12, 2002. A total of 1,766 tomatoes were harvested from the potable water plants (Table 3). The total recorded weight was 339 pounds. The average weight was 0.19 lb. The plants raised in the Tensleep formation water yielded a total of 1,591 tomatoes, totaling 111 pounds. The average weight of the produced water tomatoes was 0.07 pounds.

Generally, the produced water tomatoes tasted slightly more acidic and saltier than the potable water tomatoes. In addition, they were significantly smaller than the potable water tomatoes. Three tomatoes from each demonstration group were sent to an independent commercial laboratory for toxicity testing. The results are listed in Table 3.

Issues

Public concern over coal bed methane development chiefly centers around the effect such development will have on local communities, the de-watering of groundwater aquifers and regulatory issues such as water quality and disposal methods. Long and short-term economic and social impacts, especially to small communities include:

- Impact of "Boom and Bust" development to small communities.
- Environmental mitigation.
- Landowner mitigation.
- Strain on community resources and services.
- Adverse effects on local property values.
- Competitive wages measured against natural gas industry.

State governments struggle to answer the concerns of the stakeholders, develop good scientific reasoning for setting and/or altering discharge limits, and instituting controls to preserve the ecological systems unique to this semi-arid region of the U.S. Ecological concerns items such as soil problems (elevated SAR), enhanced erosion in streambeds and streambed adaptability.

Neighboring states have differing standards governing disposal methods (surface discharge). Wyoming disposal options are based on specific water-quality limits for different types of streambeds. Discharge limits for basic parameters such as EC, TDS and TPH content of the effluent remain the same across the board. Where discharge water will reach a Class II water system and potentially used for irrigation purposes, more stringent limits for Ra 226, chlorides, sulfates and metals is placed on discharges. Wyoming also uses the EPA agricultural and wildlife effluent limitation guidelines (ELGs) when setting discharge limits.

The Powder River Basin drainage extends into Montana. Water discharged into tributaries in Wyoming eventually commingle and reach the Powder River which flows north into Canada. Recently Montana and Wyoming entered into a Memorandum of Cooperation (MOC) to help mitigate some of the environmental concerns with regard to water quality in the Powder River. This interim agreement documents the States' commitments to protect water quality conditions in Montana, while still allowing discharges in Wyoming. Ultimately, the MOC will define protective water quality standards for both States. Montana has issued one permit to-date. See www.deq.state.mt.us/coalbedmethane/MT0030457.htm. This permit includes extensive site-specific calculations to ensure that state water quality standards for TDS, specific conductance, SAR, iron, dissolved aluminum, ammonia, fluoride, Ra226 and chloride are not exceeded.

Colorado disposal options take into consideration agricultural and water quality standards, use by agriculture and wildlife and include a stricter oil and grease limit (10 mg/L) than the national 35 mg/L ELG discharge standard. In addition, discharge permits to particularly sensitive streams have limits that are more rigorous and require an organic pollutant scan for every 10th discharge point.

Recently, public concern and involvement has prompted CBM producing states to revisit their regulatory standards for surface discharge. Not all wastewater, including produced water from coal bed methane extraction is suitable for reuse applications. Some irrigation water standards have limits for sodium absorption ratio (SAR), total dissolved solids (TDS), chlorides, barium, and selenium. Waters that exceed those standards may require treatment prior to reuse in aquaculture, hydroponic, and irrigation applications. Road application or misting operations using untreated waters may impact the environment in the long-term. To protect public health, considerable efforts have been made to establish conditions and regulations that would allow for safe use of reclaimed industry wastewater for irrigation, aquaculture and other re-use applications.

Options

Like most oil and gas producers, CBM producers are concerned with the cost of handling the CBM water. Operators select the disposal method or combination of disposal methods they will use based on cost and regulatory drivers. State discharge limits are set by taking into account technology, EPA ELGs, and water quality. (See Table 4.)

CBM operators favor as much flexibility in produced water management as possible. A comprehensive best management practices approach to marrying the regulatory, social, economic and ecological issues is the first step toward addressing concerns. Identifying geographic areas in which CBM discharges could be pre-approved under a general permit or other standardized limits is one option. Alternatively, treatment requirements could be set-up in a series of tiers depending upon the discharge location, reuse application, and/or potential environmental impact.

Summary

Onshore produced water treatment costs can range from less than one cent to a few dollars per barrel depending on the chemistry of the produced water, treatment technology, and regulatory requirements. Treatment for surface discharge or reuse purposes may entail solids removal, desalting, emulsion breaking, metals removal and/or water-soluble organic compound (WSO) removal. Many domestic oilfields are old, stripper fields in remote locations. This water is not typically reused for irrigation, but it might be used for livestock and wildlife where water is scarce due to draught and arid regional conditions.

There is a variety of technologies available to economically treat the produced water so that it may be reused for beneficial purposes. With appropriate treatment, produced water may be reused as irrigation water for agriculture and rangeland grasses for livestock and wildlife, in creation of wildlife habitat, and/or for aquaculture. Operators should first consider regulatory requirements and then factor in the socioeconomic benefits of water reuse into producing oil & gas in today's operating environment. Sometimes a combination of water reuse technologies is most practical.

In the case at NPR-3, we found based on water chemistry data and experiences with treatment wetlands that our produced water is suitable to demonstrate water reuse opportunities in raising fish and greenhouse crops. Based on the success of the demonstrations, we have further studies planned.

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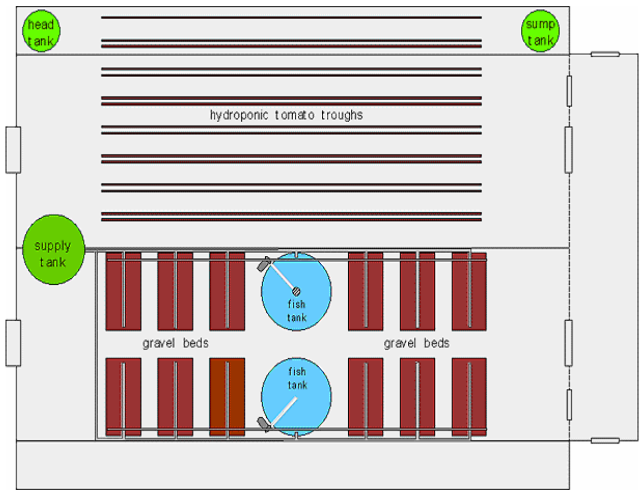

Figure 1. Conceptual RMOTC Science Center Layout.

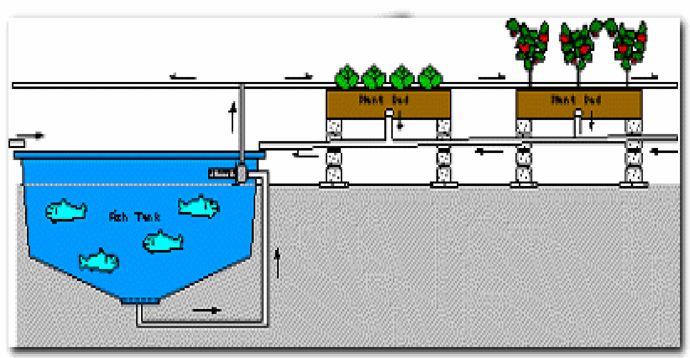

Figure 2. Aquaponics System Layout.

Table 1. Tensleep Formation Water Quality Characteristics					
Analyses	**Result**	**Units**	**Method**	**Irrigation Water Standards (Excellent)**	**Irrigation Water Standards (Unsuitable)**
Major Ions					
Bicarbonate as HCO3	148	mg/L	A2320 B		
Calcium	268	mg/L	E200.7		
Carbonate as CO3	ND	mg/L	A2320 B		
Chloride	870	mg/L	E200.7		
Magnesium	34.2	mg/L	E200.7		
Potassium	90.3	mg/L	E200.7		
Sodium	642	mg/L	E200.7		
Sulfate	887	mg/L	E200.7		
Physical Properties					
Conductivity	4740	umhos/cm	A2510 B	250	>300
pH	7.93	s.u.	A2320 B	6.5	>8.0
Solids, Total Dissolved TDS @ 180 C	3220	mg/L	A2540 C	175	>2100
Sodium Content (as Na)	62	meq/L		22	>80
Metals – Total					
Iron	0.546	mg/L	E200.7		
Organic Characteristics					
Oil and Grease – Total Recoverable	2.2	mg/L	413.1		
Sodium Adsorption Ratio	9.79		Calculated	3.0	>15.0

Table 2. NileTilapia Growth Results.

Parameter	**Tank A**	**Tank B**
Water	Tensleep Produced Water	Potable
Number of Fish Stocked	394	394
Number of Fish Harvested	286	394
% Mortality	27%	See comments
Weight of Fish	169 lb	183 lb
Average Weight	9.5 oz	7.5 oz
Maximum Weight	16.0 oz	12.9 oz
Minimum Weight	1.8 oz	0.4 oz
Weight Food Fed	12.3 oz/d	12.3 oz/d
Food:Fish Ratio (yield)	1.5:1	1.6:1
Comments		Fish reproduced.

Table 3. Hybrid Tomato Growth Test Results.		
Parameter	**Tomato A**	**Tomato B**
Water	Tensleep Produced Water	Potable
Number of Plants	28	28
Number of Tomatoes Harvested	1591	1766
Total Weight of Harvest	111	339
Average Tomato Weight (lb)	0.07 lb	0.19 lb
Maximum Weight(lb)	4.675	6.0
Minimum Weight (lb)	0.875	1.2
Average Plant Height	10 ft ?	14 ft ?
Date of Plant Flowering	April 17	April 20
Comments	Bumblebees introduced to aide pollination. 1st year tomato plant variety grew better than 2nd year.	Bumblebees introduced to aide pollination.

Table 4. Tomato Toxicity Test.			
Analyses	**Units**	**Potable Tomatoes**	**Produced Tomatoes**
Benzene	Mg/kg	<.0055	<.0114
Toluene	Mg/kg	<.0055	<.0114
Ethylbenzene	Mg/kg	<.0055	<.0114
Xylene(s)	Mg/kg	<.011	<.0228
Magnesium	Mg/kg	103.95	125.4
Sodium	Mg/kg	65.45	215.46
Chloride	Mg/kg	583	1140
Arsenic	Mg/kg	<.00275	.0057
Barium		.066	.1539
Cadmium		<.00275	<.0057
Chromium	Mg/kg	.022	.0399
Lead		.00825	.0285
Mercury		<.00275	<0057
Selenium		.00825	.0171
Silver		<.00275	.0057

Table 5. Common Produced Water Disposal Methods of Operators in WY, CO, UT and NM			
Method	**Estimated Cost ($/bbl)**	**Limitations**	**Benefits**
Surface Discharge	0.01-0.80	Energy costs	Livestock, wildlife, irrigation
Secondary Recovery	0.05-1.25	Infrastructure	Increased production
Misting Towers	NA	Tower design, puddling	Enhanced Evaporation
Shallow Re-injection	0.10-1.33	Energy $ and maintenance	Recharge Aquifer
Evaporation Pits	0.01-0.80		Livestock impoundment
Commercial Water Hauling	1.00-5.50	Distance	
Disposal Wells	0.05-2.65		
Commercial Disposal Wells			
FTE	2.65-5.00		
Commercial hauling + Commercial injection	0.01-2.10		
Evaporation pits + flowlines	1.00-1.75		
Frac Water	NA	New Wells	E&P
Road Spray		Seasonal	Dust Abatement
Converting Old Well to Disposal Well			
Constructed Wetland	.001-	Land Area	Livestock, wildlife habitat, communities, education
Electrodialysis (ED)	0.02-0.64		
Induced Air floration for De-oiling	0.05		
Anoxic/Aerobic GAC	0.083		