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Evaluation of Subsurface Flow and Free-water Surface Wetlands Treating NPR-3 Produced Water –Year No. 1

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ABSTRACT

This paper is a summary of some of the activities conducted during the first year of a three-year cooperative research and development agreement (CRADA) between the Department of Energy (DOE) Rocky Mountain Oilfield Testing Center (RMOTC) and Texaco relating to the treatment of produced water by constructed wetlands. The first year of the CRADA is for design, construction and acclimation of the wetland pilot units. The second and third years of the CRADA are for tracking performance of pilot wetlands as the plant and microbial communities mature.

A treatment wetland is a proven technology for the secondary and tertiary treatment of produced water, storm water and other wastewaters. Treatment wetlands are typically classified as either free-water surface (FWS) or subsurface flow (SSF). Both FWS and SSF wetlands work well when properly designed and operated.

This paper presents a collection of kinetic data gathered from pilot units fed a slipstream of Wyoming (NPR-3) produced water. The pilot units are set up outdoors to test climatic influences on treatment. Monitoring parameters include evapotranspiration, plant growth, temperature, and NPDES discharge limits. The pilot wetlands (FWS and SSF) consist of a series of 100-gal plastic tubs filled with local soils, gravel, sharp sand and native wetland plants (cattail (*Typha spp.*, bulrush (*Scirpus spp.*), dwarf spikerush (*Eleocharis*)). Feed pumps control hydraulic retention time (HRT) and simple water control structures control the depth of water. The treated water is returned to the existing produced water treatment system. All NPDES discharge limits are met. Observations are included on training RMOTC summer students to do environmental work.

INTRODUCTION

Wetlands are an evolving water treatment technology. We are still learning how to design and operate treatment wetlands for specific applications. Pilot studies can test a wide range of possible wetland designs and operational practices. The pilot work can target specific pollutants for degradation, and the pilot data can be used to design and operate full-scale treatment wetlands. Pilot wetlands are also relatively inexpensive to construct and operate.

Free water Surface (FWS) Wetlands

FWS wetlands are designed and operated to not only improve water quality, but may also provide high quality wetland habitat for waterfowl and other wildlife. FWS wetlands look and function much like natural wetlands. The root zone of the submergent plants acts as a point of attachment for microbes. There are several processes involved in treating the water in wetlands. The combination of plants, soils and microbes treats the influent through sedimentation, filtration, precipitation, flocculation, and bio-chemical transformation.

Subsurface Flow (SSF) Wetlands

Modern-day SSF wetlands began in Europe several decades ago for the treatment of sewage. Today SSF wetlands are used throughout the world to treat storm water, acid-mine drainage, agricultural runoff, feedlot runoff, and industrial wastewater. The major advantage of using a subsurface flow wetland is that the wastewater stays below the gravel surface thereby decreasing or eliminating exposure to wastewater, odor, and insect vectors, reducing evapotranspiration rates and maintaining water temperature for optimal plant growth. Another advantage is that SSF wetlands are smaller in area than FWS wetlands.

OBJECTIVES

The primary objective of this three-year pilot study is to evaluate the performance of FWS and SSF wetlands treating produced water at Naval Petroleum Reserve No. 3, located north of Casper, Wyoming. The first year is for the design, construction and acclimation of the pilots. The second and third years are for tracking the treatment performance of the wetlands as the wetland plant and microbial communities mature in the extremes of the Wyoming climate. The secondary objective is train RMOTC summer students from the DOE Mickey Leland Energy Fellowship Program to do environmental work.

SCOPE

Design of the FWS and SSF pilot wetlands is based on previous pilot unit experience by Texaco personnel. The construction of the pilot wetlands was done jointly by RMOTC and Texaco personnel and RMOTC summer interns. Local plants, soils and rocks were used in the construction. The summer students constructed and operated the pilot wetlands during the acclimation phase. Several parameters were evaluated during acclimation phase. The parameters include:

- Design and Construction Methods for FWS and SSF Pilot Wetlands
- Treatment Efficiency
  - Effects of Evapotranspiration
  - Plant Growth
  - Effects of Temperature
  - Chemical Oxygen Demand
  - pH
  - Conductivity
- Solids Deposition
- Troubleshooting Pilot Wetlands

MATERIALS AND METHODS

Pilot Unit Construction

The produced water originates at tank battery B-Tp-10. It is transferred to a 150-barrel cooling tank where the water reaches ambient temperature before being pumped into smaller feed tanks. The produced water is introduced to the pilot wetlands using a variable-speed injector pump. The pumps are electrically operated. Pump flow rates control the hydraulic retention time (HRT).

Each pilot system consists of four 100-gallon tubs, one-inch PVC pipe and fittings (Table 1). The units are placed in series, elongated, and at descending elevations to facilitate gravity water flow. Sampling ports are built into the tubing connecting each pilot unit. The water is discharged from the pilot wetland system into a sump. From the sump, the treated water is discharged into the existing bio-treatment pond (Figure 1).

One feature of the SSF pilot wetlands is the arrangement of the discharge and outflow headers. The discharge header provides an even flow through the wetland and prevents channeling and plugging. The header is assembled by drilling holes into one-inch PVC pipe, approximately one inch apart using a spiral pattern. It is set inside of the pilot wetland and covered by 18 inches of gravel.

A similar apparatus was designed as an outflow header for each wetland. Again, holes were drilled into one-inch PVC pipe. The pipe was covered by a screen and set at approximately a 45° angle, perpendicular to the discharge outlet of the wetland. This design allows the water to discharge through several ports instead of just one avoiding dead spots and channeling.

Wetland Plants

Softstem bulrush and cattail are emergent aquatic plants. Emergent plants can stabilize the wetland bed surface, provide an attachment surface for microbes, insulate the bed, and assist in decomposition of pollutants. During the active growth period, plants are able to significantly reduce pollutants in the water by providing oxygen to the microbes in the root zone and consuming nutrients to build additional plant biomass. During the senescent phase, plants still contribute to the reduction of pollutants by providing oxygen to the microbes.

Softstem Bulrush was collected approximately one-half a mile from the test site. Bulrush can survive over a wide pH range of 5.4 to 7.5, and their adaptability is high. The Wyoming growth period for bulrush is approximately six months (spring to fall).

Broadleaf Cattail was collected from same site as the bulrush. The cattail growth period extends from April to August. Cattails can tolerate pH levels from 5.5 to 7.5. Studies indicate cattail is a good wetland plant for removing organic pollutants from the water. Cattail oxidizes the soil creating an aerobic environment.

Key FWS Pilot Wetland Design Features

When constructing the FWS pilot wetlands for tertiary treatment, there are a few key design features: elevation, standpipe height adjustment and water distribution. This pilot system was constructed outdoors, near the water source. The natural grade of the site was used to maximize gravity flow for the system. However after we built and "test drove" the system, we discovered that FWS pilot wetland No. 1 would not flow into No. 2. No. 1 was raised a few inches to compensate for ground settling. The elevation problem was corrected, and gravity flow worked (Figure 2).

Pilot wetland elevation and standpipe height adjustments are linked. If the standpipe needs to be lowered in order to reduce the volume of water in the wetland, it cannot be adjusted below the level of the distribution pipe for the next wetland. In FWS pilot wetlands, the standpipe was placed to set the maximum water level (6-8 inches). However, the standpipe placement did not take into consideration the elevation of the distribution pipe for the next pilot wetland. This made adjustments to the standpipe nearly impossible (Figure 2).

Water is distributed from one pilot wetland to the next by collection into the standpipe where it flows out of the discharge outlet. From the discharge outlet the head pressure pushes the water up the distribution pipe and into the next wetland. To facilitate laminar flow conditions and maximize contact time with the wetland, it is important to discharge the water from the distribution pipe on the centerline of the next wetland in series (Figure 3).

Key SSF Pilot Wetland Design Features

Our summer students learned that the SSF pilot wetlands require more attention to design parameters and materials than do the FWS pilot wetlands. Adjustments to SSF pilot wetlands required removing the plants and rock material, fixing the problem and then resetting the wetland. This process interrupts data collection, as well as plant and system acclimation. The students got to:

1. Fix leaks.
2. Address plugging challenges.
3. Adjust flows from pilot wetland to pilot wetland.
4. Transplant plants.

In all but one of the SSF pilot wetlands, leaking from the discharge outlet was a problem. The original plumbing and fittings did not seal around the outlet. This was repaired with a new outlet plumbing system from a specialty store.

There are three ways to address plugging of the SSF pilot wetlands. (1) Excavate all material from the wetland, wash the gravel until clean, and reset wetland. (2) Install a backflow port. (3) Purchase clean washed gravel.

Improper flow distribution may be the easiest challenge to remedy assuming the flow is being affected by the positioning of the standpipe and not due to elevations. Much like the FWS system, flow from SSF pilot wetland to pilot wetland is dependent upon the elevation of the standpipe and distribution pipe into the next wetland. The standpipe must be higher than the distribution pipe, otherwise gravity flow will not be achieved. It is usually easier to adjust the standpipe since this pipe is on the outside of pilot wetland rather than the distribution pipe, which is buried in gravel material inside the wetland. The students learned to inspect these elevations before gluing the pipe together.

Finally, it is important to note the level of water within the SSF pilot wetland is equal to the elevation of the standpipe on the outside of the wetland. Plants will die if the water level is below the root zone. The student solutions were to dig out the plants and reset them to the water level within the wetland and/or to adjust the height of the standpipe.

The RMOTC summer students learned that it is more efficient to design and construct the pilot wetland properly the first time than it is to fix the pilot wetlands during operation. The SSF pilot wetland elements are shown in Figure 4 at the end of this paper.

SAMPLING AND ANALYTICAL TESTS

See Table 2 at the end of this paper.

RESULTS AND DISCUSSION

Free-water Surface Pilot Units

During the acclimation phase, water samples were collected from each of the four sampling ports on weekdays. The pH, electrical conductivity, evapotranspiration, flow rates, hydraulic retention time, total dissolved solids, chemical oxygen demand, and water temperatures were measured. In addition, stem height and density of the wetland plants were noted. The discussion below compares and contrasts the treatment efficiency of each of the two systems.

pH

The pH value measures the amount of H^+ ions available in solution and equals the negative log of the concentration of H^+. Most plants and microbes live with pH values of 6.5-8.5 standard units.

The overall pH of the FWS pilot wetland treated water was neutral and fell within the NPDES discharge limit. There were occasional spikes in pH levels, which may be attributed to evapotranspiration and intermittent interruptions of flow due to power outages during the month of August (Table 3 and Figure 5).

The pH of SSF pilot wetlands remained neutral throughout the acclimation stage. All readings fell well below the NPDES discharge limit of 8.5 standard units (Table 12 and Figure 6).

Electrical Conductivity (EC)

The conductivity values were measured with a HACH sensION5 portable conductivity/TDS meter. EC is a measurement of the ability of an aqueous solution to carry an electrical current, and it can be used to detect a change in the salt content of water and indirectly measure the amount of evaporation.

Conductivity measurements for the FWS pilot wetlands leveled out compared to initial treatment readings. Bentonite was added to three of the four pilot wetlands to seal leaks from the discharge outlets. This addition in concert with high evapotranspiration rates may have contributed to the elevated conductivity measurements (Table 4and Figure 7).

The conductivity values in the SSF pilot wetlands stabilized during the latter part of July. During August, three of the wetlands were reset and the systems were plagued with weekly power outages. Measurements were not taken during this time. Subsequent readings during September show a noticeable step-wise reduction at each sample port indicating salts are being removed as the water flows through the system (Table 12 and Figure 8).

Evapotranspiration (ET)

ET can affect the electrical conductivity of a wetland by evaporating the water and leaving the salts. This causes the ion concentration in the water to increase.

The average ET for the FWS pilot wetland ranged between 1/8 to 1/3 inches of water loss each day from July 3 through July 26, 2001. (Figure 9) The measurements were collected with a modified pan evaporator.

Due to the reconstruction of the SSF tubs, data gaps are present.

Flow Rates

Pump flow rates were measured twice weekly. The flow rates help to set the hydraulic retention time (HRT). Differences between influent and effluent pilot wetland flow rates were used to diagnose occasional plugging challenges (Table 5).

Hydraulic Retention Time (HRT)

The HRT is a measurement of how long on average the water is in contact with the wetland. The HRT is equal to water volume divided by the flow rate. By plotting HRT v. pilot wetland treatment performance data, one can begin to size of a full-size treatment wetland (Table 6 and Figure 10).

Flow rates for each of the FWS pilot wetlands were measured at the influent distribution pipe to each wetland. The working volumes of the wetlands were measured by filling and draining the wetlands. The target HRT was a 24 hours per wetland. The actual HRTs ranged from 14.1 to 36.1 hours due to variations in the feed tank head pressure and evapotranspiration.

HRT measurement in SSF pilot wetlands is more difficult to do than in the FWS pilot wetlands. Two methods were used to determine the volume of the SSF pilot wetlands. The empirical method was fill and drain. The theoretical method calculated the volume based on the volume and porosity of the gravel. The RMOTC summer students learned that both methods worked.

Typically, pea gravel has a 30% porosity and hydraulic conductivity between 10^{-1} to 10^{2} cm/sec. With 30% porosity the water is able to flow through the media. Sufficient pore space is available for microbes to attach to the surface area of the gravel and permit plant roots to expand.

The use of the small rock size has a number of advantages. (1) There is more surface area available on the media for treatment as compared to large rock. (2) Small void spaces are compatible with development of the roots and rhizomes of the vegetation. (3) It creates laminar flow conditions (*USAE WES-Constructed Wetlands Design*) (Table 7).

Total Dissolved Solids (TDS)

TDS was measured using a HACH conductivity/TDS meter. TDS is an indication of ionic strength and an indirect measure of the salt content of the water.

In comparison with the conductivity measurements of each pilot wetland, the TDS rates have stabilized. The stepwise reduction in TDS is in agreement with the conductivity measurements (See Tables 8 & 12 and Figures 11 & 12).

Chemical Oxygen Demand (COD)

Chemical oxygen demand is the equivalent quantity of oxygen used to oxidize the organic matter in a wastewater. The COD was measured using the HACH dichromate COD method**,** a HACH COD reactor, and spectrometer.

During the acclimation phase, the general trend for COD in the FWS pilot wetlands was a stepwise decrease from Port 1 through Port 4. This trend suggests that microbes are oxidizing the hydrocarbons in the produced water. There is still some scatter to COD data indicating that acclimation is not over yet (Table 9 and Figure 13).

COD was not successfully measured for the SSF pilot wetland by the summer students. The plugging of the SSF pilot wetlands made sample collection impossible. COD sampling of the SSF pilot wetlands is now underway after the plugging was corrected and the students returned to school. Those data are not reported.

Temperature

Water temperature is a critical parameter to the operation of a wetland. Most wetland plants cannot sustain growth in waters with temperatures greater than 100°F. At low temperatures, microbial activity slows down and plants become senescent. Temperature was measured with a HACH sensION5 portable conductivity/TDS meter.

Water temperature in the FWS pilot wetlands ranged from 64°F to 83.6°F. These water temperatures provided an ideal environment for wetland plant growth (Table 10 and Figure 15).

Water temperatures in the SSF pilot wetlands were slightly lower than in the FWS pilot wetlands. Average temperatures ranged from 58°F to 75°F. These temperatures are slightly below the optimal plant growth range. The effect on SSF wetland plant growth was evident when compared to the FWS wetland plants (See Table 12 and Figure 16). The temperature difference are attributed to the FWS pilot wetlands with the open water heating up faster during daylight hours than the below ground water of the SSF pilot wetlands.

Plant Growth Rates

Plant growth rates are an indicator of the quality of the water and how well a wetland is operated. Plant height and stem density are common ways of measuring plant growth. Students found that plant height was considerably easier to measure than stem density.

In the FWS pilot wetlands, broadleaf cattail averaged 7 inches of growth per week. Softstem bulrush grew an average of almost 6.5 inches per week, while the average growth for Olney's bulrush was approximately 4.3 inches of growth per week (See Table 10 and Figure 14 15).

The plants in SSF pilot wetlands did not fair as well as the FWS pilot wetlands. Each of the four wetlands was reset during the acclimation phase. The plants were removed during the resetting of the pilot wetlands and transplanted. Many of the transplants died and growth of the remaining plants was slow. Frequent transplantation is not good for plants.

SSF Wetland Coupon Testing

In this wetland pilot, 1 x 1 x ¼ inch coupons were used to measure solid and scale (CO_3) deposition from the waste stream. The coupons were placed at different depths in the pilot wetlands to determine where solids and scale might cause future plugging in SSF wetlands.

The three coupon pipes were placed on a spacing of approximately 15 inches apart in each SSF pilot wetland. The pipes were set at depth of 28, 17 and 21 inches respectively (Figure 4). Insertion of the pipes into the gravel bed was difficult. Pipes were initially hammered into the gravel bed. The same procedures were used in the remaining wetlands to install coupon pipes. For reset SSF pilot wetlands, the pipes were placed in the wetland as the gravel was added to avoid the difficulty in hammering.

The acclimation phase coupon testing data are inconclusive due to continuous interruptions and resetting of the system. Although we did not collect enough data to compare solids deposition to TDS, the coupons were good indicators for poor flow, determination of water levels, and locating bed plugging (Table 13)

SUMMARY OF YEAR ONE CRADA WORK

FWS Wetland Conclusions

The FWS pilot wetland system was successful.

- RMOTC summer students can set up FWS systems with minimal supervision.
- The FWS pilot wetlands are nearing completion of the acclimation phase.
- Wyoming plants and soils work in treatment wetlands and meet discharge limits.
- COD is removed.
- The pH is regulated.

- Electrical conductivity and total dissolved solids meet discharge limits.

The FWS pilot wetland system was successful during the acclimation phase at lowering the COD below the current NPR-3 discharge limit NPDES permit. The pilot wetlands met the pH limits. The FWS pilot wetland treating produced water had good plant growth and an abundant population of insects indicating that the water was of high quality.

SSF Wetland Conclusions

The SSF pilot wetland system was successful.

- RMOTC summer students require more attention when setting up SSF than FWS pilot wetlands.
- The SSF pilot wetlands are in the acclimation phase.
- Wyoming plants and rock work in treatment wetlands and meet discharge limits.

The native Wyoming wetland plants and rocks (gravel) work well in SSF wetlands. Although the reconstruction of several of the wetlands disrupted plant growth, the plants grew well after the plugging and elevations were corrected. Based on the plant growth, the system is still in the acclimation stage. Careful attention must be paid to the design and construction specifications on SSF wetlands.

Observations on Training Summer Students

Training summer students to do environmental work is an interesting undertaking, especially for environmental professionals who are not educators. The RMOTC summer students are mostly undergraduates with limited laboratory and field experiences. Some of the common environmental concepts are easily grasped while other concepts can take a long time. Over the 10-week period of working with the summer students, we found:

- Explanation of an environmental concept worked best when it was based on the student's major field of study.
- Documentation of field and lab journals has become a lost art.
- As is common among environmental professionals, the first-time pilot unit is a "throw-away." The second or third pilot unit is the keeper.
- Summer students required more attention when setting up SSF than FWS pilot wetlands. The Civil Engineering idea about water flows down hill is easy to see in a FWS wetland and not so easy to see in a SSF wetland.
- Students who have never done any gardening are good at killing wetland plants.
- There is no substitute for laboratory experience when it comes to analytical testing.
- Field engineering is an art form for gifted and a disaster for the mechanically challenged.
- For the learning experience, it is best to let the student struggle with the challenge and then provide potential solutions.
- Wyoming can be a culture shock for students from large cities.

FUTURE PILOT WETLAND WORK

FWS and SSF Wetlands

Over the next two years, the FWS and SSF pilot wetland work will follow the maturation of the wetlands. As the plant and microbial communities mature, wetland treatment performance and operations will be monitored. Some of the monitoring activities are listed below.

- Data collection
    - HRT and Flow Rates
    - Plants and Soils
    - Water Depth
    - Pan evaporation
    - REDOX
- Wetland Operations
    - Fertilizer for plants
- Microbial Testing
    - Biological Activity Reaction Tests
        - Heterotrophic bacteria
        - Sulfur reducing bacteria
        - Fluorescing bacteria

Table 1. Equipment List

Item	**Description**
Vessel	Rubbermaid, 100-gallon tub
Feed pump	Adjustable stroke and speed injection pump to feed produced water to pilot wetland
Feed tank	300-gallon tank
Cooling tank	150-barrels (42 gallons = 1 barrel)
Sump	5-gallon bucket
PVC pipes	Ultra-violet resistant 1” pipe
PVC fittings and adaptors	Elbows, ball valves, T connectors, stoppers
Sealant	Silicon and bentonite
Plants	Broadleaf cattail (*Typha latifolia*.), Olney’s bulrush (*Scirpus americanus*), and softstem bulrush (*Scirpus validus*)
Plastic tubing	3/8” OD, ¼” ID
Zip Ties	Various sizes
Topsoil	1 yard
Cooling Tank	150-barrels
Feed Tank	300-gallons
Rock	3/8” to ¾” pea gravel; 2” sewer rock
Plants	Bulrushes (Scirpus validus) and Broadleaf Cattail (Typha latifolia)
Pallets	3 x 3-feet
Stabilizers (wooden stakes)	16-inches in length
Nylon Screen	2 x 2-inch, 1/16 mesh

Table 2. Sampling Plan for Treatment Performance Parameters

Sampling Parameter	Frequency			
	Weekly	**Monthly**	**Quarterly**	**Annually**
Chemical Oxygen Demand (COD)	X			
Biological Oxygen Demand (BOD)	X			
pH	X			
Total Dissolved Solids (TDS)	X			
Temperature	X			
Oil and Grease (O&G)			X	
Total Petroleum Hydrocarbons (TPH)			X	
Total Suspend Solids (TSS)	X			
Plant Height		X		
Stem Density		X		
Stem Diameter		X		
Hydraulic Conductivity			X	
Reduction and Oxidation (Redox)	X			
Hydraulic Retention Time (HRT)		X		
Residence Time Distribution (RTD) Diagram				X
Solids Deposition	X			

Table 3. FWS Wetland pH

Date	Sample Site	pH (s.u.)	Date	Sample Site	pH (s.u.)	Date	Sample Site	pH (s.u.)
7/9/01	Port 1	8.3	7/19/01	Port 1	7.6	7/30/01	Port 1	7.5
	Port 2	8.0		Port 2	7.6		Port 2	7.6
	Port 3	7.9		Port 3	7.7		Port 3	7.6
	Port 4	8.3		Port 4	7.8		Port 4	7.6
07/10/01	Port 1	7.7	7/20/01	Port 1	7.6	9/14/01	Port 1	8.0

Date	Sample Site	pH (s.u.)	Date	Sample Site	pH (s.u.)	Date	Sample Site	pH (s.u.)
	Port 2	7.9		Port 2	7.6		Port 2	7.9
	Port 3	7.9		Port 3	7.7		Port 3	7.9
	Port 4	8.1		Port 4	7.8		Port 4	8.1
7/11/01	Port 1	7.4	7/23/01	Port 1	7.6	9/17/01	Port 1	8.0
	Port 2	7.4		Port 2	7.6		Port 2	8.0
	Port 3	7.5		Port 3	7.7		Port 3	7.9
	Port 4	7.6		Port 4	7.8		Port 4	8.0
7/12/01	Port 1	7.5	7/24/01	Port 1	7.5	9/20/01	Port 1	7.8
	Port 2	7.5		Port 2	7.6		Port 2	8.0
	Port 3	7.6		Port 3	7.7		Port 3	8.1
	Port 4	7.8		Port 4	7.8		Port 4	8.2
7/17/01	Port 1	7.7	7/25/01	Port 1	7.5			
	Port 2	7.6		Port 2	7.6			
	Port 3	7.6		Port 3	7.7			
	Port 4	7.7		Port 4	7.8			
7/18/01	Port 1	7.7	7/26/01	Port 1	7.5			
	Port 2	7.7		Port 2	7.7			
	Port 3	7.8		Port 3	7.8			
	Port 4	7.9		Port 4	7.8			

Table 4. FWS Conductivity Readings

Date	Sample Site	Conductivity (mS/cm)	Date	Sample Site	Conductivity (mS/cm)	Date	Sample Site	Conductivity (mS/cm)
7/9/01	Port 1	6.84	7/19/01	Port 1	6.08	7/30/01	Port 1	5.57
	Port 2	6.92		Port 2	6.29		Port 2	6.09
	Port 3	6.68		Port 3	5.19		Port 3	6.19
	Port 4	7.33		Port 4	6.51		Port 4	5.84
07/10/01	Port 1	4.87	7/20/01	Port 1	6.69	9/14/01	Port 1	6.08
	Port 2	5.62		Port 2	6.41		Port 2	5.05
	Port 3	5.73		Port 3	6.66		Port 3	6.11
	Port 4	6.55		Port 4	6.16		Port 4	3.56
7/11/01	Port 1	6.38	7/23/01	Port 1	6.29	9/17/01	Port 1	5.93
	Port 2	6.34		Port 2	6.2		Port 2	5.79
	Port 3	6.22		Port 3	6.23		Port 3	5.84
	Port 4	6.08		Port 4	5.9		Port 4	4.29
7/12/01	Port 1	6.02	7/24/01	Port 1	6.12	9/20/01	Port 1	5.8
	Port 2	6.04		Port 2	5.77		Port 2	6.03
	Port 3	5.78		Port 3	6.26		Port 3	5.79
	Port 4	5.26		Port 4	5.93		Port 4	4.99
7/17/01	Port 1	5.53	7/25/01	Port 1	5.69			

Date	Sample Site	Conductivity (μS/cm)	Date	Sample Site	Conductivity (μS/cm)	Date	Sample Site	Conductivity (μS/cm)
	Port 2	5.8		Port 2	5.63			
	Port 3	5.76		Port 3	6.12			
	Port 4	4.93		Port 4	5.88			
7/18/01	Port 1	5.68	7/26/01	Port 1	5.87			
	Port 2	5.82		Port 2	6.00			
	Port 3	5.81		Port 3	5.54			
	Port 4	5.15		Port 4	4.83			

Table 5. FWS Wetland Flow Rates (ml/min)

Week Of	Tub 1	Tub 2	Tub 3	Tub 4
7/9/01	128	170	150	236
7/17/01	64	63	66	62
7/20/01	72	70	68	60
7/24/01	87	81	94	91
9/14/01	72	61	76	56
9/17/01	97	105	99	90
9/19/01	94	97	113	103

Table 6. FWS Wetland Hydraulic Retention Times

	Volume (cm^3)	Average Flow Rate (ml/min)	HRT (hr)
Tub 1	134,150.41	158	14
Tub 2	144,469.67	86	28
Tub 3	154,788.93	93	28
Tub 4	185,746.72	100	31

Table 7. SSF Hydraulic Retention Time

Volume (cm^3)	Average Flow rate (cm^3/min)	HRT	HRT (hr)	HRT (day)
237638.52	150	1584.257	26.40428	1.10

Table 8. FWS Wetland TDS

Date	Sample Site	TDS (mg/ L)	Date	Sample Site	TDS (mg/ L)	Date	Sample Site	TDS (mg/ L)
07/10/01	Port 1	2	7/19/01	Port 1	2.4	7/30/01	Port 1	2.2
	Port 2	2.2		Port 2	2.5		Port 2	2.4
	Port 3	2.3		Port 3	2		Port 3	2.5
	Port 4	2.5		Port 4	2.6		Port 4	2.0
7/11/01	Port 1	2.6	7/20/01	Port 1	2.7	9/14/01	Port 1	2.3
	Port 2	2.5		Port 2	2.6		Port 2	2.1
	Port 3	2.4		Port 3	2.7		Port 3	2.4

Date	Sample Site	TDS (mg/ L)	Date	Sample Site	TDS (mg/ L)	Date	Sample Site	TDS (mg/ L)
	Port 4	2.6		Port 4	2.5		Port 4	1.6
7/12/01	Port 1	2.4	7/23/01	Port 1	2.5	9/17/01	Port 1	2.3
	Port 2	2.4		Port 2	2.5		Port 2	2.2
	Port 3	2.3		Port 3	2.5		Port 3	2.3
	Port 4	2.1		Port 4	2.4		Port 4	1.8
7/17/01	Port 1	2.2	7/25/01	Port 1	2.1	9/20/01	Port 1	2.4
	Port 2	2.3		Port 2	2.3		Port 2	2.2
	Port 3	2.2		Port 3	2.4		Port 3	2.2
	Port 4	2		Port 4	2.4		Port 4	1.7
7/18/01	Port 1	2.2	7/26/01	Port 1	2.3			
	Port 2	2.3		Port 2	2.4			
	Port 3	2.3		Port 3	2.2			
	Port 4	2.1		Port 4	1.9			

Table 9. FWS Wetland Chemical Oxygen Demand

Date	Sample Site	COD (mg/L)	Date	Sample Site	COD (mg/L)	Date	Sample Site	COD (mg/L)
7/9/01	Port 1	79	7/17/01	Port 1	45	7/23/01	Port 1	50
	Port 2	66		Port 2	80		Port 2	40
	Port 3	52		Port 3	131		Port 3	4
	Port 4	44		Port 4	114		Port 4	55
7/12/01	Port 1	142	7/20/01	Port 1	112			
	Port 2	81		Port 2	59			
	Port 3	75		Port 3	15			
	Port 4	58		Port 4				

Table 10. FWS Wetland Temperatures

Date	Sample Site	Temperature (°F)	Date	Sample Site	Temperature (°F)	Date	Sample Site	Temperature (°F)
7/9/01	Port 1	70.3	7/19/01	Port 1	70.9	7/30/01	Port 1	78.2
	Port 2	71		Port 2	69.9		Port 2	74.8
	Port 3	70.8		Port 3	69.2		Port 3	77.7
	Port 4	70.6		Port 4	69.5		Port 4	83.3
07/10/01	Port 1	71.2	7/20/01	Port 1	74.3	9/14/01	Port 1	64.7
	Port 2	72.2		Port 2	73.9		Port 2	64.4
	Port 3	72		Port 3	74.1		Port 3	63.6
	Port 4	71.8		Port 4	74.3		Port 4	62.7
7/11/01	Port 1	69.7	7/23/01	Port 1	68.9	9/17/01	Port 1	64.2
	Port 2	69.3		Port 2	69.2		Port 2	62.4

Date	Sample Site	Temperature (°F)	Date	Sample Site	Temperature (°F)	Date	Sample Site	Temperature (°F)
	Port 3	70.1		Port 3	70.1		Port 3	66.5
	Port 4	70.4		Port 4	71.2		Port 4	66.7
7/12/01	Port 1	71.6	7/24/01	Port 1	72.1	9/20/01	Port 1	59.3
	Port 2	70.7		Port 2	72.5		Port 2	57.5
	Port 3	69.8		Port 3	73.2		Port 3	56.3
	Port 4	71.6		Port 4	78.2		Port 4	58.2
7/17/01	Port 1	71.6	7/25/01	Port 1	76.6			
	Port 2	68.9		Port 2	77.9			
	Port 3	69.8		Port 3	76.2			
	Port 4	69		Port 4	83.6			
7/18/01	Port 1	66	7/26/01	Port 1	73.4			
	Port 2	65.1		Port 2	73.2			
	Port 3	64		Port 3	72.6			
	Port 4	68.7		Port 4	73.4			

Table 11. FWS Wetland Plant Growth Rates*****

Plant Growth Rate (in/week)				
	Tub No. 1	**Tub No. 2**	**Tub No. 3**	**Tub No. 4**
Cattails	10.09	5.82	9.05	3.31
Softstem bulrush	4.96	7.142	8.81	5.17
Olney’s bulrush	4.24	3.27	5.63	4.21

***Note: Table depicts average weekly growth rates from July 3 through July 26, 2001.**

Table 12. SSF Wetland Data Summary

SSF						
Date	**Sample Site**	**Electric Conductivity (mS/cm)**	**COD (mg/L)**	**pH (s.u.)**	**TDS (mg/L)**	**Temp (°F)**
7/11/01	Tub 1					
	Tub 2	6.16		7.7	2.5	76.4
	Tub 3	6.03		7.8	2.4	77.1
	Tub 4	5.22		7.8	2.3	75.7
7/12/01	Tub 1	5.23		7.7	2.1	87.2
	Tub 2	5.55		7.7	2.3	76.2

SSF						
Date	Sample Site	Electric Conductivity (mS/cm)	COD (mg/L)	pH (s.u.)	TDS (mg/L)	Temp (°F)
	Tub 3	6.31		7.8	2.5	77.3
	Tub 4	5.97		7.8	2.5	76.2
7/16/01	Tub 1	4.85		7.6	1.9	78.5
	Tub 2	4.91		7.7	1.9	73.9
	Tub 3	4.98		7.6	1.9	77.9
	Tub 4	4.92		7.8	1.8	77.8
7/17/01	Tub 1	5.38		7.7	2.1	77.5
	Tub 2	5.56		7.7	2.2	70.5
	Tub 3	5.61		7.7	2.2	70.8
	Tub 4	5.71		7.8	2.2	71.0
7/18/01	Tub 1	5.73		7.7	2.2	68.5
	Tub 2	5.82		7.8	2.3	68.1
	Tub 3	5.85		7.8	2.3	68.7
	Tub 4	5.9		7.9	2.3	69.4
7/20/01	Tub 1	6.79		7.6	2.8	88.5
	Tub 2	6.79		7.9	2.7	86.9
	Tub 3	6.72		7.6	2.7	90.3
	Tub 4	6.69		8.0	2.7	80.4
7/23/01	Tub 1	6.47	68	7.6	2.6	67.6
	Tub 2	6.52	123	7.7	2.6	71.7
	Tub 3					
	Tub 4					
7/30/01	Tub 1	5.52		7.6	2.1	86.4
	Tub 2	6.32		7.5	2.4	92.4
	Tub 3					
	Tub 4					
9/14/01	Tub 1	5.88		7.4	2.2	66.2
	Tub 2	5.45		7.8	2.3	67.8
	Tub 3	5.92		7.5	2.3	67.4
	Tub 4	5.41		7.6	2.1	71.9
9/17/01	Tub 1	5.94		7.6	2.4	65.3
	Tub 2	5.90		7.9	2.3	66.0
	Tub 3	5.49		7.6	2.2	68.0
	Tub 4	5.42		7.7	1.9	69.2
9/20/01	Tub 1	5.68		7.6	2.2	59.3
	Tub 2	5.68		7.9	2.3	60.2
	Tub 3	5.50	502	7.7	2.2	59.5

SSF						
Date	Sample Site	Electric Conductivity (µS/cm)	COD (mg/L)	pH (s.u.)	TDS (mg/L)	Temp (°F)
	Tub 4	5.13		7.8	2.1	61.3

Table 13. SSF Wetland Coupon Data

Date		Tub 1	Tub 2	Tub 3	Tub 4
7/9/01	Pipe 1	28.2	28.7	29.2	28.6
	Pipe 2	28.9	28.3	28.3	29.3
	Pipe 3	29.0	28.6	29.1	29
Date					
*7/10/01	Pipe 1	28.0	28.7	29.1	28.4
	Pipe 2	29.9	28.3	28.8	29.2
	Pipe 3	27.5	28.5	28.2	29.2
Date					
7/12/01	Pipe 1	27.9	28.7	29.4	28.4
	Pipe 2	29.2	28.2	28.6	29.0
	Pipe 3	28.8	28.5	29.1	28.9
Date					
*7/16/01	Pipe 1	28.9	28.7	28.9	28.9
	Pipe 2	28.7	28.5	30.5	28.7
	Pipe 3	29.0	28.8	28.9	29.3
Date					
7/20/01	Pipe 1	28.5	28.8	29.5	28.3
	Pipe 2	29.5	28.4	29.2	29.4
	Pipe 3	29.4	28.6	29.9	28.8
Date					
7/23/01	Pipe 1	29.0	28.8	29.1	28.2
	Pipe 2	29.5	28.4	29.0	29.2
	Pipe 3	29.6	29.5	29.3	28.9

Table 14. B-Tp-10, Naval Petroleum Reserve No. 3, Natrona County, WY, NPDES Discharge Limits.

Parameter	**NPDES Discharge Limit**
Chemical Oxygen Demand	100 mg/L
Oil and Grease	10 mg/L
pH	6.5-8.5 standard units (must remain within range)
Conductivity	7.5 µS/cm

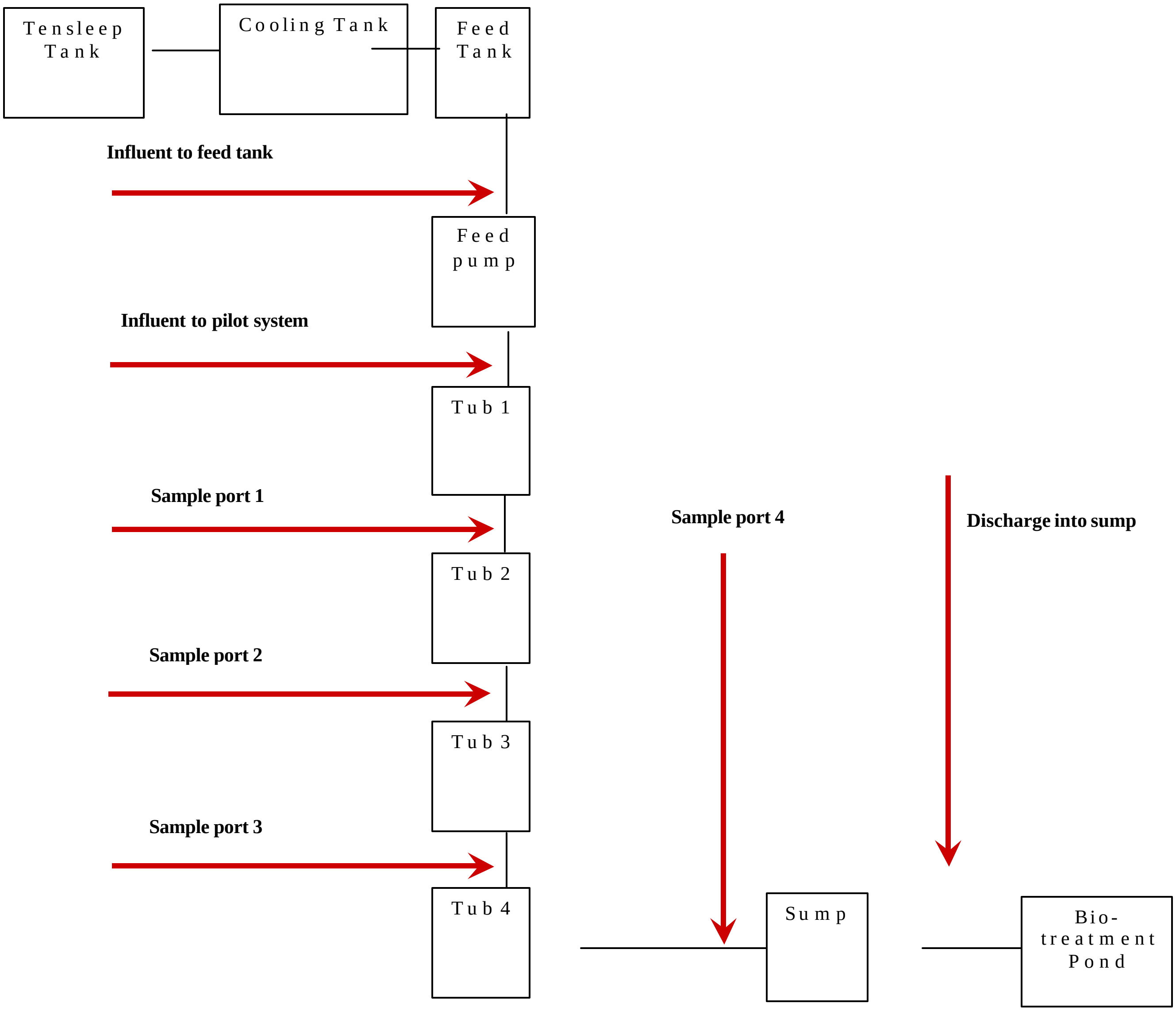

Figure 1. Pilot Unit System Process Flow Diagram

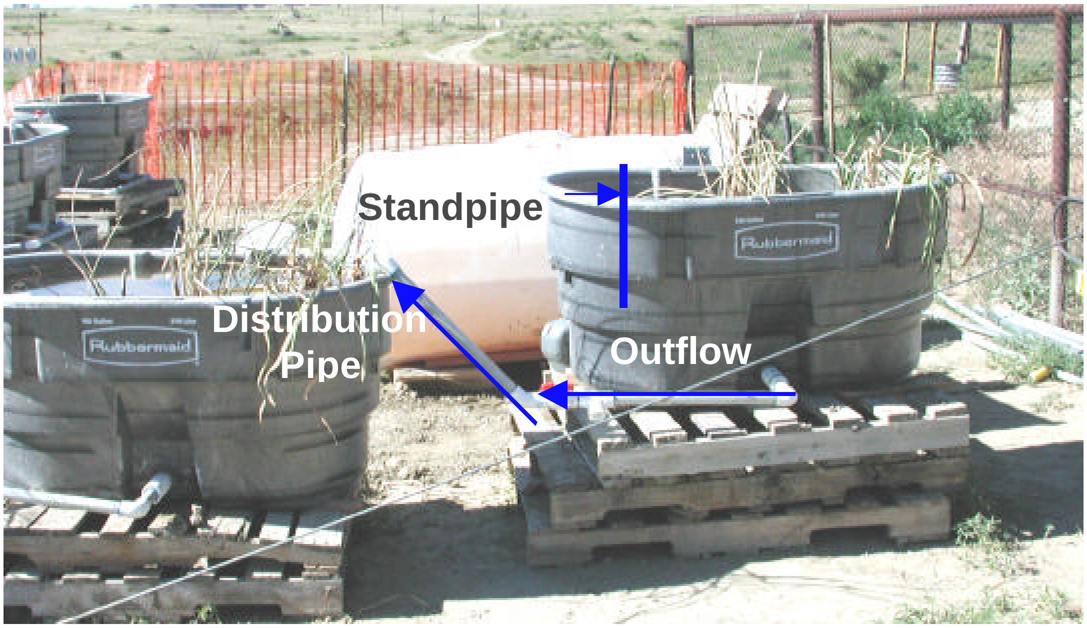

Figure 2. FWS Tub flow. Note elevation changes, ground settling, standpipe position relative to distribution pipe position and centerline position of distribution pipe on FWS Tub 2.

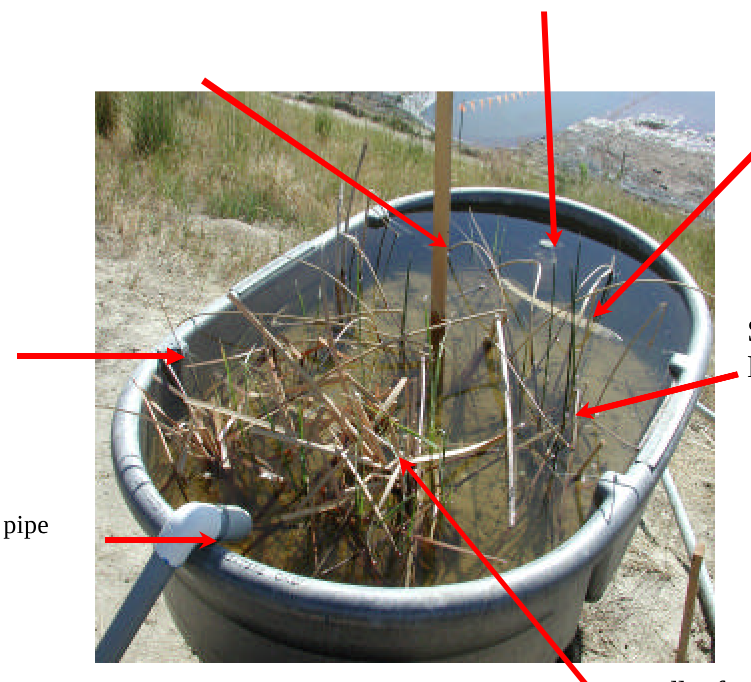

Figure 3. FWS Pilot Unit Elements

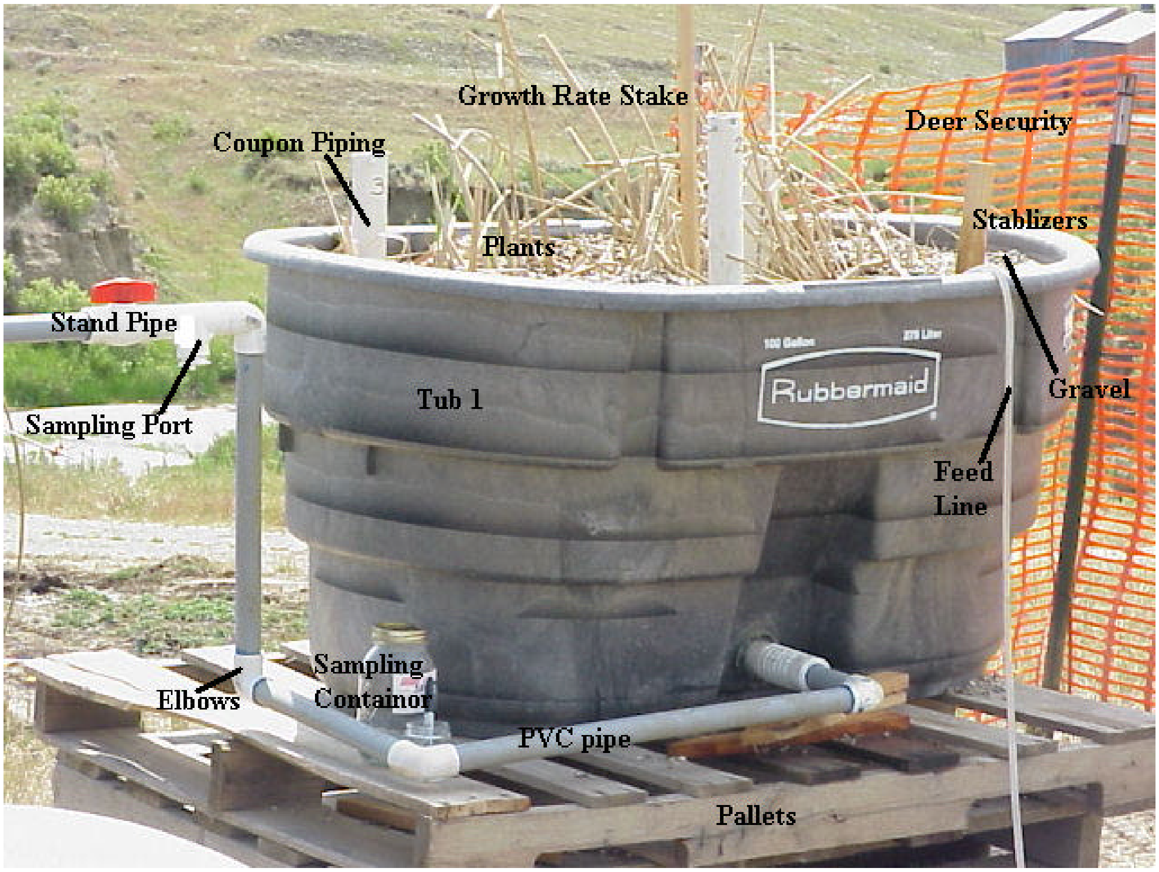

Figure 4. SSF Pilot Unit Elements

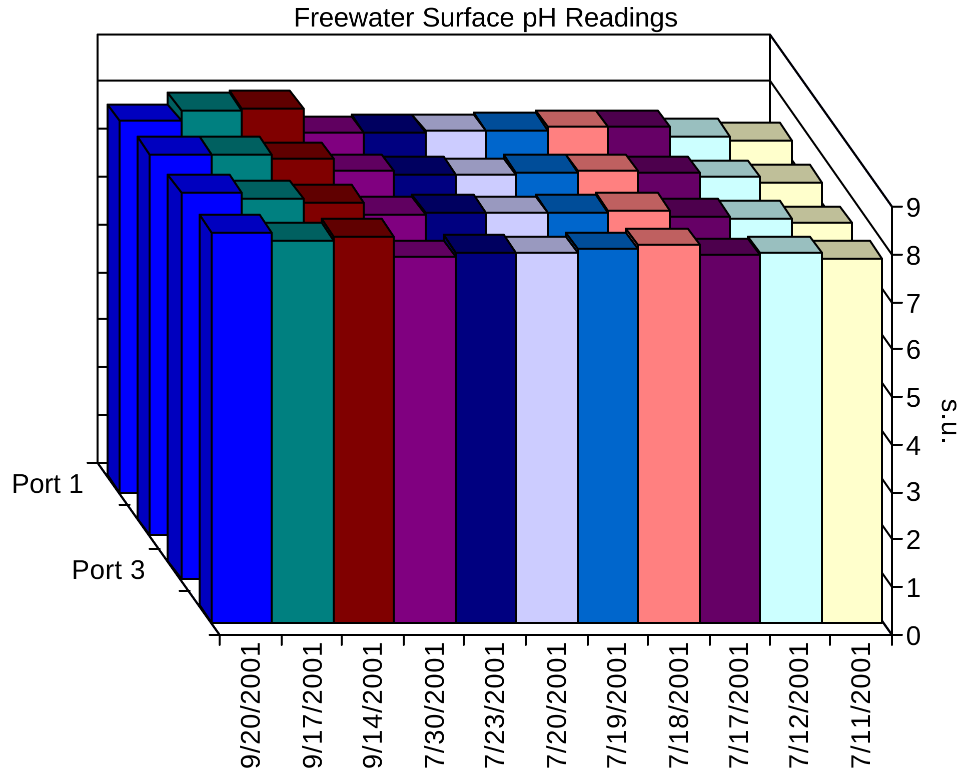

Figure 5. Freewater Surface pH Readings

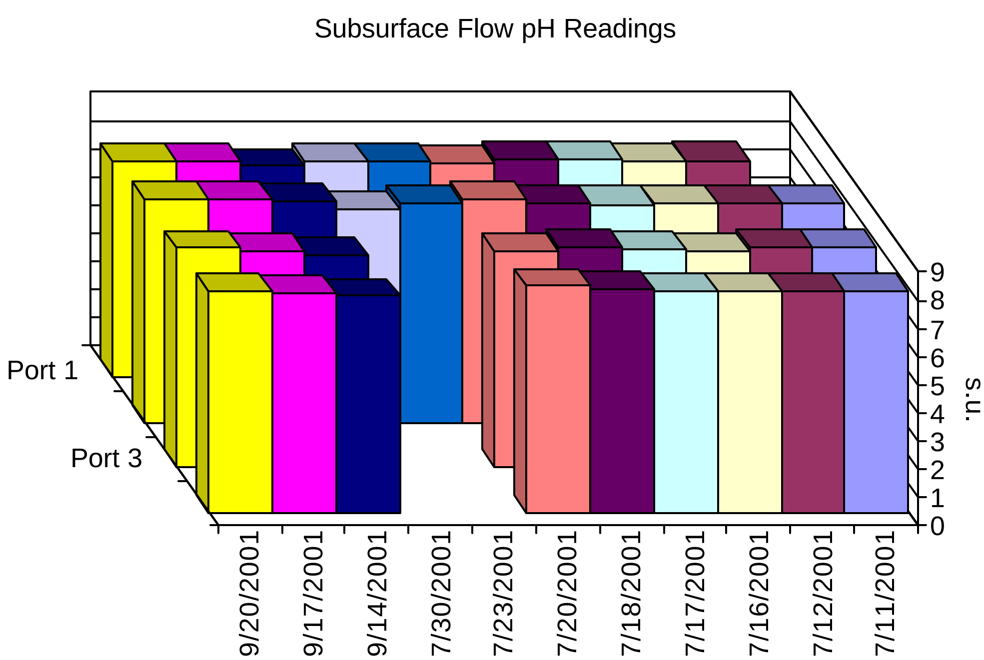

Figure 6. Subsurface Flow pH Readings

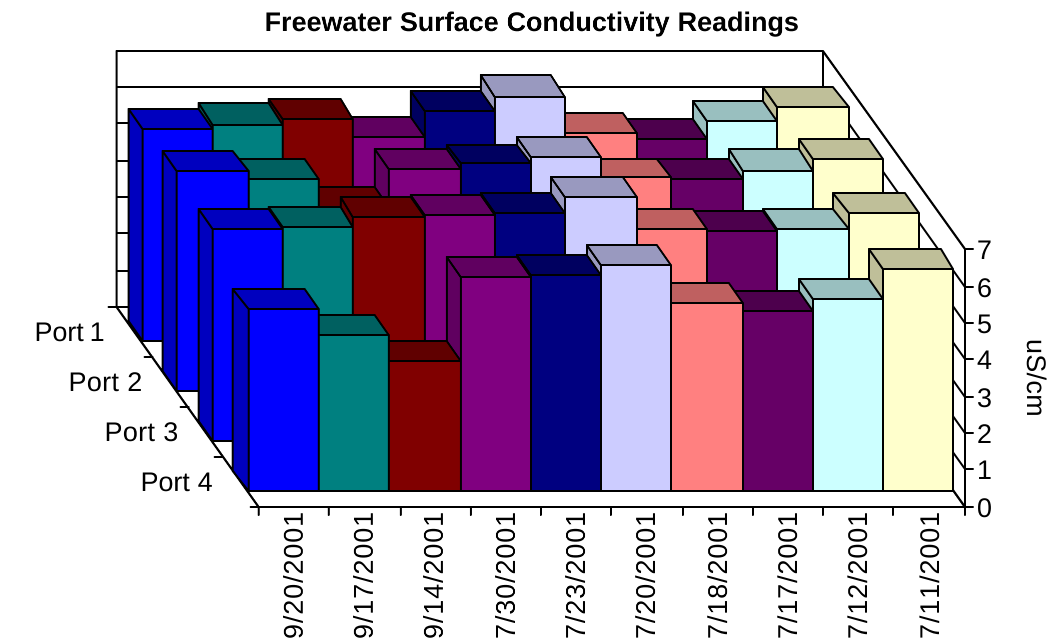

Figure 7. Freewater Surface Conductivity Readings

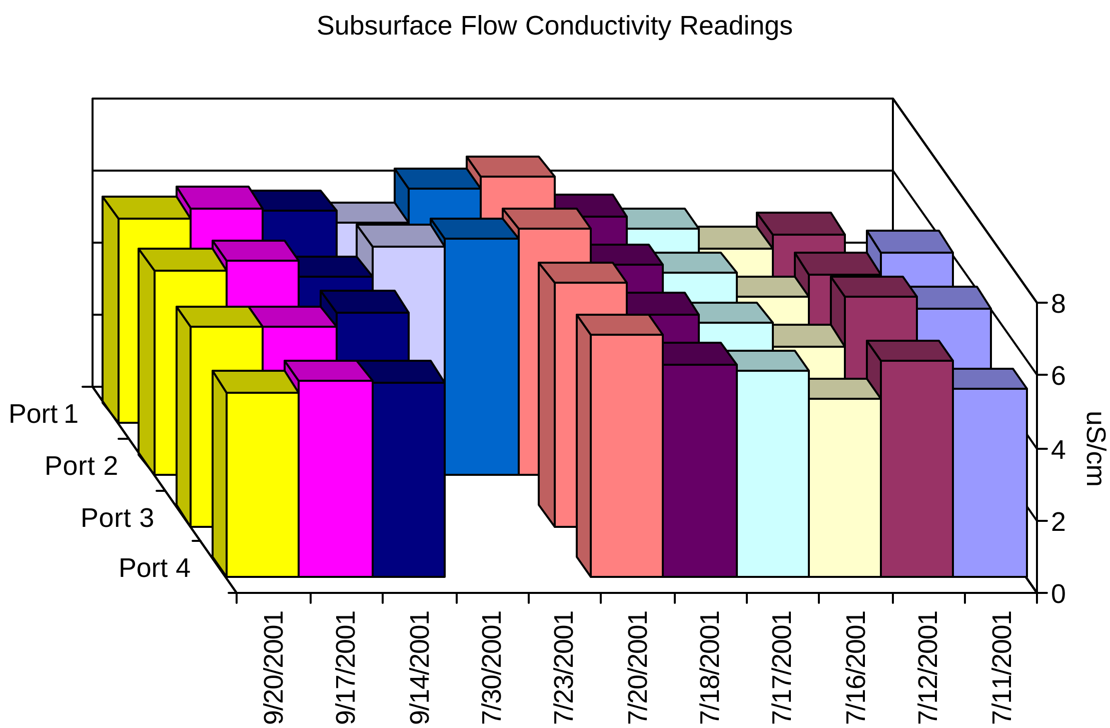

Figure 8. Subsurface Flow Conductivity Readings

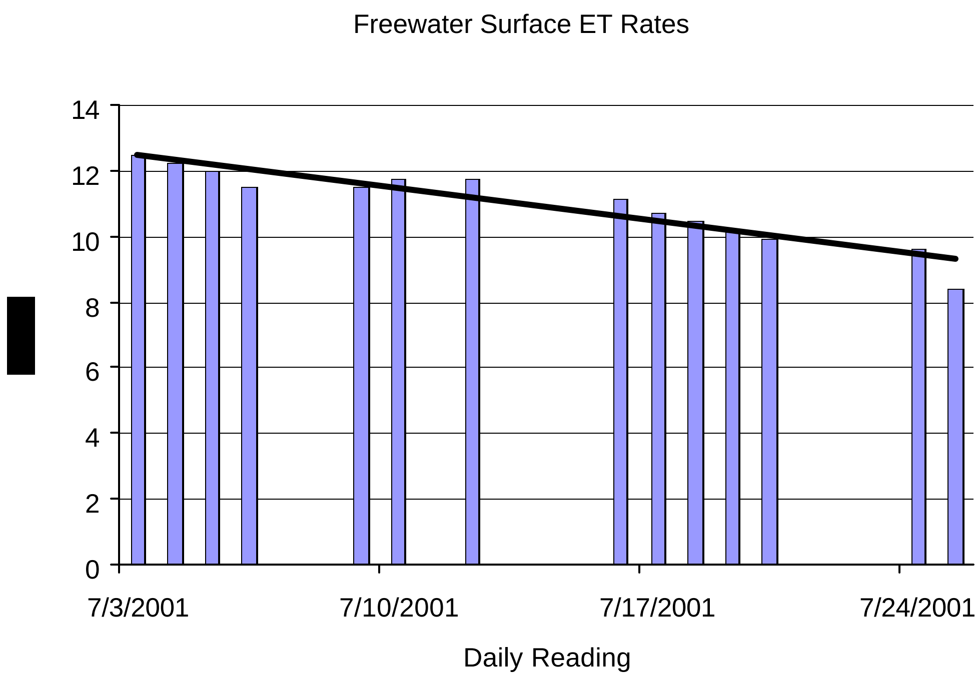

Figure 9. Freewater Surface Evapotranspiration Rates - July 3, 2001 through July 25, 2001

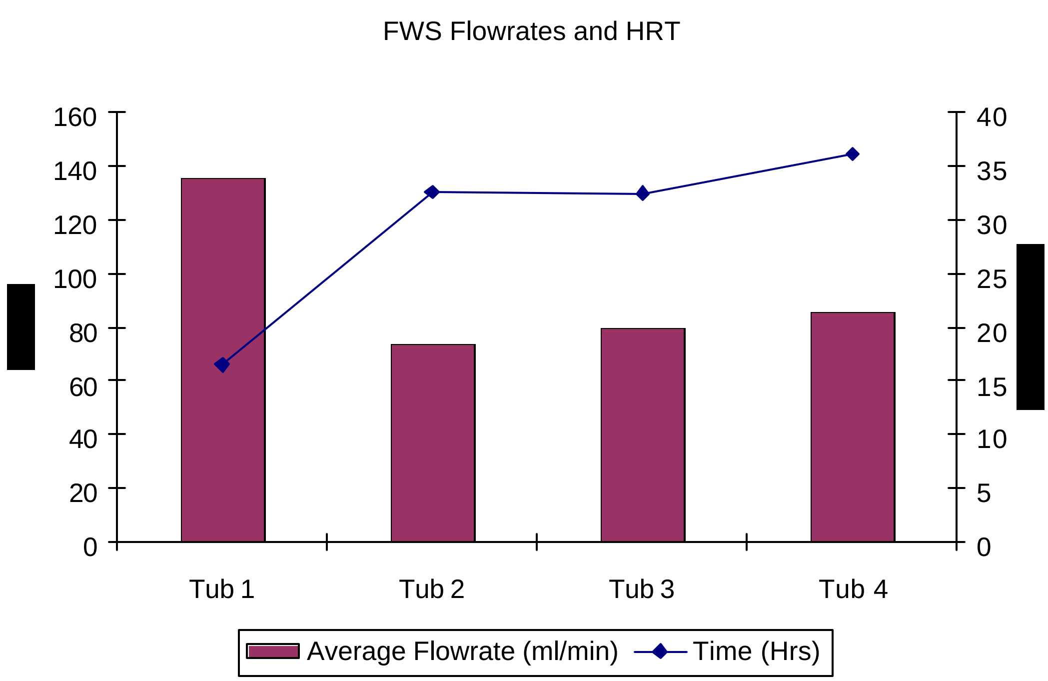

Figure 10. FWS average flowrates and hydraulic retention time

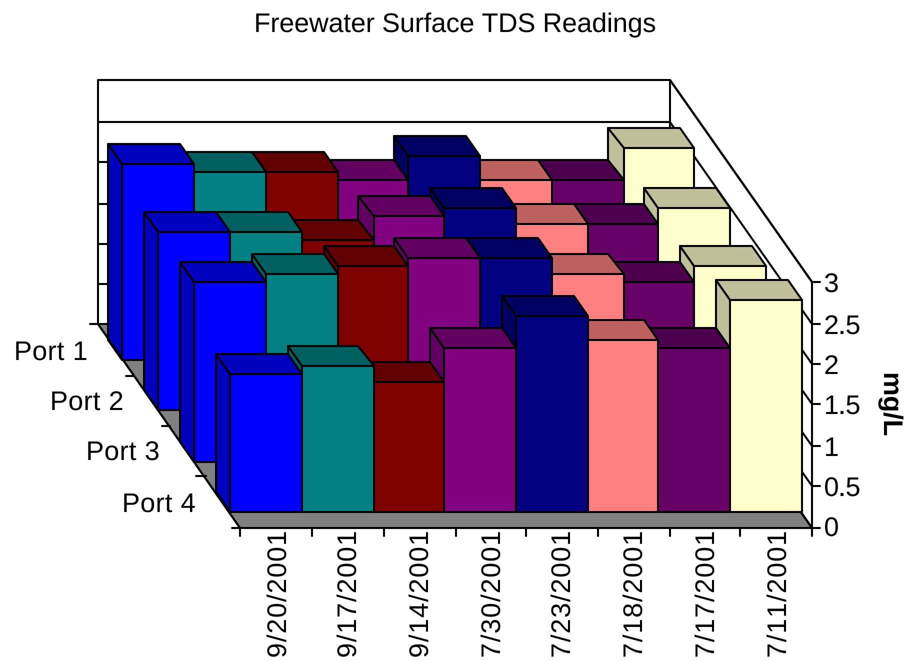

Figure 11. FWS Total Dissolved Solids Readings

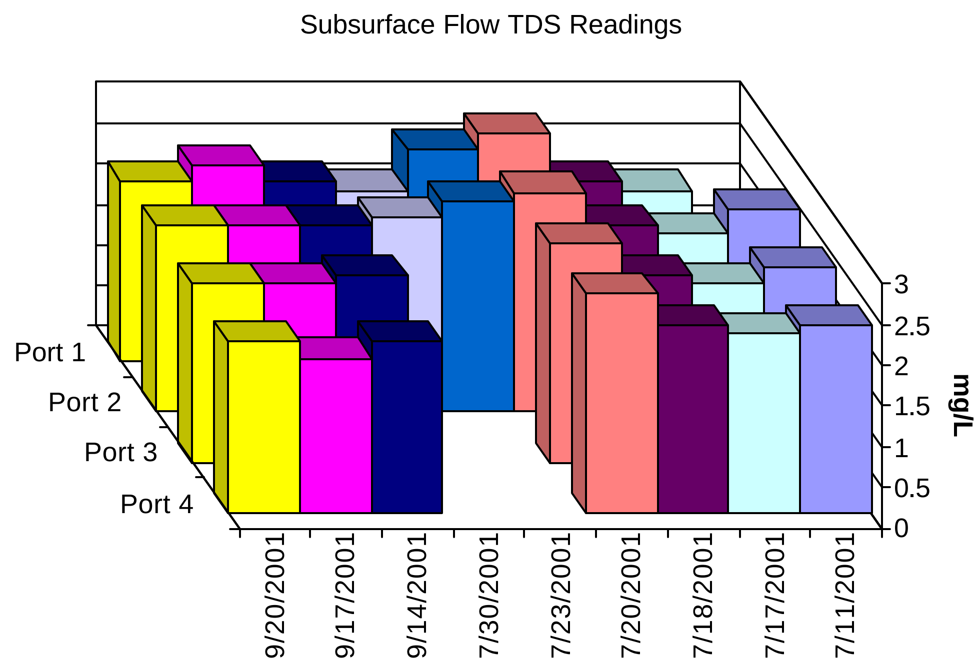

Figure 12. SSF Total Dissolved Solids Readings

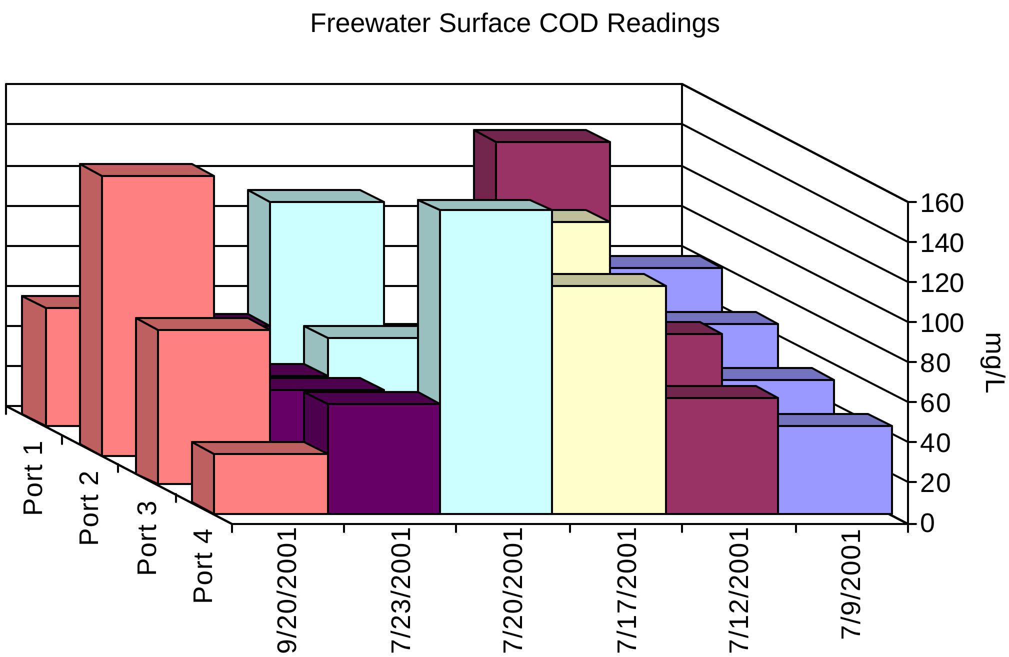

Figure 13. FWS Chemical Oxygen Demand Results

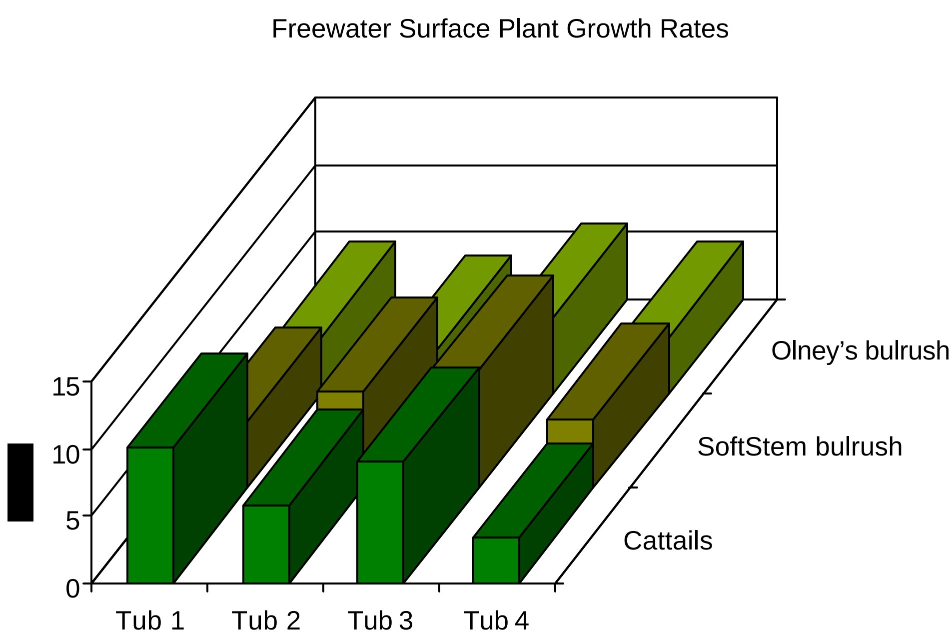

Figure 14. FWS Average Plant Growth Rates (Measurements taken July 3 through July 26, 2001)

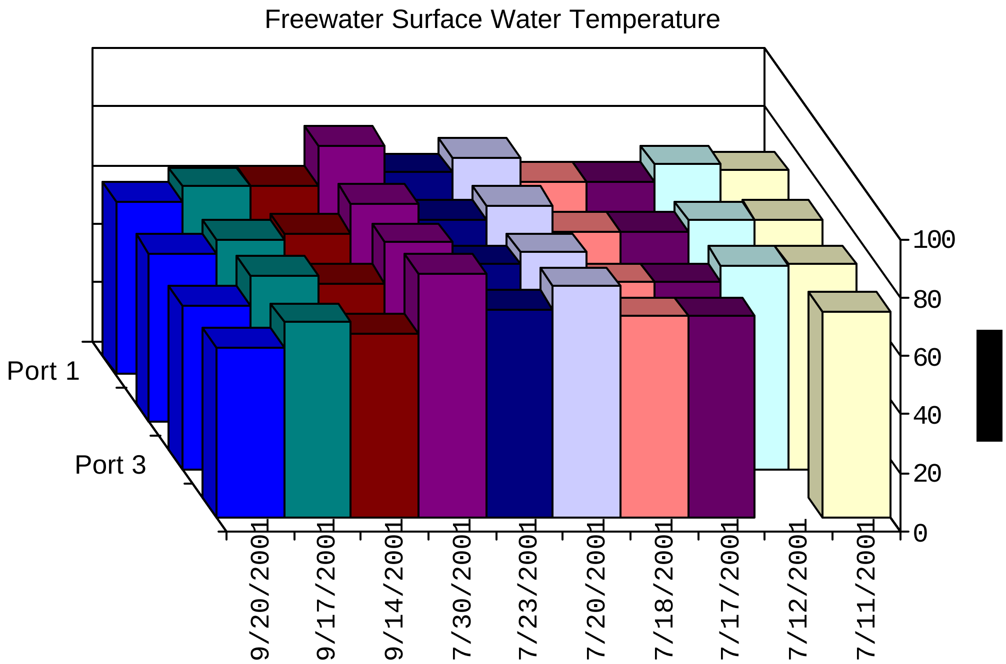

Figure 15. FWS Water Temperatures July and September 2001

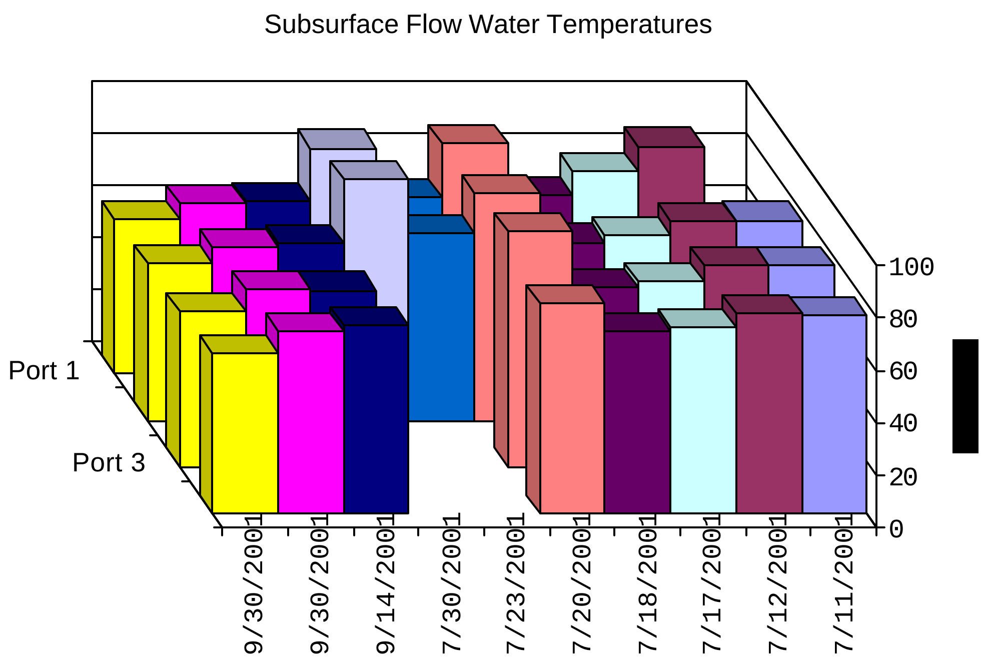

Figure 16. SSF Water Temperature Readings July and September 2001

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