Technical Progress Report

April 1, 2006 to June 30, 2006

DOE Award No. 41906

Use of Produced Water in Recirculating Cooling Systems at Power Generating Facilities

Deliverable Number 12

Progress Report for ZeroNet Amendment
Wet Surface Air Cooling (WSAC) Test at San Juan Generating Station

Adaptation of a Deterministic Watershed Model for Climate-Hydrology Analysis in the San Juan Basin

Robert Goldstein and Kent Zammit, EPRI Project Managers

Electric Power Research Institute, Inc.
3412 Hillview Ave.
Palo Alto, CA 94304-13952

Disclaimer

Wet Surface Air Cooling (WSAC) Test at San Juan Generating Station

[a]Michael N. DiFilippo

[a]Consultant, 2803 Woolsey Street, Berkeley, CA 94705; PH: 510-655-6629; FX: 510-653-5874; mndconslt@aol.com

Abstract

Wet surface air cooling (WSAC) technology was tested at the San Juan Generating Station (SJGS) to determine its capacity to cool power plant circulating water using degraded water. WSAC is a commercial cooling technology and has been used for many years to cool and/or condense process fluids. In the WSAC, water is applied in dense spray patterns to the exterior of tubes carrying the liquid or gas to be cooled. At the same time, air is also drawn down and around the perimeter of the tubes in the same direction as spray water. The purpose of the pilot test was to determine if WSAC technology could cool process water at cycles of concentration considered excessive (highly scale forming) for mechanical draft cooling towers. The WSAC pilot was online for a total of 147 days – from July 5 to November 29, 2005, during which, it was in service for 2,898 hours. It was configured to cool circulating water from Unit 3, and at the same time, use Unit 3 circulating water for make-up. In this mode, the WSAC operated at an equivalent of 24 to 70 cycles of concentration (based on freshwater fed to SJGS cooling towers). Ten cycles of concentration is considered a safe limit at this plant to control mineral scale formation. An additional benefit of operating in this mode is that WSAC could also function as a concentrating device by reducing the volume of a large plant wastewater stream.

At the completion of testing, there was no visible scale on the heat transfer surfaces (tube externals) and cooling was sustained throughout the test period.

Table of Contents

1. Introduction

Wet surface air cooling (WSAC) technology was tested at the San Juan Generating Station (SJGS)[1] to determine its capacity to cool power plant circulating water using degraded water. WSAC is a commercial cooling technology and has been used for many years to cool and/or condense process fluids. In the WSAC, water is applied in dense spray patterns to the exterior of tubes carrying the liquid or gas to be cooled. At the same time, air is also drawn down and around the perimeter of the tubes in the same direction as spray water. What is unique about this type of cooling is that the dense flow of spray water continuously flushes the tube surfaces, preventing suspended matter and mineral scale from depositing. Scale and suspended solids eventually settle in the WSAC basin or on non-cooling surfaces. Lastly, WSAC operates similarly to a mechanical draft cooling tower in that it utilizes air to evaporate water to provide cooling.

The purpose of the pilot test was to determine if WSAC technology could cool process water at cycles of concentration considered excessive (highly scale forming) for mechanical draft cooling towers. To accomplish this, blowdown from the Unit 3 Cooling Tower at SJGS was fed to the WSAC pilot as make-up. An additional benefit of operating in this mode is that WSAC could also function as a concentrating device by reducing the volume of a large plant wastewater stream.[2]

The WSAC pilot was online for a total of 147 days – from July 5 to November 29, 2005. During this period, it was in service for 2,898 hours. It was configured to cool circulating water from Unit 3, and at the same time, use Unit 3 circulating water for make-up.[3] In this mode, the WSAC operated at an equivalent of 24 to 70 cycles of concentration (based on freshwater fed to SJGS cooling towers). Ten cycles of concentration is considered a safe limit at this plant to control mineral scale formation. At the completion of testing, there was no visible scale on the heat transfer surfaces (tube externals) and cooling was sustained throughout the test period.

The report is presented in the following four sections – Pilot Design Parameters, Data Collection and Controls, Test Data and Summary of Findings. Section 2, Pilot Design Parameters, contains a detailed description of how WSAC technology cools water along with a process schematic showing flow paths for cooling water, air and process fluids. A description of the Unit 3 Cooling Tower at SJGS – the source of water for the testing – is also provided. Section 3, Data Collection and Controls, outlines WSAC instrumentation and design elements, measurement and analytical test parameters, and the operating approach for the testing. Section 4, Test Data, covers the flow, temperature and chemistry data collected during WSAC testing. The results of a corrosion analysis are presented at the end of this section. Section 5, Summary of Findings, summarizes observations, findings and conclusions as well as unresolved issues and recommended follow-on study.

---

[1] SJGS is four-unit 1500-MW coal-fired plant in the Four Corners Area of New Mexico and is operated by Public Service of New Mexico (PNM).

[2] SJGS is a zero-liquid discharge plant. The plant utilizes brine concentrators (wastewater evaporators) to reduce wastewater volume prior to disposal in evaporation ponds. Cooling tower blowdown is usually the largest wastewater stream at power plants.

[3] A small fraction of cooling tower circulating water is bled from the cooling system, as blowdown, to control salt build-up.

2. Pilot Design Parameters

This section of the report describes the parameters that were used to design and operate the WSAC pilot equipment. The section begins with a more detailed description of how WSAC technology cools water along with a process schematic showing flow paths for cooling water, air and process fluids (to be cooled). A process flow schematic is provided that shows the pilot test equipment, metallurgy, instrumentation, etc. Pictures of the pilot equipment are also provided. Lastly, a description of the Unit 3 Cooling Tower at SJGS – the source of water for this phase of testing – is provided.

2.1 WSAC Technology

WSAC technology has been in commercial use for many years. There is one large WSAC installation in Massachusetts cooling a 150MW power plant and there are thousands of smaller installations throughout the world.

Warm water enters the WSAC and passes through a heat exchanger (inside the tubes). Refer to Figure 1. WSAC cooling water is deluged via spray nozzles (high flow, low pressure) on the outside of the exchanger tubes. Spray nozzles are mounted on headers and located above the tube bundles (one header per bundle). Cooling air flows downward over the tubes in the same direction as the deluge water. The air is drawn through and around the tubes, through a demister (for drift control) and to the fans where it is exhausted. Cooling water is collected in a basin directly beneath the tube bundles and circulated back to the nozzles to be sprayed again. Cooling occurs as a small fraction of circulating water evaporates (into the air stream) while deluging the tubes and falling to the basin, i.e. evaporating water extracts heat from the system in the same manner as a mechanical draft cooling tower. As water evaporates, make-up water is fed to the WSAC to compensate for the loss, and at the same time, blowdown is withdrawn to control chemistry.

The deluge spray configuration, in theory, will allow cooling water to be cycled much higher than in conventional mechanical draft cooling towers as described below.

- In a cooling tower, droplets and films of circulating water are encouraged to form. Cooling takes place on surfaces where films of water are formed (cooling tower packing) and on droplets in the freefall to the basin[4]. If the chemistry of the circulating water exceeds saturation limits, crystals of scaling salts (e.g. calcium sulfate) will start to nucleate. The nucleating crystals will adhere to rough surfaces in low-flow regions throughout the cooling circuit <u>including the condenser tubes</u>.
- The deluge water in a WSAC is in a separate circuit from the circulating water that cools the condensers, i.e. deluge water is sprayed onto the outside of the tube bundles that carry condenser circulating water. The WSAC is designed to spray relatively large volumes of water on the exterior surfaces of the tube bundles. The constant movement of the deluge water on the surfaces of tubes keeps scale (that may form) in the bulk spray water.

[4] A small fraction of the circulating water evaporates into the air stream. As the water evaporates, it extracts heat from the circulating water. In the design of mechanical draft cooling towers, an effort is made to expose as much of the surface of the circulating water as possible (in the form of films and droplets) to maximize intimate air-water contact.

2.2 Pilot Test System Design Parameters

A pilot WSAC was built by Niagara Blower Company and delivered to SJGS in late May of 2005. It went through shakedown and was started on June 14, 2005. Testing started on July 5, 2005. This time was necessary to set-up WSAC sampling, instrumentation and equipment check-in schedules with plant laboratory and maintenance staff. Also, pH and conductivity instruments had to be installed and the data logger purchased and installed.

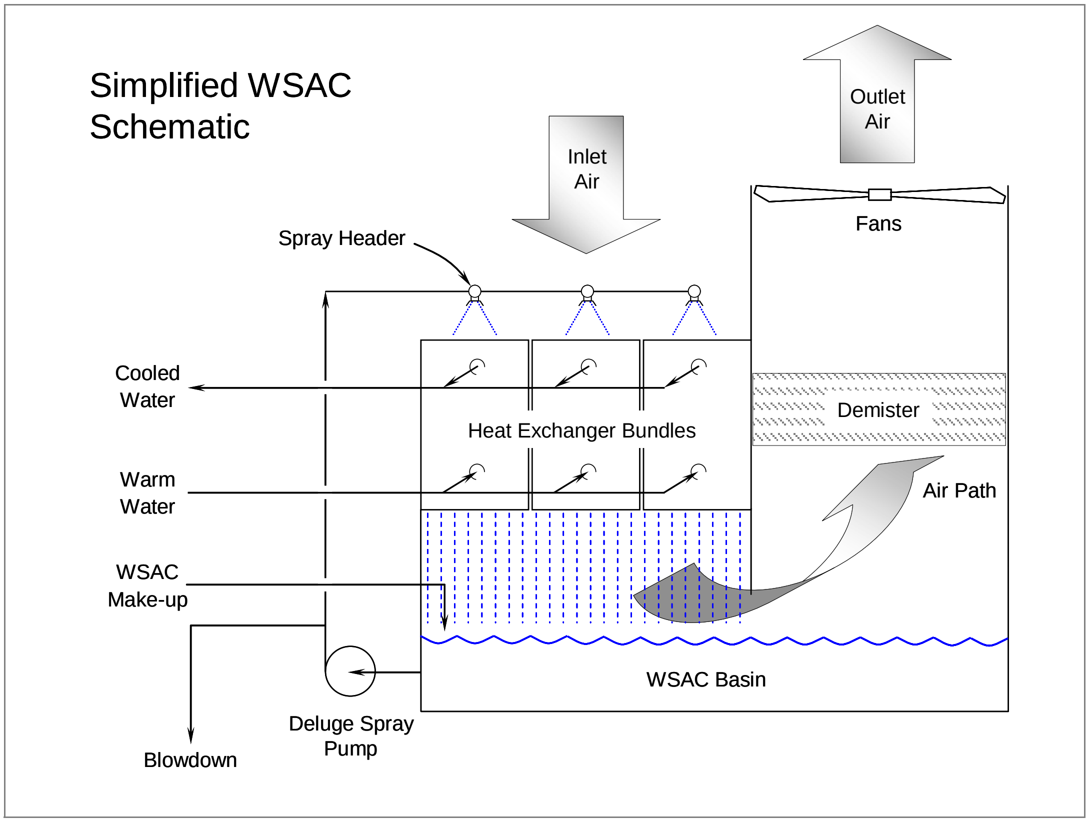


Figure 1. Schematic of West Surface Air Cooling Pilot Unit (WSAC)

Three tube materials were selected – 316 stainless steel, 90-10 copper-nickel (Cu-Ni) and titanium (Grade 2) – to evaluate tube corrosion potential.[5] Stainless steel was selected because it is susceptible to chloride stress corrosion and would provide a good baseline as compared to more corrosion-resistant and costly metals. Copper-nickel is a metallurgy frequently used for once-through cooling at seawater and brackish-water power plants. Titanium is highly resistant to corrosion and is commonly used for condenser tubes in recently installed cooling systems using brackish or degraded water.

Table 1 summarizes the design specifications of the WSAC pilot unit.

[5] It was not expected that cooling tower blowdown from Unit 3 would be a problem for any of the metallurgies selected. The metallurgy was selected for possible follow-on testing using a more saline degraded water.

Table 1-1. Pilot Wet Surface Air Cooler Design Specifications

Heat load, BTU/hour	3,000,000		
Flow Rate, gpm	260		
Spray Rate, gpm	650		
Spray Pump Motor, HP	7.5		
Spray Nozzles (total)	36		
Design Wet Bulb, °F	66		
Temperature In, °F	103		
Temperature Out, °F	80		
Tube Bundles	3		
Flow Passes	12		
Tube Material	316 SS (east bundle)	90-10 Cu-Ni (center bundle)	Ti Grade 2 (west bundle)
Tube OD, inches	1.25	1.25	1.25
Wall Thickness, inches	0.049	0.049	0.035
Demister Rating	0.005%		
Fans	3		
Total Fan Capacity, cfm	62,000		
Fan Power, HP	7.5 (each)		

Refer to Figures 2 and 3 for end and side elevations of the pilot equipment. Water from the Unit 3 Cooling Tower riser (water to be cooled) was fed the WSAC bundles (bottom) by way of a header. The unit was designed such that any or all of the bundles could be isolated, i.e. receive no flow. Cooled water exited through the top header and was returned to the Unit 3 Cooling Tower basin. Make-up to the WSAC was also Unit 3 circulating water and was supplied by the same feed line (from the riser at Unit 3). The spray pump, which was used to circulate the WSAC cooling water, can be seen in Figure 3.

Figures 4 and 5 are photographs of the WSAC pilot unit. Figure 6 shows the valve nest for inlet and outlet lines to the tube bundles. Figure 7 shows the WSAC circulating water (spray) pump with the Unit 3 Cooling Tower in the background. Tube bundles and spray headers can be seen in Figure 8.

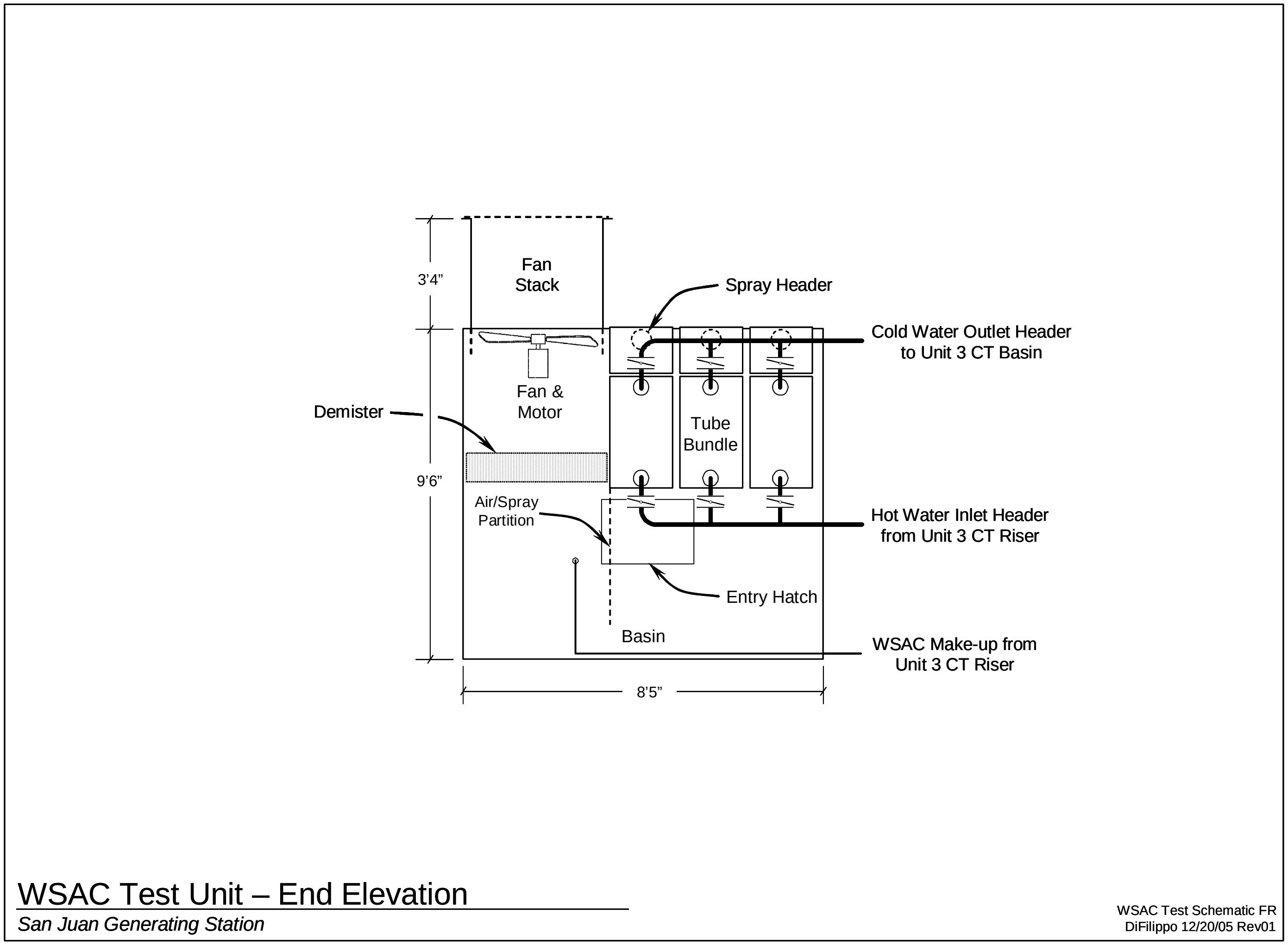


Figure 2. End Elevation of WSAC Test Unit

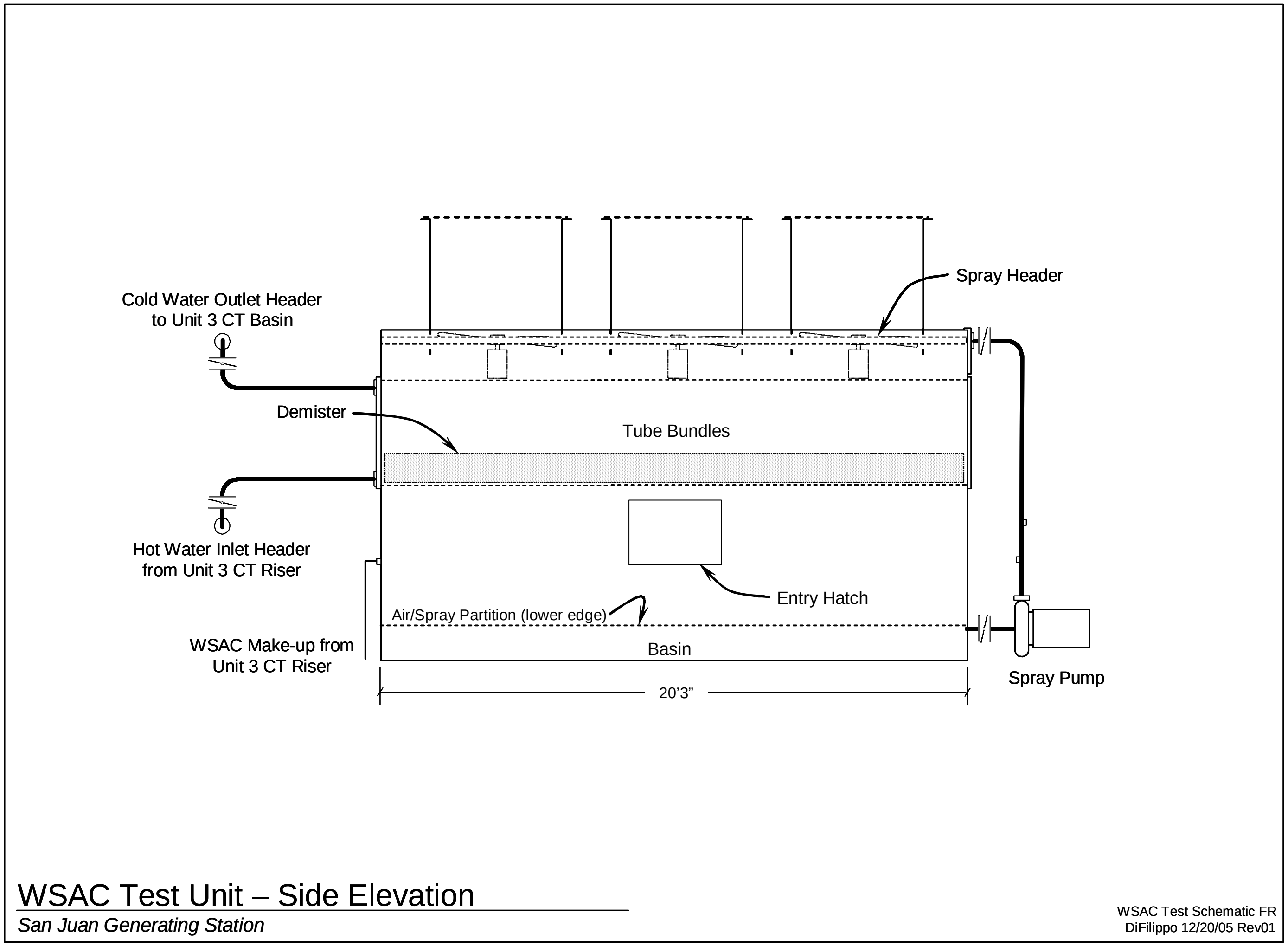


Figure 3 Front Elevation of WSAC Test Unit

Figure 4. WSAC Pilot Unit and Monitoring Shed

Figure 5 Inlet-Outlet Piping at WSAC Pilot Unit

Figure 6. Inlet-Outlet Valving at WSAC Pilot Unit

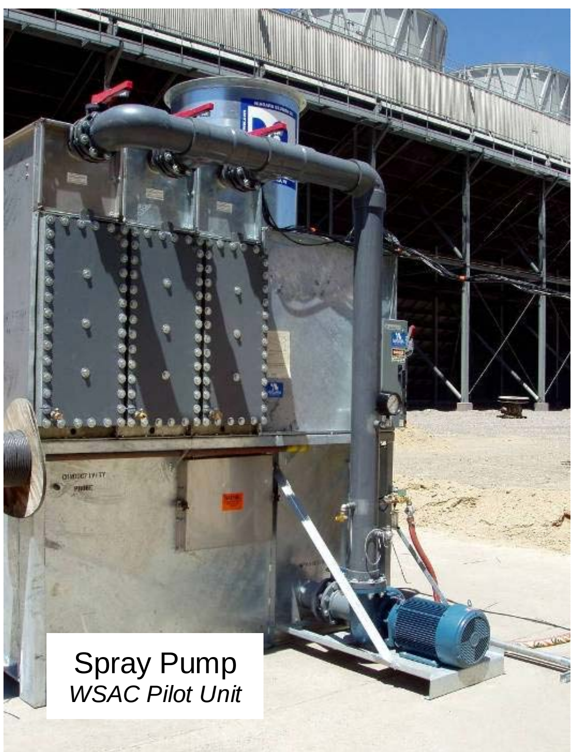


Figure 7. Spray Pump at WSAC Pilot Unit

Figure 8. Spray Headers and Tube Bundles at WSAC Pilot Unit

2.3 Unit 3 Cooling Tower

The Unit 3 Cooling Tower provides cooling for a 550 MW coal-fired generating unit at SJGS. It cools 220,000 gpm of water and operated as follows during pilot testing:

Parameter	Range During Testing
Cycles of Concentration	5.6 to 7.9 (average = 7.0)
TDS, mg/l	2,400 to 3,000
Calcium, mg/l	200 to 420
Chloride, mg/l	75 to 135
Sulfate, mg/l	575 to 1,350
Silica, mg/l	20 to 60
Control pH Range	7.5 to 8.1

Continuous chlorination is used to maintain a residual of 0.1 to 0.2 mg/l_{Cl2} in the cooling tower circulating water. A phosphonate-type inhibitor is used for scale control[6] and an azole-type corrosion inhibitor is used to protect the copper-based admiralty brass metallurgy of the main condenser.

[6] Calcium sulfate is the limiting scale-forming salt in the cooling towers at the San Juan Generating Station. Unit 3 Cooling Tower operates at 70 percent of calcium sulfate saturation. Calcium carbonate scale formation is controlled by pH.

3. Data Collection and Controls

The WSAC pilot was designed to monitor a number of performance parameters and control pH and conductivity. This section outlines WSAC instrumentation and design elements, measurement and analytical test parameters, and the operating approach for the testing.

3.1 Instrumentation

Refer to Figure 9 for a process flow diagram (PFD) of the WSAC pilot. The PFD schematically shows the analytical probes, elements and instrumentation used for the test. The following parameters were monitored at ten-minute intervals throughout the testing:

- Inlet and outlet temperature (°F) of each tube bundle
- Skin temperature (°F) of two tubes in each bundle – top and mid-level
- Skin temperature of three dummy[7] tubes located at bottom of each tube bundle (a heating element was installed in these tubes to monitor heat flux)
- Hot-water flow rate (gpm) to each bundle
- Make-up water flow rate (gpm) to the WSAC (flow was also totalized)
- WSAC blowdown rate (gpm) (flow was also totalized)
- WSAC spray water pH
- WSAC spray water conductivity (μS/cm, Micro-Siemans per centimeter)
- Three removable tube sections (one per bundle) for metallurgical analysis at the completion of the testing

Flow, temperature, conductivity and pH were recorded every ten minutes during the operation of the WSAC. Data was stored on a data logger and downloaded once per week.

3.2 Analytics

The following volume and chemistry control measures were implemented:

- Make-up was controlled by a float valve in the WSAC basin (on/off).
- A conductivity controller actuated the blowdown valve (on/off).
- pH was monitored (but not controlled) – 93 percent sulfuric acid was added at a constant rate.
- Chemical analyses were conducted on a daily basis (5 days per week) by onsite SJGS laboratory personnel: calcium, chloride (occasional), silica, pH, turbidity, Cl_2 residual and conductivity.

[7] A dummy tube was located below (and center to) each tube bundle. The dummy tube was open at each end so a heating element could easily be inserted to monitor a fixed rate of heat transfer.

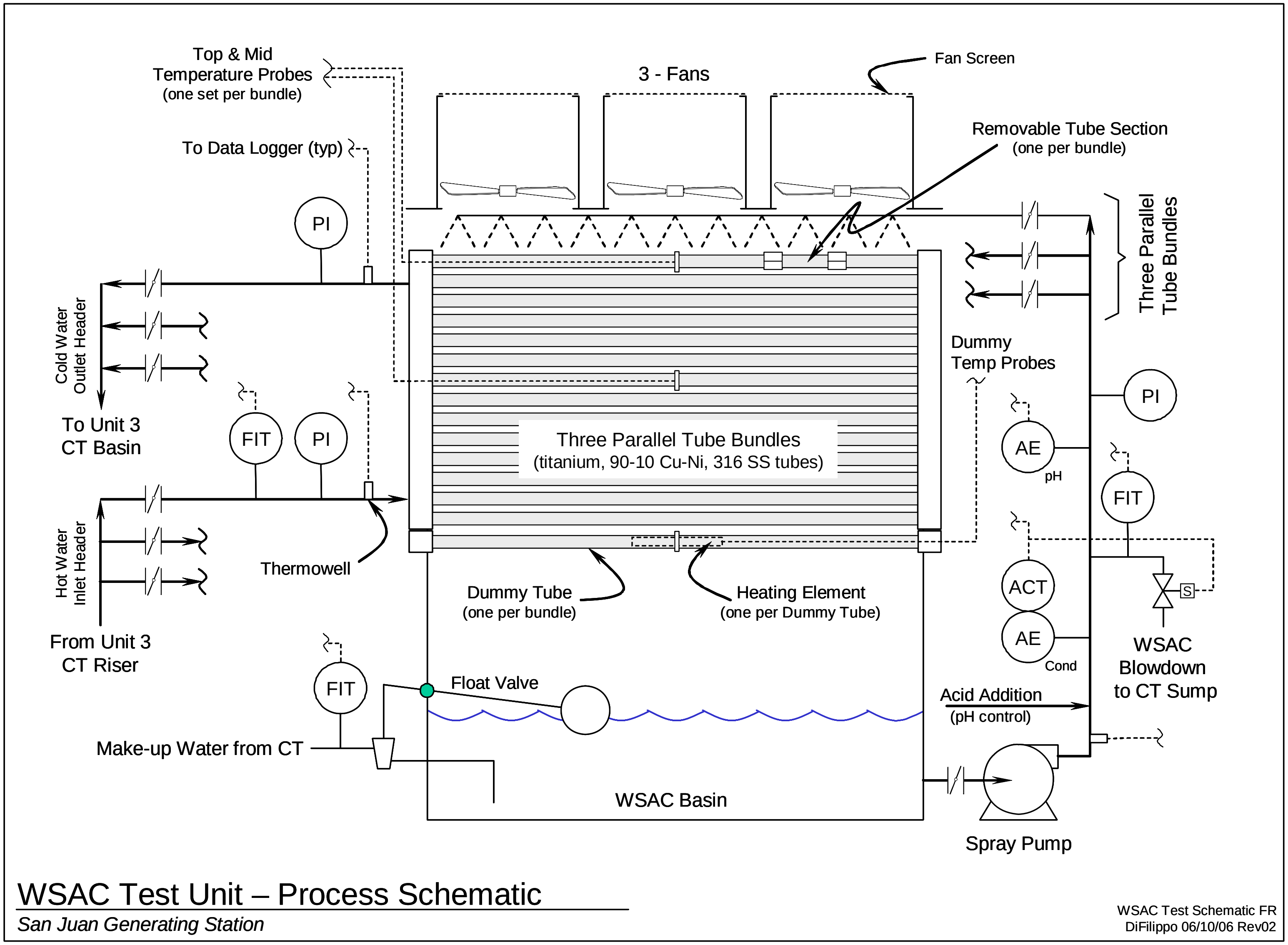


Figure 9. Process Flow Diagram of the WSAC Pilot Unit.

3.3 Operating Plan

The goal of the testing was to determine the degree to which blowdown from Unit 3 Cooling Tower could be concentrated in the WSAC and still maintain heat transfer. At the outset of testing it was decided to operate at 5,000 μS/cm conductivity (blowdown from Unit 3 to the WSAC had a conductivity of about 2,500 μS/cm). Three methods were routinely used to crosscheck and verify cycles of concentration during WSAC testing:

- The ratio of WSAC conductivity to Unit 3 Cooling Tower conductivity (operated on average at 7.0 cycles – approximately 70 percent of calcium sulfate saturation)
- Mass balance around the WSAC using totalized volume from make-up and blowdown flow
- The temperature difference across the bundles of the WSAC was used to calculate evaporation rate

Cycles of concentration were also calculated using the ratios of certain chemical constituents in the WSAC and Unit 3 blowdown – namely silica, calcium and chloride concentration.

As testing progressed, the conductivity control setting was to be increased on a stepwise basis. The intention was to determine the cycles of concentration (and chemistry) at which heat transfer would start to deteriorate. This threshold was never reached. As will be discussed later, conductivity control quickly became problematic; however, useful data was obtained.

4. Test Data

This section of the report covers the flow, temperature and chemistry data collected during WSAC testing. Refer to Figure 8 for the location of flow meters, temperature probes and analysis elements. WSAC cycles of concentration are calculated for each type of data – flow (mass balance), flow/temperature (heat balance) and chemistry. The results of a corrosion analysis are presented at the end of this section.

4.1 Flow Measurement

Flow measurement was critical in determining WSAC performance. In particular, it was used to perform a mass balance around the pilot unit, estimate evaporation rate, calculate cycles of concentration and determine overall pilot heat transfer.

4.1.1 Tube Bundle Flow

Flow to the WSAC tube bundles is shown in Figure 10. Note that hot-water flow (blowdown from the Unit 3 Cooling Tower) to individual bundles was fairly constant during testing. The flow meter monitoring the east exchanger (316 SS tube bundle) failed after five weeks of operation. Flow to each bundle was assumed to be same (within 3 to 5 gpm of each other). Gaps in data represent pilot downtime (discussed in more detail later). Flow to the bundles dropped slightly over the test period (2 to 3 gpm). There was no apparent reason for this.

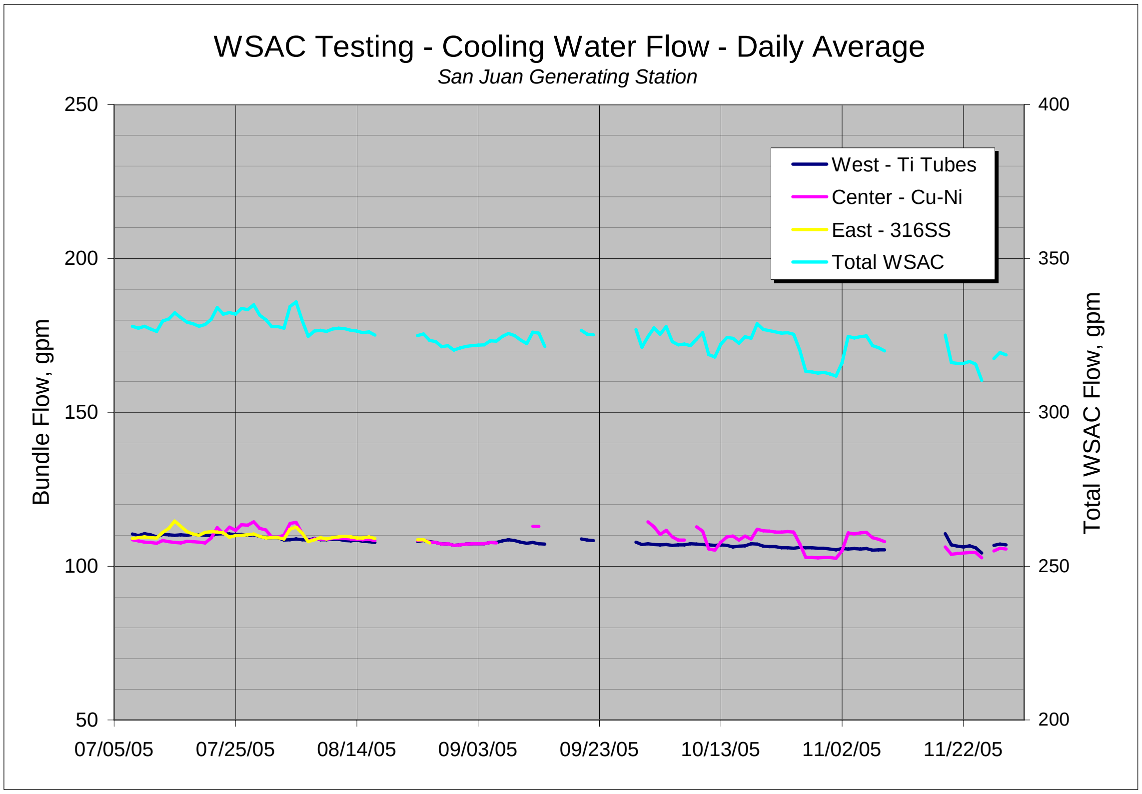


Figure 10. Tube Bundle Coolant Flow Rates during the WSAC Test Period

The east bundle (316 SS tubes) flow meter failed after one month of operation. East bundle flow was estimated by averaging the flows to the other bundles. At one time the center bundle flow meter stopped working, but started again.

4.1.2 Flow-Based Cycles of Concentration

Refer to Figure 11 for make-up, blowdown and flow-based calculated cycles of concentration. The flow rates are based on 24-hour daily averages. Make-up flow was controlled by a float valve in the WSAC sump, i.e. when the sump level reached a low point, the make-up valve would open to admit feedwater (Unit 3 blowdown). WSAC blowdown was controlled by conductivity. When conductivity reached the control set point, a solenoid valve would open to release circulating spray water (from the discharge side of the Spray Pump).

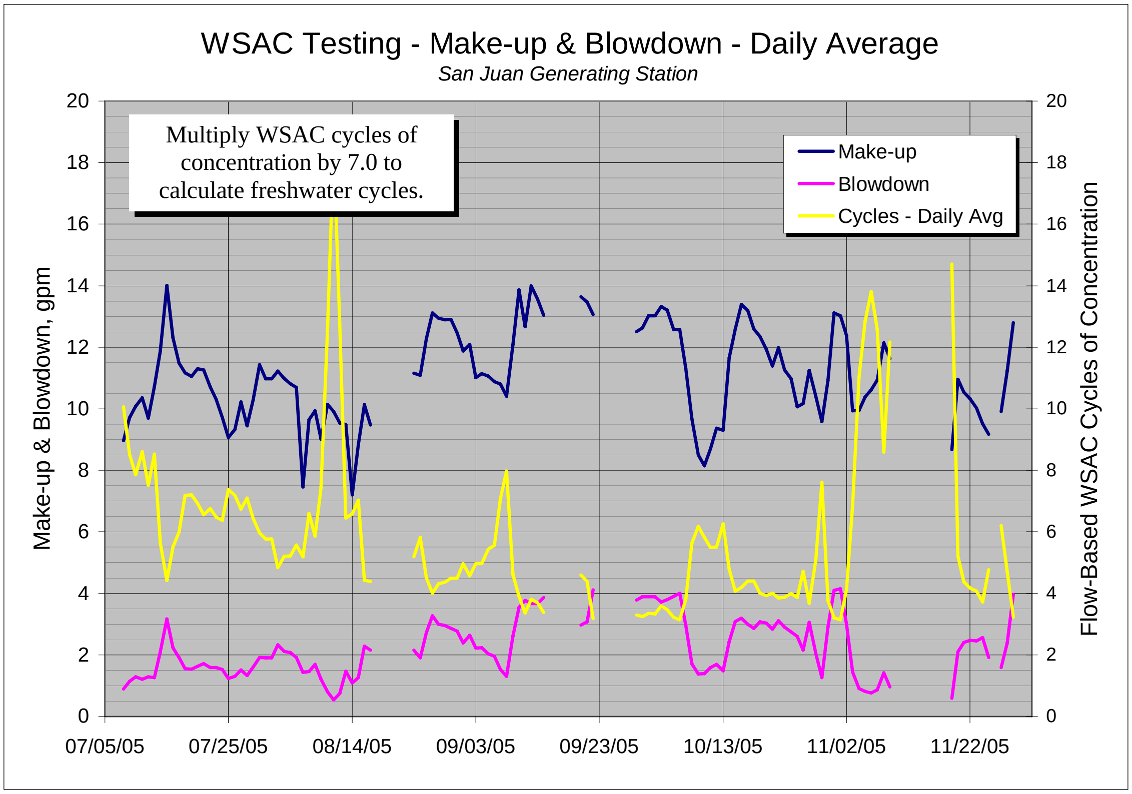


Figure 11. Make-up Water and Blowdown Flowrates and Cycles of Concentration during the WSAC Test Period

WSAC cycles of concentration in Figure 11 were calculated using make-up and blowdown flow rates as follows:

$$Cycles\ of\ Concentration = \frac{Make \cdot up\ Flow}{Blowdown\ Flow}$$

Cycles of concentration are highly sensitive to blowdown rate, and as can be seen in Figure 10, it fluctuated significantly at times – from 3.2 to 18.6 (4.4 cycles average). On August 21, 2005, daily average blowdown dropped to ~0.5 gpm while make-up remained at 9 to 10 gpm. As a result, cycles of concentration soared to 18.6.[8] Recall that WSAC cycles of concentration are equivalent to seven times that of the fresh water being fed to the Unit 3 Cooling Tower. Duration-of-project WSAC cycles of concentration averaged 30.8 (on a freshwater basis).

Part of the observed erratic behavior was the inability of controller to maintain conductivity (which actuated the blowdown solenoid valve). Suspended matter "blinded" the conductivity probe at times (discussed later in more detail).

4.1.3 Heat-Based Cycles of Concentration

Figure 12 shows the evaporation rate of the WSAC unit using two calculation approaches:

- Flow based – calculated taking the difference of the make-up and blowdown rates
- Heat basis – calculated using bundles flow rate and bundle inlet/outlet temperature difference

Also included in Figure 12 is the ratio of flow-based to heat-based evaporation rates. Despite the somewhat erratic flow-based evaporation rate, there is generally good agreement between the two methods of measurement, i.e. the ratio averaged 1.04.

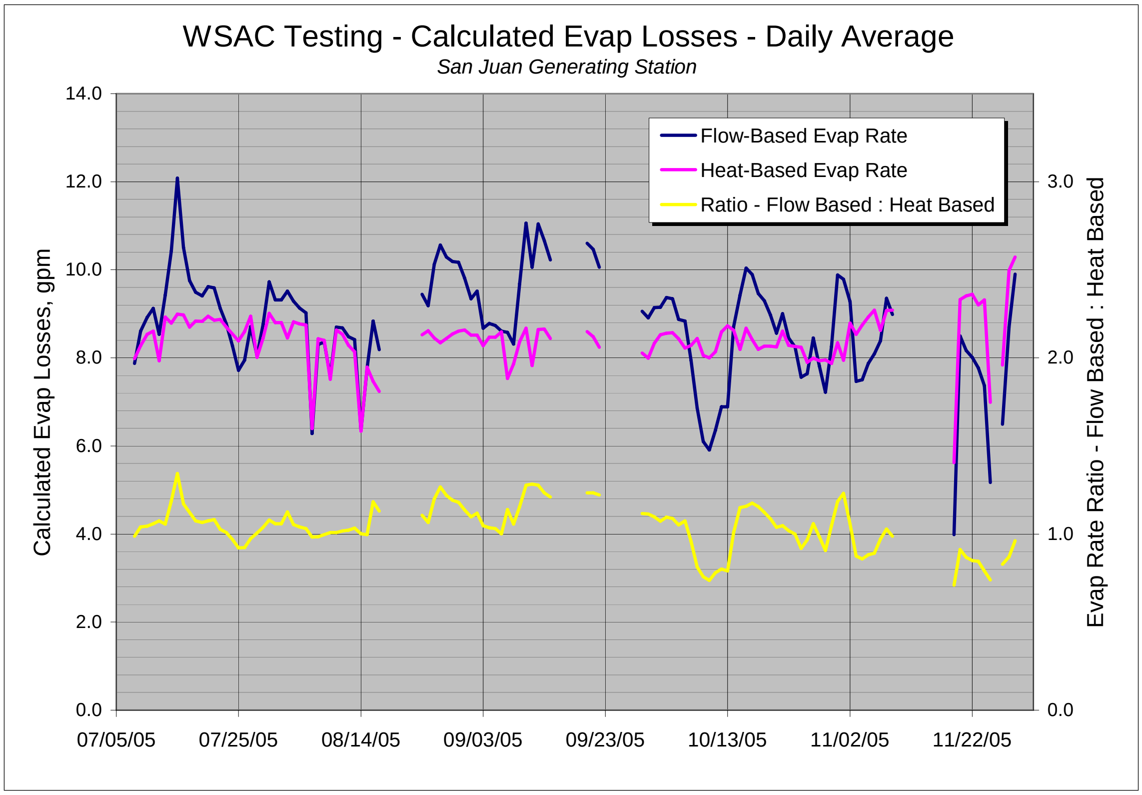


Figure 12. Calculated Evaporative Looses and Evaporation Rate Ratios during the WSAC Test Period

[8] 18.6 cycles of concentration was not supported by WSAC conductivity, which remained fairly constant.

The WSAC releases heat in the same manner as a mechanical draft cooling tower, i.e. as circulating water (deluge/spray water) evaporates latent heat is released. Heat-based evaporation was calculated based on the heat flux of the WSAC tube bundles as follows:

$$Heat \cdot Based\ Evaporation\ Rate = \frac{Flow\, \Delta T\, C_{P,H_2O}}{H_{Evap,H_2O}}$$

Where C_{P,H_2O} is the heat capacity of water (1 BTU/$\#_{H_2O}$/F) and H_{Evap,H_2O} is the latent heat of evaporation of water (1,000 BTU/$\#_{H_2O}$). Heat-based evaporation was less erratic because it is based on the relatively steady flow rate of water to be cooled and the fairly constant temperature drop across the tube bundles (discussed next).

4.2 Temperature Measurement

The inlet and outlet temperature differences across the WSAC bundles are found in Figure 13. Refer again to Figure 8 for the location of temperature probes and thermocouples. There are a number of data gaps which were caused by necessary repairs or upgrades to the WSAC pilot, a power plant outage and a data logger failure.

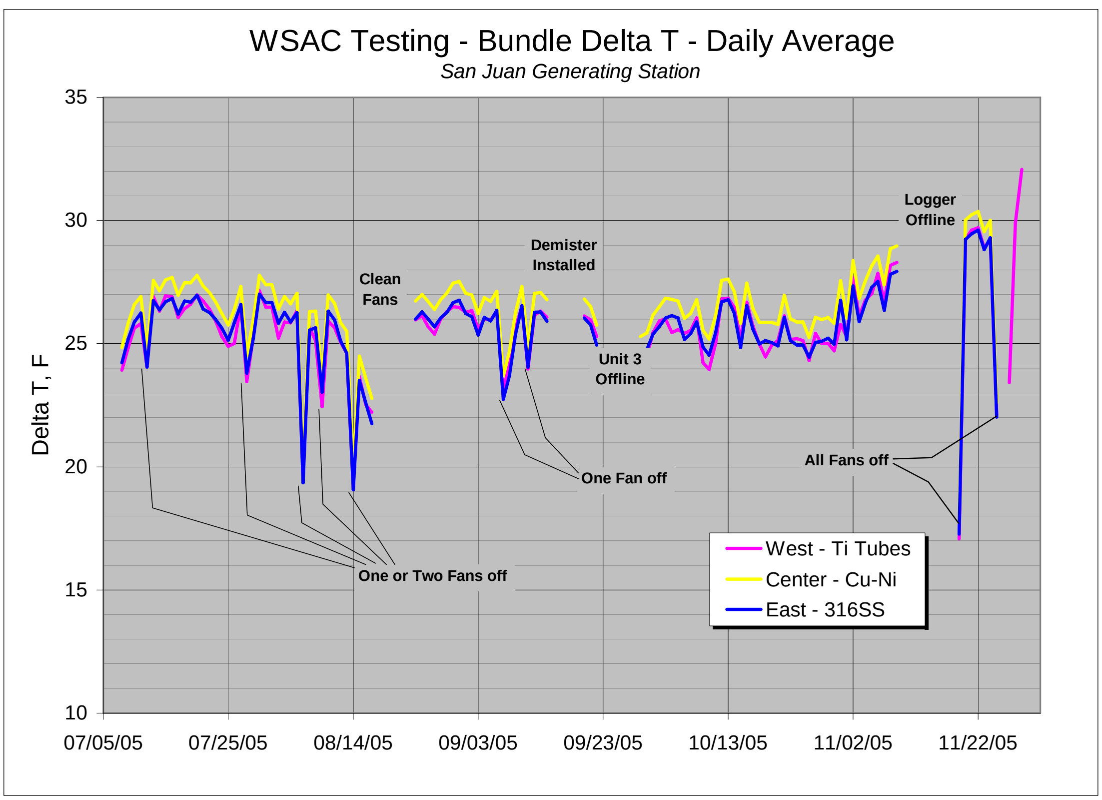


Figure 13. Temperature Differences between Coolant and Circulating Water the during WSAC Test Period

As early testing proceeded, significant fan vibrations developed. One or more fans were turned off to reset their motor starters (sometimes to reconnect the wiring).[9] As can be seen in Figure 13, when one or more fans were off, the temperature difference (delta T) clearly dropped. In mid August 2006, the pilot was shut down to clean the fans, which had significant mineral deposits on the blades. It was noted at that time that the demister section was not installed in the WSAC prior to shipping from the manufacturer. In mid September, the demister was installed and the fan vibrations ceased.

4.2.1 Tube Bundle Delta T

The fine detail of tube-bundle inlet-outlet temperature differences in Figure 13 shows that the 90-10 Cu-Ni tubes had the best relative heat transfer characteristics – a difference of about 1 ºF. The performance of the Ti and 316SS tubes tracked closely. The sudden rise in delta T in November 2006 was the result of the onset of fall weather and much colder ambient air temperatures. Interferences and data gaps aside, tube-bundle delta T remained fairly constant from mid-July through October 2005.

4.2.1 Tube Bundle Heat Transfer

Refer to Figure 14 for tube bundle heat transfer (expressed as 10^6 BTU/hour). As with Figure 13, there are data gaps and spikes in heat transfer where one or more fans were offline and there were test interruptions. This analysis shows that the bundle with Cu-Ni tubes had the best heat transfer. The bundle with stainless steel tubes had slightly better heat transfer than the bundle with titanium tubes. Tube-bundle heat transfer remained reasonably constant from mid-July through October 2006.

4.2.3 Tube Skin Temperature

Skin temperature was measured at two points on each tube bundle – center top and center mid-bundle. Thermocouples were attached to the tubes using standard stainless-steel hose-band clamps. Refer to Figure 15 for a four-day interval comparing skin temperatures of the Ti, 90-10 Cu-Ni and 316 SS tube bundles. Diurnal temperature effects are evident (cyclic variations) – data was recorded on ten-minute intervals. Bundle delta T was 29°F to 30°F, and as stated previously, the Cu-Ni tubes provided slightly better heat transfer, i.e. lower outlet temperatures.

The skin temperature was the coldest at the top of the bundle, where cooled spray water first meets the tube bundles. Bundle outlet water temperature (accounting for diurnal variations) was consistently close for all the bundles (within 1 ºF).

There were significant differences in mid-bundle skin temperatures. The Ti tubes were significantly warmer at mid-bundle by 8°F to 9°F compared to Cu-Ni and 316 SS. The probe measuring mid-bundle Ti skin temperature could have been sensing incorrectly (probe defect, insufficient probe/tube contact, etc.). Also, there could have been a flaw in the flow pattern of deluge water with reduced flow in the vicinity of the temperature probe. Again, outlet water temperatures were very close.

[9] The motor starters were mounted on the side wall of the WSAC just below the fans. Refer to Figure 4.

Some thermocouples started to fail shortly after start-up – corrosion was observed at the thermocouple-tube interface. It was not clear whether the thermocouples or the hose bands were corroding. Top and dummy-tube thermocouples (located below the center bottom of each tube bundle) were replaced with self-adhering thermocouples. Mid-bundle thermocouples were not changed because they could not be reached. The failures did not recur.

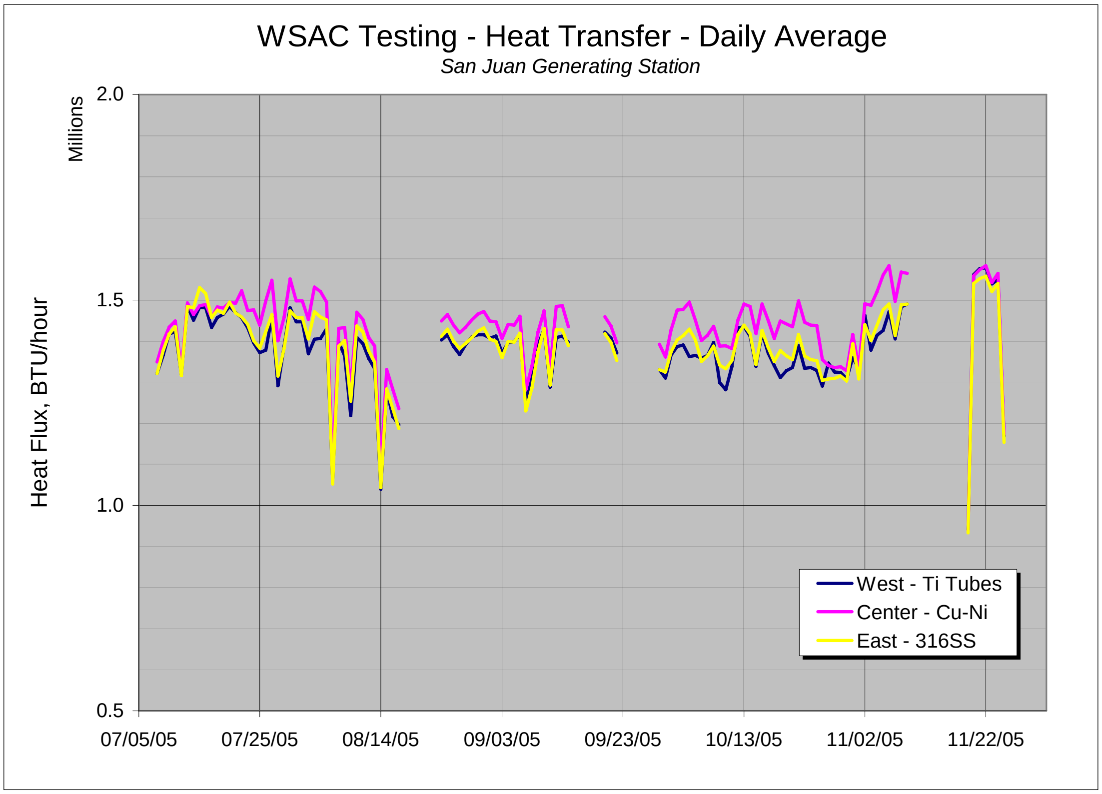


Figure 14 Heat Flux to Tube Bundles during WSAC Test Period

4.2.4 Heat Transfer Coefficient

Heating elements were installed in the dummy tubes located below the center of each tube bundle. The tubes were designed such that a heating element could be inserted into either end of the tube. The 14-inch heating element would impose a constant heat load on the tube section where a thermocouple would monitor skin temperature. This arrangement would allow the measurement of the heat transfer coefficient of the tubes under typical water flow conditions across the exterior of the tube. Changes in skin temperature would identify slight changes (degradation) in heat transfer.

The heating elements, which arrived after start-up, were not installed until the testing was well underway. Problems were encountered in centering the elements in line with the thermocouples. Only one element worked properly (titanium dummy tube). Instead of a repeating diurnal pattern, skin temperature rose and fell dramatically. As discussed previously, this could have been due to probe/tube contact or uneven flow patterns. across the surface of the tube. Also, the heat output of the element was too high (elements were not sized correctly), therefore, the skin temperature, which was 40°F to 50°F higher than the surrounding tubes, was not representative of the heat load of working the tubes in the bundles. Given these circumstances, the data was deemed unusable.

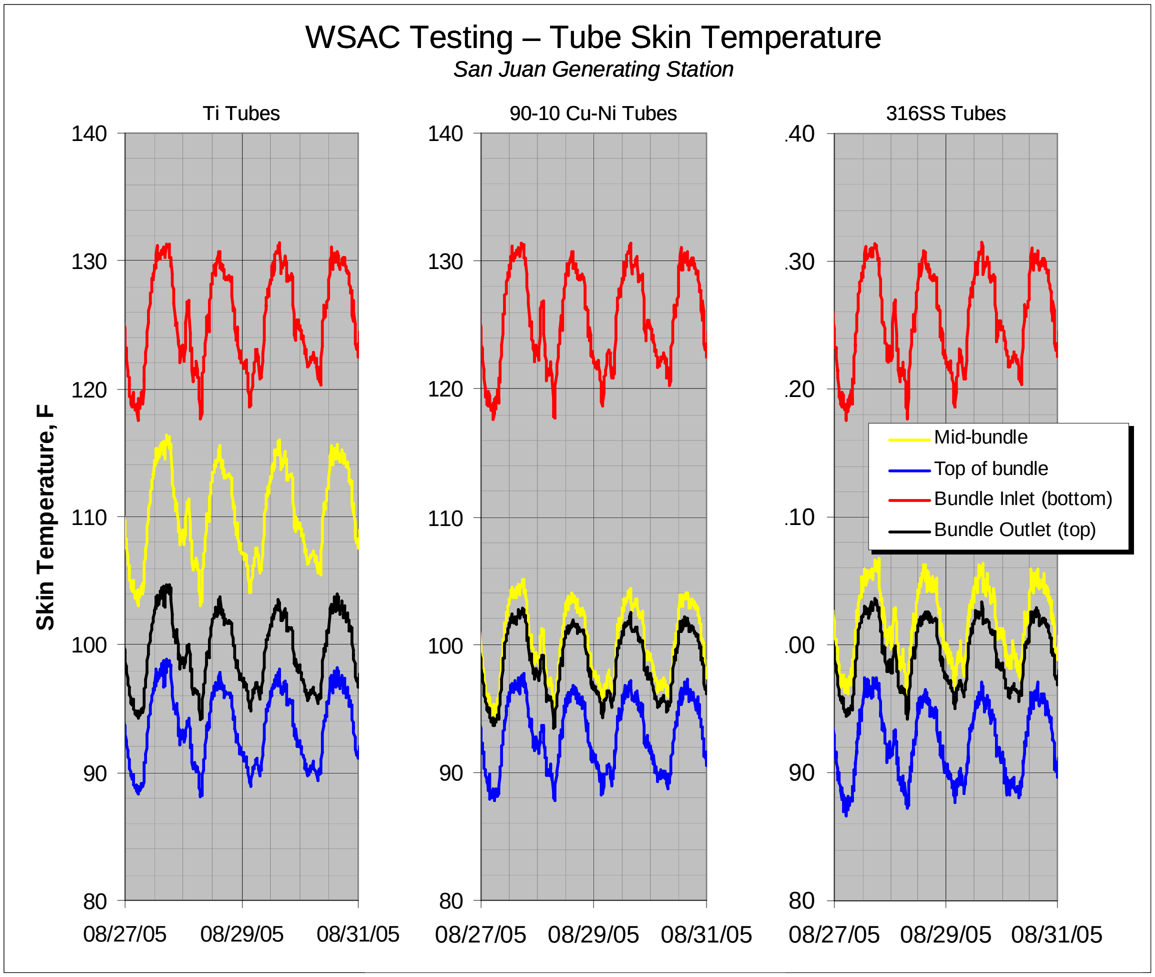


Figure 15. Tube Bundle Skin Temperatures during the WSAC Test Period

4.3 Chemistry

Chemistry was monitored throughout the testing. The following control and sampling measures were implemented:

- pH and conductivity were monitored on ten-minute intervals.
- A conductivity controller actuated the blowdown valve (on/off).
- pH was monitored (but not controlled) – 93 percent sulfuric acid was added at a constant rate to achieve a somewhat constant pH of 7.6 (roughly that of the Unit 3 Cooling Tower).

- Chemical analyses were conducted on a daily basis (5 days per week) by onsite SJGS laboratory personnel: calcium, chloride (occasional), silica, pH, turbidity, Cl_2 residual and conductivity
- A chlorine residual (0.05 to 0.2 mg/l_{Cl2}) was maintained to control biological growth – none was observed.[10]

4.3.1 pH & Conductivity

Refer to Figure 16 for WSAC pH and conductivity observations. pH was easily controlled in a relatively narrow range throughout the testing.[11] There were two episodes of high pH as a result of losing acid feed (the injection quill was plugged). Conductivity for the WSAC and Unit 3 Cooling Tower are also shown in Figure 16. WSAC conductivity control was problematic while Unit 3 conductivity was fairly constant. WSAC conductivity remained at 5,000 μS/cm despite frequent adjustments to the controller set point (to increase conductivity) even after recalibrating the instrument. The conductivity probe was being blinded by high levels of suspended matter in the WSAC deluge water. In hindsight, the sample stream should have been filtered (with a strainer) to keep the conductivity cell free of debris and operable at all times. Toward the end of the testing conductivity was increased to 6,000 μS/cm after repeated attempts to clean and calibrate the instrument.

There were a number of small process leaks, especially around the deluge/spray pump. These leaks, which were very small and immeasurable, could have contributed to the loss of conductivity control in that they are comparable to a steady blowdown stream.

There was secondary effect that impeded conductivity. As the cycles of concentration of the Unit 3 cooling water were raised in the WSAC, constituents like calcium and sulfate were dropping out of solution. Recall that in Unit 3, calcium sulfate is the limiting parameter at 70 percent of saturation. Therefore, as the cycles increased in the WSAC, soluble calcium and sulfate ions were being removed from solution, i.e. their removal from solution as mineral scale reduced the conductivity of the WSAC circulating water.

4.3.2 Constituent-Based Cycles of Concentration

In Figure 17, constituent-based cycles of concentration for calcium, silica and chloride are presented with flow-based and heat-based cycles. There is relatively good agreement among flow-based and heat-based cycles of concentration. For the most part, these parameters paralleled each other – from 3.5 to over 10 cycles of concentration (24 to 70 cycles based on Unit 3 freshwater make-up). The limited number of data points for chloride-based cycles agreed with flow-based and heat-based cycles (except for one point). As discussed previously, conductivity-based cycles of concentration were practically constant (varying between 2 to 2.5 cycles) and were always less than flow-based and heat based cycles. This was likely the result of problems with the conductivity probe/controller and ionic constituents (calcium and sulfate) dropping out of solution and forming mineral scale. Calcium-based and silica-based cycles of

[10] A chlorine residual was maintained by adding a chlorine puck (tablet of calcium hypochlorite) every day or two. This type of addition is commonly used to control chlorine levels in swimming pools. This control method added very little chloride and calcium to the background levels in the WSAC bulk fluid volume.
[11] Sulfuric acid was fed at a fixed rate for pH control. The acid pump was powered to start and stop with the Deluge/Spray Pump.

concentration paralleled flow-based and heat-based cycles, but were almost always less as a result of dropping out of solution.

Figure 16

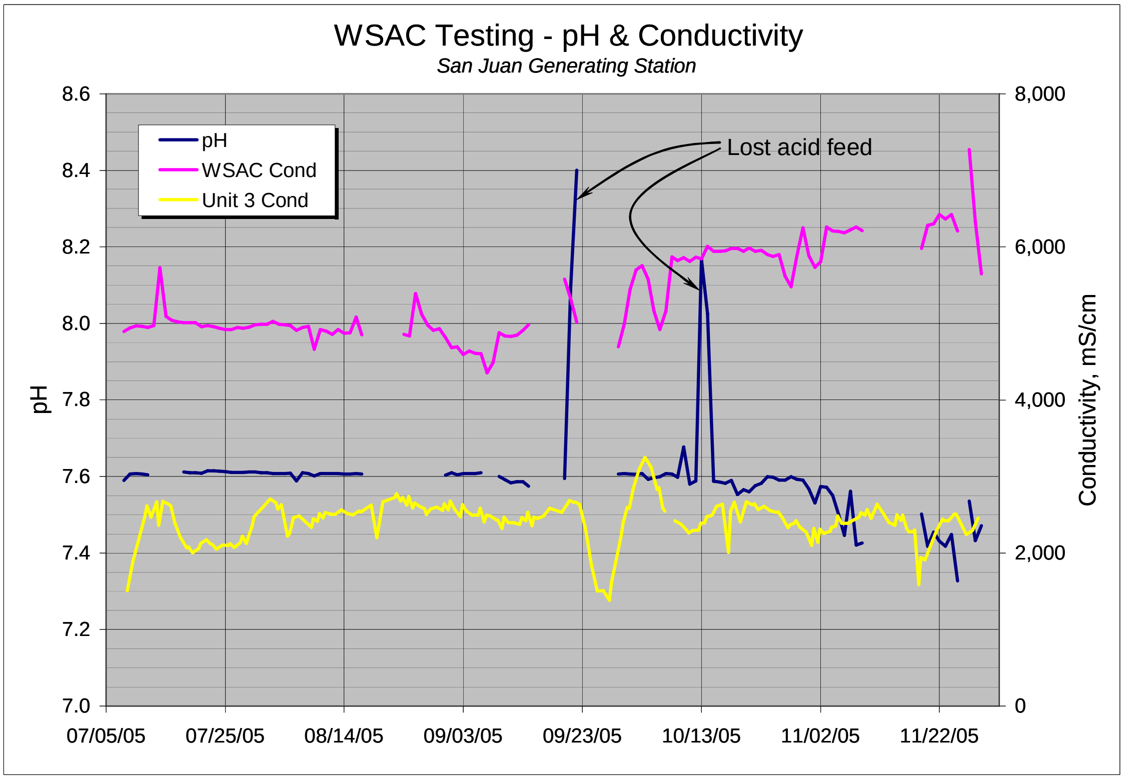


Figure 16 Coolant pH and Conductivity during the WSAC Test Period

Figure 17

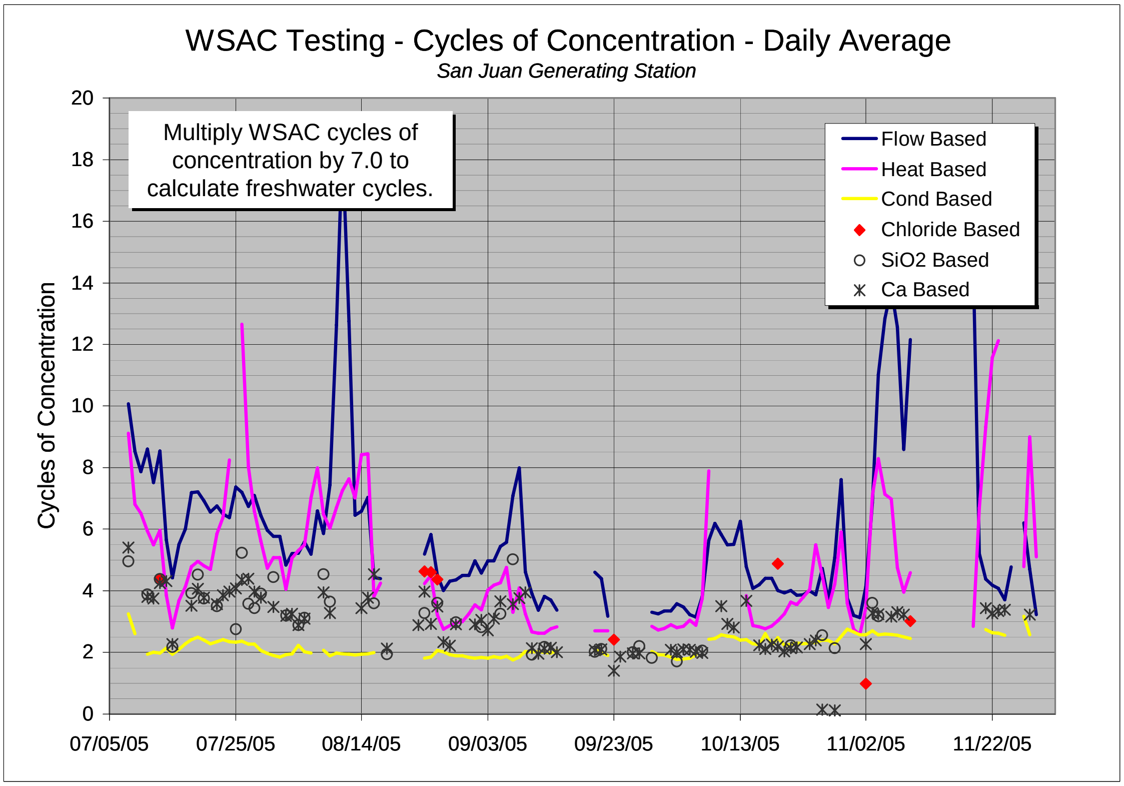


Figure 17 Cycles of Concentration of Cooling Water based on Heat, Conductivity, Chloride, Silica, and Calcium during the WSAC Test Period.

4.3.3 Suspended Matter

During the testing, solids build-up on tube bundle side walls was fairly significant. High levels of suspended matter (TSS, total suspended solids) were carried in the bulk fluid and continuously washed over tubes surfaces. Turbidity, an indirect measure of TSS, was monitored daily (one grab sample per day).[12]

Figure 18 shows how the turbidity of the WSAC deluge/spray water and Unit 3 Cooling Tower circulating water varied during day-to-day testing. WSAC Turbidity exceeded 1,000 NTU at the outset of testing, averaged 350± NTU in the early stages and attenuated to 200± NTU in the last half of the testing. Based on extrapolated data, the turbidity of Unit 3 Cooling tower blowdown at 200 NTU is equivalent to about 400 mg/l of TSS. Refer to the inset in Figure 18 for a relationship between TSS and turbidity in the Unit 3 cooling system.[13] Extrapolated values for TSS were not attempted for turbidity levels above 200 NTU because of the limited range of the data.

[12] Turbidity is expressed as Nepthlometric Turbidity Units (NTU) which are a measure of light interference.
[13] This TSS-NTU relationship was developed from 44 data points taken from Unit 3 cooling Tower chemistry records.

Using the TSS-NTU relationship in Figure 18, TSS levels were very high during the first few months of testing and settled to around 400± mg/l (200± NTU). These levels of TSS are considered very high for a cooling system.[14] What can be inferred from the data is that the WSAC was "moving" significant amounts of suspended matter in the bulk deluge/spray water. At the same time, solids were being deposited on and in quiescent areas, i.e. tube bundle side walls and the basin. Refer to Figure 19.[15] Mineral scale was deposited on tube-bundle side walls to thicknesses up to 0.25 inches. At places in the WSAC basin, sludge depths were in excess of 3 to 4 inches. Even with all the scale on non-wetted surfaces, the stainless steel tubes in Figure 19 remained clean – visually and to the touch. Refer to the insert in Figure 19 to see the condition of the spray header, bundle side walls and tubes before testing.

4.3.4 Residual Scale and Corrosion Inhibitors

The WSAC pilot unit may have benefited from residual concentrations of scale and corrosion inhibitors in Unit 3 Cooling Tower blowdown. A phosphonate-type scale inhibitor is used to control mineral scale and an azole-type corrosion inhibitor is used to protect copper-bearing metallurgy in all of the cooling towers at San Juan Generating Station The scale inhibitor may have benefited the pilot, but it was not possible to determine its effects (if any). Given the degree of mineral scale formed during testing, the scale inhibitor was likely overwhelmed and had no measurable beneficial effect. As will be discussed next, the metallurgical limits of the tubes were not challenged during WSAC testing, i.e. none of the tube specimens showed any signs of external surface corrosion. It was assumed that the salinity[16] of the WSAC water was not high enough to initiate corrosion.

[14] Cooling tower operators usually try to keep TSS below 100 mg/l with a nominal operating average of 50 mg/l.

[15] This photograph of the WSAC East Cell (316 SS tubes) was taken in November 2005 – note the ice formation along the side walls.

[16] For the 316 SS tube bundle, the concern was high chloride content. High levels of chloride can cause stress-cracking corrosion.

Figure 18

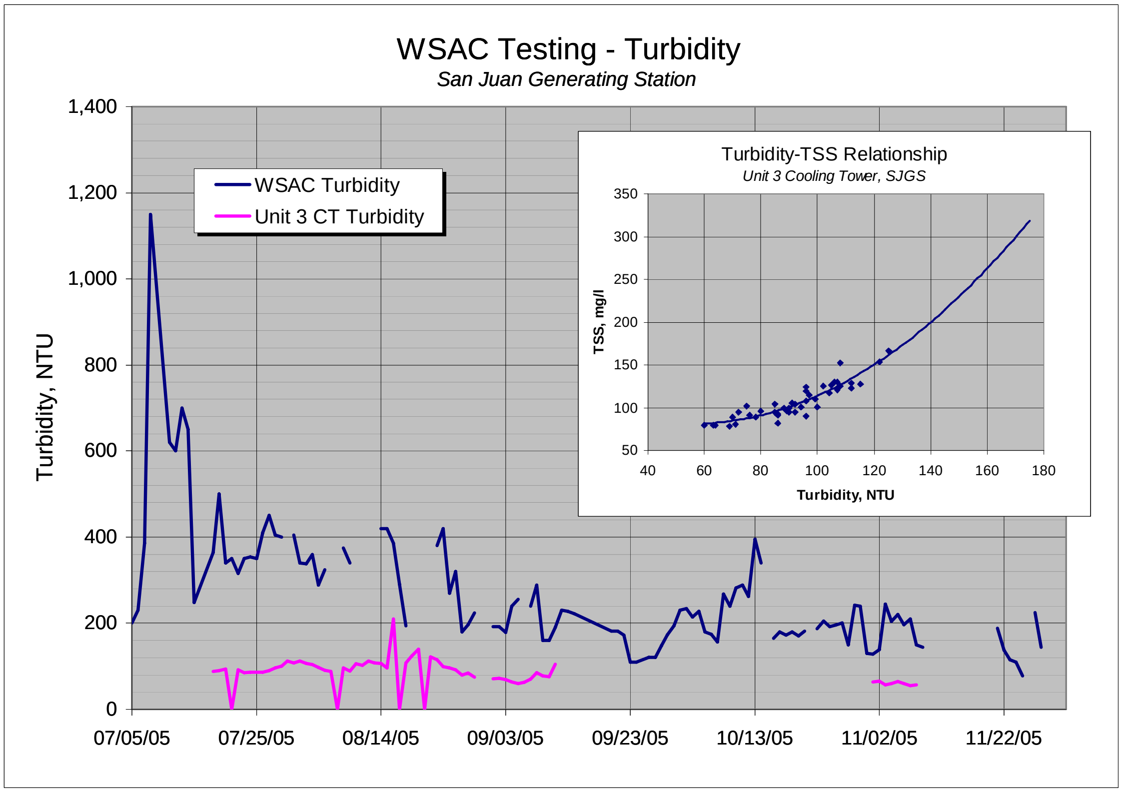
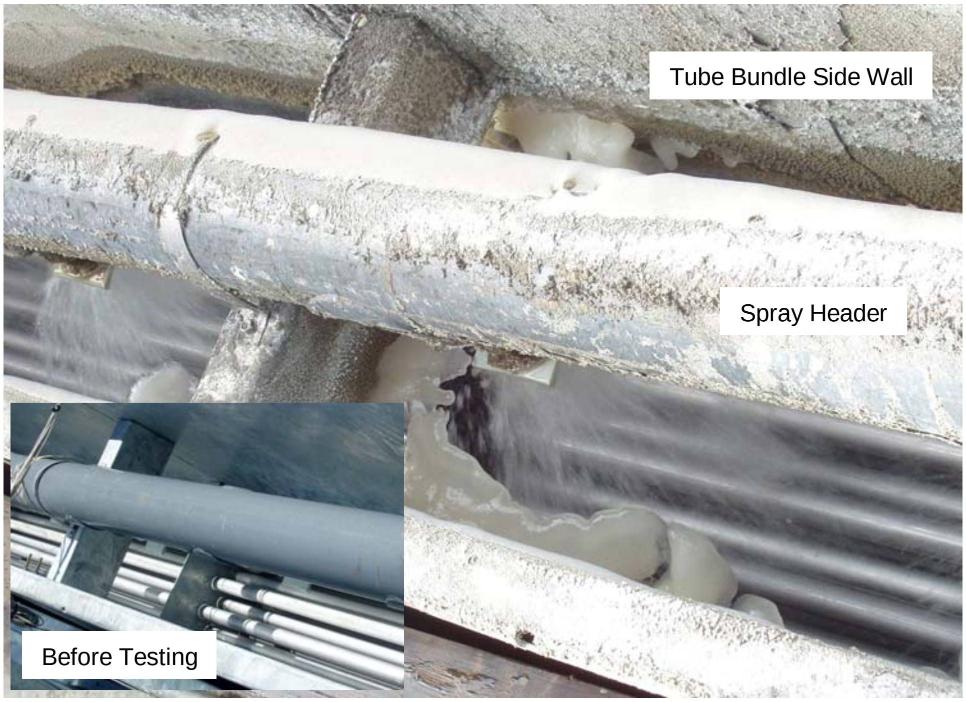


Figure 19

Mineral Scale Deposition - 316 SS Tube Bundle

WSAC Pilot Unit



4.4 Corrosion Analysis

The WSAC pilot unit has removable 12-inch tube sections – one per bundle located in the top row. Each tube section[17] was removed and sent to an outside laboratory[18] for a complete metallurgical assessment (the report is found in Appendix A). During the assessment, each tube specimen was cut in half lengthwise to inspect its interior surfaces.

The laboratory concluded that the external surfaces of the tubes were smooth and had no visible signs of corrosion. It was estimated that a thin layer of deposition – 0.001 to 0.003 inches – had formed on the external surfaces. This deposition layer could have occurred at shut down. The unit was to be flushed immediately after the fans and deluge/spray pump were turned off to remove residual suspended matter and mineral scale found in the bulk spray water. The flushing procedure could not be followed because of other maintenance demands in the plant at the time of shut down.

The interior surfaces of titanium and 316 SS tube sections were smooth with no visible signs of corrosion (there were occasional deposits). Conversely, the 90-10 Cu-Ni tube section showed signs of pitting corrosion on the interior surface. Recall that the interior surfaces of the WSAC tubes were only exposed to circulating water from Unit 3 Cooling Tower. Interestingly, the Cu-Ni tubes showed the best heat transfer characteristics during testing.

[17] The tube sections were held in place with water-tight metal collars.
[18] GE Infrastructure Water & Process Technologies performed the analysis.

5. Summary of Findings

The goal of the WSAC testing at San Juan Generating Station was to determine the extent to which degraded water could be used for cooling without impeding heat transfer. Although the testing never achieved this goal, the WSAC operated at very high cycles of concentration with significant levels of suspended matter without degrading heat transfer.

5.1 Observations, Findings and Conclusions

The following observations, findings and conclusions summarize the test results:

- Throughout the testing, the tube exterior surfaces appeared visually clean. The surfaces were always smooth to the touch, i.e. no apparent mineral deposits or biological film.
- The maximum cycles of concentration that would impede heat transfer were not determined. The inability to progressively increase conductivity over time in a stepwise manner (i.e. control conductivity) prevented the testing from achieving higher sustained cycles of concentration.
- There were a number of small process leaks, especially around the Deluge/Spray Pump. These could have contributed to the inability to control conductivity in that they were comparable to a steady (albeit small) blowdown stream.
- Cycles of concentration varied (somewhat erratically at times) from 3.5 to over 10 during the test period – the average for the test period was 4.4 cycles. This was equivalent to 24 to 70 cycles of concentration (30 cycles average) based on Unit 3 Cooling Tower freshwater make-up. This was far in excess of the control level for the cooling system – 10 cycles of concentration (based on calcium sulfate saturation).
- Cycles of concentration were determined by a number of methods – make-up and blowdown flow rates, evaporative loss via tube-bundle temperature difference, and chloride concentration. All methods showed general agreement.
- Heat transfer was maintained throughout the testing, i.e. the temperature difference across the bundles was steady. Heat transfer was only a problem when one or more of the three fans were taken out of service.
- The bundle with Cu-Ni tubes had slightly better heat transfer than the titanium and 316 SS bundles (even with signs of corrosion in the interior Cu-Ni surfaces).
- Calcium and silica cycles of concentration paralleled flow-based and heat-based cycles, *but they were always less*. This was attributed to calcium and silica dropping out of solution to form mineral salts at elevated cycles.
- Conductivity and pH (by acid addition) were the only variables controlled during the testing, i.e. no other means of scale control were employed.
- There was no measurable benefit to the WSAC pilot from residual concentrations of scale and corrosion inhibitors in Unit 3 Cooling Tower blowdown.
- The exterior surfaces of the tubes fared well with respect to visible scale and corrosion. Only the Cu-Ni tubes showed signs of corrosion on the internal surfaces (non-WSAC side).
- Mineral scale and suspended matter (measured as turbidity) were very evident throughout the testing. TSS levels greatly exceeded cooling system standards. <u>It was clear that solids control is important if WSAC technology is to be used in this manner</u>.

Given the operating conditions of high cycles of concentration, formation of extensive mineral scale and very high levels of suspended matter in the bulk cooling water, the WSAC performed well by maintaining heat transfer throughout the test period.

5.2 Unresolved Issues

The following issues were not resolved during WSAC testing in 2005 at San Juan Generating Station.

- The WSAC did not reach the heat transfer threshold where mineral scale deposition on external tube surfaces would interfere with heat transfer.
- The WSAC did not challenge the 316 SS, 90-10 Cu-Ni or Ti tube metallurgy (this was not anticipated in this round of testing).
- Suspended matter interfered with conductivity control (i.e. the ability to control cycles of concentration) and created a huge solids burden in non-heat transfer areas of the pilot unit.

If further testing is pursued for the WSAC pilot, higher cycles of concentration, potential tube corrosion and solids control should be evaluated by:

- Protecting instruments with upstream strainers to enable conductivity control and higher cycles of concentration.
- Finding a degraded source water with higher salt content than Unit 3 Cooling Tower blowdown at San Juan Generating Station to approach the corrosion limit of tube bundle metals.
- Installing a filter on a slip stream off the deluge/spray riser to continuously remove mineral scale (in the bulk fluid) as it is formed. Mounting freshwater spray headers with low pressure nozzles above the bundle side walls and below the demister to intermittently flush these surfaces and keep them free of mineral scale.

Specific areas of concern are discussed next.

5.2.1 Instrumentation

Critical instrumentation needs to be shielded from the high solids environment of degraded water at elevated cycles of concentration. This is especially applicable to analysis probes – in particular, conductivity and pH. Sample streams that feed these instruments should have upstream strainers to remove suspended material. Suspended material blinds the analysis element making it difficult to obtain usable information.

Flow meters should also be selected carefully for high TSS and high salinity duty. Paddlewheel-type flow meters should be avoided because of suspended material in the bulk fluid. Vortex meters should be erosion resistant (from suspended matter). For any type of flow meter, materials of construction are critical, i.e. the material (metal or plastic) must be compatible with WSAC chemistry and possibly abrasive solids.

5.2.2 Solids Control

Solids generation and accumulation in the WSAC were significant. Blowdown (which was intermittent) did not remove enough solids to control its deposition on bundle side walls and accumulation in the basin. Additionally, it was shown that, when the WSAC was operated without demisters, there was significant carryover to the fans. Therefore, deposition on the underside of the demisters will likely be a problem as well.

Consideration must be given to removing solids from the WSAC as they are generated over and above the capability of the blowdown stream. One method could be to filter a slip stream of deluge/spray water. Side-stream filtration has been used for years on a number of full-scale industrial cooling towers to control solids build-up. Filtrate from these systems is returned to the cooling tower basin. For the WSAC, the flow capacity of the Deluge/Spray Pump would have to be increased by the amount of flow for the side-stream filter. Side-stream filters are sized anywhere from 5 to 10 percent of the circulating flow of a cooling system.

Side-stream filtration should control solids accumulation, especially in the basin. Filtration may not completely control deposition on bundle side walls and on the inlet side of the demisters, since some of the deposition in these areas is coming from droplet carryover (to the demister) or splashing at and around the spray header. These areas could be wetted intermittently with a small volume of freshwater to wash away deposition that has not dried in place.

5.2.3 Metallurgy

The metallurgical limits were not challenged during WSAC testing, i.e. none of the tube specimens showed signs of external surface corrosion. The 316 SS was expected to be the least capable metal. Chloride stress-cracking corrosion was expected, but did not occur.

Water to be cooled must be compatible with the WSAC tube-bundle metallurgies (316 SS, 90-10 Cu-Ni and Ti). Pitting corrosion, which was not expected, was found on the interior tube surfaces of the Cu-Ni test specimen. Unit 3 Cooling Tower circulating water was apparently not compatible with Cu-Ni.

5.3 Need for Further Study

As a result of the testing at San Juan Generating Station, WSAC showed great potential to cool degraded water significantly beyond normal cooling tower operating limits. Further testing is required to demonstrate the operating limits of the technology, i.e. the point at which heat transfer starts to degrade either from mineral scale or corrosion. Therefore, additional testing would be used to validate this application of WSAC technology, i.e. determine its operating limits and identify operating and reliability issues.

Upgrades will be necessary to conduct further WSAC testing. Improvements include:

- Strainers to protect conductivity and pH analysis elements for better controls of cycles of concentration
- Side-stream filter to remove suspended matter from the bulk cooling fluid
- Spray headers to intermittently wash tube-bundle side walls and the inlet side to the demister

In addition to these improvements, flow meters and analysis elements will be replaced to improve data gathering and data quality. Pipe connections and hatchways will be tightened to minimize process leaks. Lastly, the unit will be thoroughly cleaned using high pressure water to remove mineral scale and deposited suspended matter.

If it can be demonstrated with further testing that WSAC can reliably use degrade water as a cooling source without performance degradation, an economic analysis would be conducted to determine efficacy of using WSAC technology in lieu of mechanical draft cooling towers.[19] The economic analysis was to be part of the original phase of testing, but given the problems encountered with scale generation and instrument blinding, it was decided to postpone the analysis until these critical issues could be proven manageable.

The economic analysis would evaluate several configurations, e.g. WSAC could be utilized as an auxiliary cooler and use power plant wastewater as a make-up source (e.g. at inland plants). In this mode, it would be a pre-concentrating device to a zero-liquid treatment system and could provide significant economic benefit by reducing capital and operating costs of wastewater treatment. WSAC could also be incorporated into the main cooling circuit and share the load with the main cooling tower(s) while using their blowdown as make-up.

[19] Standard cooling technology, in addition to special materials of construction for degraded water, would require pre-treatment to protect the cooling system from mineral scale. Also, post-treatment is sometimes required to reduce the volume of blowdown for waste disposal at inland plants that require zero-liquid discharge.

Adaptation of a Deterministic Watershed Model for Climate-Hydrology Analysis in the San Juan Basin

Laura H. Z. Weintraub[a], Paul M. Rich[b], Limin Chen[c], Robert A. Goldstein[d], Cathy J. Wilson[e]

[a]Corresponding Author: Senior Engineer, Systech Engineering, Inc., 3180 Crow Canyon Place, Suite 260, San Ramon, CA, 94583, PH: 925-355-1780, FX: 925-355-1778, laura@systechengineering.com

[b]GIS Team Leader, Los Alamos National Laboratory, Mailstop D452, EES-9, Los Alamos, NM 87545, PH: 505-667-1850, FX: 505-667-1628, pmr@lanl.gov

[c]Engineer, Systech Engineering, Inc., 3180 Crow Canyon Place, Suite 260, San Ramon, CA, 94583, PH: 925-355-1780, FX: 925-355-1778, limin@systechengineering.com

[d]Program Manager, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303, PH: 650-855-2593, FX: 650-855-2619, rogoldst@epri.com

[e]Ecohydrology Team Leader, Los Alamos National Laboratory, Mailstop J495, EES-2, Los Alamos, NM 87545, PH: 505-667-0202, FX: 505-665-3866, cjw@lanl.gov

Abstract

Well-designed and useful decision support systems (DSS) are critical tools for managing water resources. As part of the ZeroNet Water-Energy Initiative, the ZeroNet DSS was developed to evaluate effects of climate change on water budgets. The ZeroNet DSS incorporates the existing Watershed Analysis Risk Management Framework (WARMF), which was enhanced through development of a ZeroNet Module. This tool allows stakeholders to evaluate water management scenarios under different climate conditions, and to visualize flow conditions and water shortage and surplus within a basin. This application utilizes WARMF beyond its traditional deterministic roots by implementing a sampling technique to construct climate scenarios based on historical data. The application of WARMF to 16,000 mi^2 (42,000 km^2) of the San Juan Basin (CO, NM) demonstrates its application for water supply management. Scenarios were run to assess impacts of extended drought and increased temperature on surface water supply. Simulations showed that drought and increased temperature impact water availability for all sectors (agriculture, energy, municipal, industry), and lead to critical shortages. WARMF-ZeroNet, as part of the integrated ZeroNet DSS, offers stakeholders an integrated approach to long-term water management to balance competing needs of existing water users and economic growth under constraints of limited supply and potential climate change.

KEYWORDS: watershed; climate change; decision support system; WARMF.

Table of Contents

1. Introduction

The development and application of useful decision support systems (DSS) are critical for water resources decision making and management, particularly in assessing the impacts of drought and climate change. Large scale modeling has typically been used to address the impact of climate change. General circulation models or global climate models (GCMs) numerically simulate changes in climate on a coarse spatial scale (on the order of 300 x 300 km); however, they generally do not provide a good estimation of hydrological response to climate change on a watershed scale. Past studies have developed linkages between GCMs and other models using stochastic or regression based techniques (Strzepek and Yates 1997, Dibike and Coulibaly 2004, Zhu et al. 2005). Limitations of these studies include a recognized simplicity in the approach taken with respect to spatial scale and detail of human-influenced water management.

Concurrently, a set of models have been developed to address watershed management and calculation of total maximum daily loads (TMDLs) (Chen et al. 2001, Bicknell et al. 1993, Neitsch et al. 2001). These tools, not historically developed for climate studies, use a deterministic modeling approach. The models characterize a watershed as a network of land catchments, apply historical precipitation and temperature data, and simulate resulting streamflow. Significant detail regarding managed flows (e.g. diversions, reservoir releases) may be incorporated into these tools at a small spatial scale. Historical records can be selected for drought periods and used to produce a single, deterministic prediction of resulting streamflow. This approach provides a “snap shot” picture of the potential impact of drought or climate change; however conclusions drawn from the simulation may be limited due to uncertainty regarding how well a limited multiyear record of temperature and precipitation data represent a basin’s climate.

This paper discusses a unique approach to adapt a mature, map-based watershed simulation model to handle the complexity of water diversion activities and reservoir operations under varying climatic conditions using a historic sampling approach. Motivation for this work was driven by the recent severe drought in the southwestern United States. An application of the tool to the San Juan Basin (CO, NM) demonstrates an analysis of the impact of projected drought coupled with increasing mean annual temperature associated with projected climate change. While this modeling framework does not attempt to predict the full suite of impacts associated with climate change, it does enable water managers to explore potential impacts of climate change within a user-friendly, PC-based modeling framework.

2. Methods

2.1 Background

The ZeroNet Water-Energy Initiative was initiated by the U. S. Department of Energy to help address critical issues facing water users in arid watersheds. One of the goals of the ZeroNet Initiative is to develop a decision support system (DSS) to support water management (Rich et al. 2005). The ZeroNet DSS was designed to provide tools that synthesize critical water supply and demand information and assist water owners and managers with planning for shortages. Watershed stakeholders can use the ZeroNet DSS to understand four aspects of water management: 1) the functioning of their river basin; 2) how new technologies and use of degraded water for power plant cooling can affect freshwater availability; 3) how to formulate and evaluate management options for water shortage sharing schemes under drought conditions; and 4) how future growth and development and possible climate change may affect water availability. The ZeroNet DSS has three major components: Watershed Tools, a Quick Scenario Tool (QST), and a Knowledge Base, based on foundations of stakeholder input, watershed data, and geographic information system (GIS) capabilities. This paper emphasizes the development of the Watershed Tools component of the ZeroNet DSS via adaptation of a mature watershed model to simulate impacts of drought and climate change via a historical sampling technique to construct drought scenarios.

2.2 Watershed Tools: WARMF

The Watershed Analysis Risk Management Framework (WARMF) was selected as the Watershed Tools component of ZeroNet DSS. WARMF contains a dynamic watershed simulation model that calculates daily surface runoff, ground water flow, non-point source loads, hydrology, and water quality of river segments and stratified reservoirs (Chen et al. 2005, Chen et al. 2004, Herr et al. 2003, Keller 2000, Weintraub et al. 2001). In WARMF, a watershed is divided into a network of land catchments, river segments, and reservoir layers. Land catchments are further divided into land surface and soil layers. These watershed compartments are seamlessly connected for hydrologic and water quality simulations. The land surface is characterized by its land uses and cover, which may include forested areas, agriculture lands, or urbanized cities. Daily precipitation, which includes rain and snow, is deposited on the land catchments. WARMF performs daily water balance calculations to partition precipitation between evapotranspiration, surface runoff and groundwater accretion to river segments. The water entering the river is then routed from one river segment to the next downstream river segment until it reaches the terminus of the watershed. The associated point and nonpoint loads are also routed through the system. Heat budget and mass balance calculations are performed to calculate the temperature and concentrations of various water quality constituents in each soil layer, river segment, and lake layer. WARMF provides a robust framework to address the complex issues proposed by the ZeroNet project.

WARMF has been applied to over nineteen watersheds in the United States and internationally and was originally designed to support modeling and planning for total maximum daily loads (TMDLs). Past watershed applications have mainly focused on single, deterministic model runs. Strengths of WARMF include its comprehensive hydrologic model, built-in database, map-based user interface, and strong stakeholder decision making tools. In order to predict the relative impact of climate change and extended drought conditions on water supply as part of the ZeroNet Initiatitve, we enhanced WARMF with a new approach for scenario construction and execution.

2.3 WARMF ZeroNet Module

To analyze the complexity of water diversion activities and reservoir operations under varying climatic conditions, WARMF was enhanced to include climate and water supply scenario generators to examine consequences of changes in climate, and water allocation. This was accomplished by development of a ZeroNet Module and a Batch Scenario Tool.

The main structure of the ZeroNet module is a series of steps, 1 through 6, which guide the user through setting up simulations and viewing model output (Figure 1). In these steps, new scenarios can be created, and designated uses (e.g. fish habitat) and criteria (e.g. minimum streamflow or reservoir elevation) can be established. In a spreadsheet tool, adjustments can be made to specified diversions and reservoir releases by setting maximum flow allocation values or percent adjustments to historical data. Scenarios may be run using a traditional deterministic approach which will produce output for a single simulation. Or the Batch Run Tool may be selected to run a set of simulations. Though not a true stochastic model, the batch scenario tool enables a user to construct hypothetical climate scenarios based on historical climate data. WARMF samples a set of historical years of data to create a long term simulation which reflects a user-specified pattern of wet, normal and dry years. After viewing a table which segregates the historical meteorologic data into wet, normal, and dry years, the user selects the number of years for simulation, the number of simulation repetitions, and a pattern of meteorologic conditions by classifying each year of the simulation as either dry, wet or normal. Parameters for degree of temperature increase to reflect climate change, and modification of reservoir releases and diversions can also be set. For each simulation, WARMF randomly selects each year from the appropriate bin of historical wet, dry or normal years. WARMF will create the needed input files for meteorology, reservoir releases, diversions, point sources and upstream boundary conditions. The sampled years are linked together to create a continuous simulation and results are saved in standard output files. Multiple simulations are run to produce a probabilistic distribution of results.

After simulations are complete, model predictions may be viewed as time series output of flow, shortage and surplus at various watershed locations. Also, the shortage/surplus tool graphically displays the magnitude of shortages and available pass through water via a color coded map. Compliance with criteria set for the watershed is also viewable via map displays. Finally, the ZeroNet module includes a mechanism for exporting results for single deterministic or full sets of batch simulations.

2.4 Study Watershed

The San Juan Basin was selected for demonstration of the modified WARMF. It is located in the four corners region of New Mexico, Colorado, Utah, and Arizona (Figure 2). Major tributaries of the San Juan River (the Piedra, Animas, and La Plata Rivers) drain melted snow pack from southern Colorado mountains into New Mexico. Drainage from the Upper San Juan and Piedra Rivers fill Navajo Reservoir, which holds approximately 1.8 million acre-feet of water and brings recreational benefits as well as water supply for drought management irrigation projects. The ZeroNet project focused primarily on the portion of the San Juan Basin in northwestern New Mexico.

A diverse set of stakeholders have immediate interest in the management of water resources in the New Mexico portion of the San Juan Basin including local, state, and federal government agencies, industry, Native American tribes, irrigation districts, and private individuals. In addition, there is a need to protect endangered aquatic species. The southwest U.S. has experienced five years of severe drought (2000-2004), during which reservoir levels continually have dropped. Stakeholders have been faced with the real situation of dwindling supplies and increased demand, including new in-stream flow recommendations for endangered species Efforts to mitigate drought impacts involved creation of a "shortage sharing" group in which stakeholders voluntarily agreed to curtail withdrawals by a set percentage.

Comprehensive analysis of drought and its impact in the basin is needed to support the decision making efforts of diverse stakeholders.

2.5 Simulations

WARMF was applied to the San Juan Basin by importing watershed data (e.g. topography, meteorology, land use, observed streamflow, diversions, point sources, and reservoir releases) and performing a hydrology calibration and validation for the time period of 1984 through 2004. After model calibration, a set of simulations were performed using the Batch Scenario Tool of WARMF to examine the impact of extended drought on water availability. Historic data for each year in the dataset (1984-2004) were organized and ranked as “wet”, “normal”, and “dry” based on annual average precipitation. The use of the tool is demonstrated by assessing impacts of a 3 year drought versus a 5 year drought, with 0, 1, and 2 degree temperature increase. A set of 6 scenarios were set up and run (Table 1). These scenarios represent a range from no climate change (0 degree temperature increase) to significant warming. A 2 degree increase in mean annual temperature is a high value often predicted by models such as the Community Climate Model (Kiehl et al. 1997) roughly 100 years into the future. In WARMF, this temperature change is applied as a uniform increase to historical minimum and maximum daily temperatures. When computing hydrology, these temperature data are used to dynamically calculate changes in snowmelt timing and the quantity of evapotranspiration.

Given the large year-to-year variation in climate data, random sampling of historical years will result in a large variation in the resulting water budget. Therefore, a repeated sampling approach was taken to reduce the model uncertainty. WARMF performed a set of runs for each scenario, sampling different combinations of “normal” and “dry” years. Preliminary testing was performed to determine the minimum number of iterations (runs) that is required in order to get a stabilized mean output. The ending elevation of Navajo Reservoir after the 3 yr or 5 yr drought was used as the main variable for evaluation. A comparison of the mean ending elevation as a function of the number of runs suggests that for a 3 year drought, mean ending elevation stabilizes after 50 runs. For a 5 yr drought, the running mean of the elevation starts to stabilize after 50 runs, however it still shows slight variation. We also compared the cumulative distributions of elevations for 3 sets of runs with 25, 50 and 75 iterations. For the 3 year drought, the cumulative distribution of the ending elevation for the 50 runs is very close to the 75 runs. For the 5 year drought, the cumulative distribution of elevation for the 50 runs shows slight deviation from the 75 runs. With consideration of these results and associated simulation time to produce results it was decided to use a repeated sampling of 50 runs to calculate a representative mean of the results for both the 3 and 5 year drought simulations.

The results were summarized as means and standard deviations of the 50 runs. Initially, all six scenarios yielded average reservoir elevations which violated the minimum elevation criteria of 5990 ft (1825 m) in Navajo Reservoir that must be met to accommodate the siphon pump for the Navajo Indian Irrigation Project (NIIP) diversion. Therefore, a reservoir release adjustment factor was introduced during the second (2°C scenarios) or third (0 and 1°C scenarios) year of drought to avoid minimum elevation violation. This factor reduces the historic prescribed reservoir releases by a user-specified percentage. A trial and error process was used to determine the approximate release adjustment that was necessary for each scenario so that the mean reservoir elevation would not fall below the minimum elevation criteria.

3. Results

The value of the historical sampling technique added to WARMF is demonstrated by looking at the large variability in predicted streamflow and reservoir elevation for the 50 runs of one scenario. For example, Figure 3 shows the predicted reservoir elevation for the D3T1 scenario at the end of the 3 year drought to range from 1769.1 m to 1853.4 m for the 50 runs. Also, the predicted elevation for the whole simulation period also shows large variation, as suggested by the relatively large standard deviation (Figure 4).

Figures 5a and 5b show the mean projected elevation for Navajo Reservoir for each of the six scenarios. As labeled in the figures, in order to keep the mean reservoir elevation above the minimum criterion, it was necessary to decrease the prescribed reservoir releases by 18% to 70% during specific drought years under various drought and temperature conditions. For the scenarios with zero and one degree temperature increase (D3T0, D3T1, D5T0, and D5T1), reservoir release reductions began during the third year of drought and continued through the end of the drought. For the scenarios with two degree temperature increase (D3T2 and D5T2) it was necessary to start the reservoir release adjustment during the second year and continue through the end of the drought period to avoid minimum reservoir elevation violations. The estimated percent of reduction in reservoir releases was set to keep predicted mean elevation above minimum. For a more conservative approach, the reservoir release adjustments could have been set based on the mean reservoir elevation minus the standard deviation (Figure 4). This would have resulted in a larger percent reduction in reservoir elevation.

The adjustment in reservoir release will cause shortage downstream. Here we summarize the basin-wide shortage for the four scenarios, both on annual and cumulative bases (Table 2). Because the La Plata tributary watershed has historically experienced significant shortages during all years (including normal and wet years) due to over allocation and under delivery from Colorado, this portion of the watershed was excluded from the water shortage analysis.

4. Discussion

We successfully adapted the deterministic WARMF model to produce simulations based on repeated sampling of climatic and watershed data. If only a single deterministic run was performed, as represented by any single curve in Figure 4, the output could have fallen on the upper or lower end of the curve and could result in decision makers implementing a plan that would be either overly aggressive or ineffective. The repeated sampling approach enables us to examine output variability as a function of input variability. A set of drought scenarios sampled with sufficient iteration will provide both a mean result and a representation of variation about the mean, enabling more informed decisions. The limitations of this approach are two. First, the set input data must satisfactorily represent a probability distribution for key parameters such as precipitation and temperature. And second, calculation time can limit the number of iterations that can be performed.

The scenario results show that under both three and five year drought conditions, significant modifications in reservoir release operations may be necessary to meet the minimum elevation criteria. Also, the watershed is likely to experience water shortages downstream of Navajo Reservoir during drought conditions. A projected climate change with an increase in average temperature by just 1 or 2°C demonstrated a more severe impact on reservoir elevation and downstream shortages. The water shortage analysis shows a predicted shortage ranging from 266 to 62,071 AF/year under various scenario conditions. During the recent drought in the San Juan Basin, a reported “shortage sharing” agreement of approximately 3,400 AF/year effectively helped the region meet the minimum reservoir elevation criteria and eliminate the need to shut down lower priority diverters. This amount of shortage falls within the range of shortages predicted by WARMF. WARMF could be used to further refine potential shortage sharing agreements in future drought situations. Likewise, the implementation of other management alternatives such as reduced power plant withdrawals due to the use of produced (degraded) water or advanced cooling techniques could be added to model scenarios. Though the approach demonstrated here used the mean calculated reservoir elevations to establish required reservoir release adjustments, the tool provides the capability to take a more conservative approach and base decisions on the mean +/- the calculated standard deviation for the multiple runs. Without a mechanism to efficiently set up multiple runs which sample the full range of potential drought conditions, the model would predict a single deterministic run which could be an upper or lower extreme condition. A “snap shot” analysis such as this could lead water managers to make planning decisions which are too conservative or not conservative enough.

Therefore, the approach presented above demonstrates a valuable improvement to an established watershed model which is now capable of predicting climate change impacts using a historical sampling approach to build scenarios. Limitations of the approach taken include a sampling from a limited database of 20 years (1984-2004) for the watershed, and a lack of efficiency and flexibility in the trial and error method used for setting the reservoir release adjustment. In addition, a simplified approach was taken to account for climate change with the use of a uniform temperature increase. Large scale climate change models predict that warming may be accompanied by more precipitation in the southwest, but not more snowpack (Thomson et al. 2005). Increased evapotranspiration may or may not outweigh increases in precipitation and snowpack is predicted to melt sooner, and contain less water than in the past. These changes in precipitation and snowmelt patterns may have greater or lesser impact than the temperature induced evapotranspiration impact examined in this analysis. Never-the-less, this is the first tool that water managers, farmers and tribes have had access to, to even begin to examine potential water planning problems associated with climate change. WARMF will be extended to examine some of these other impacts in the future.

5. Conclusions

As part of the ZeroNet DSS development, a mature physically-based watershed simulation model, WARMF, was successfully enhanced to provide a mechanism for integrating critical water supply and demand information and assisting water owners and managers with planning for drought and climate change. WARMF can now execute a historic sampling technique via a batch tool to provide mean and standard deviation output of a set of simulation runs to characterize resulting stream flow, shortage, and surplus of water in watersheds faced with potential drought and climate change. The tool also provides a record of where violations of minimum stream flow or minimum reservoir elevation may occur under such conditions. The resultant scenario library generated by the Watershed Tools is linked with the other components of the ZeroNet DSS (Knowledge Base and Quick Scenario Tool). These other tools will provide mechanisms for organizing scenarios and performing related economic analysis.

The ZeroNet DSS was distributed to the stakeholders of the San Juan Basin for their use in water planning. Potential future work includes continued development of the ZeroNet Module of

WARMF to include a more efficient method for calculating the required reservoir release adjustment for meeting minimum elevation criteria. Additional applications of the ZeroNet DSS to watersheds with other environmental characteristics and water use situations need to be conducted to test the robustness of the tool and analysis methods. Also, linkage of WARMF with climate change prediction data from a GCM could prove to be useful. Finally, the climate generation scenario technique presented here could be expanded beyond hydrology simulations to include water quality analyses.

Acknowledgements

The ZeroNet partnership includes participation from Los Alamos National Laboratory (LANL), the Electric Power Research Institute (EPRI), the Public Service Company of New Mexico (PNM), the University of New Mexico (UNM), Sandia National Laboratories (SNL), Systech Engineering, Inc., and the Department of Energy National Energy Technology Laboratory (DOE NETL).

References

1. Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr. and Johanson, R.C. 1993. Hydrological Simulation Program –FORTRAN User's Manual for Release 10. EPA/600/R-93/174, U.S. Environmental Protection Agency Environmental Research Laboratory, Athens, GA.
2. Chen, C.W., J. Herr, and L. Weintraub. 2001. Watershed Analysis Risk Management Framework (WARMF): Update One – a decision support system for watershed analysis and total maximum daily load calculation, allocation and implementation. Publication No. 1005181, EPRI, Palo Alto, CA.
3. Chen, C.W., J. Herr, and L. Weintraub. 2004. Decision Support System for Stakeholder Involvement. Journal of Environmental Engineering, ASCE, Vol 130, No. 6, June 2004, pp.714-721.
4. Chen, C.W., J.W. Herr, R.A. Goldstein, G. Ice, and T. Cundy. 2005. Retrospective Comparison of Watershed Analysis Risk Management Framework and Hydrologic Simulation Fortran Applications to Mica Creek Watershed.
5. Dibike, Y.B., P. Coulibaly. 2004. Hydrologic Impact of Climate Change in the Saguenay Watershed, Proceedings of 57th Canadian Water Resources Association Annual Congress, Water and Climate Change: Knowledge for Better Adaptation, June 16-18, 2004, Montreal, Qc, Canada.
6. Herr, J., C.W. Chen, R.A. Goldstein, R. Herd, and J.M. Brown. 2003. Modeling Acid Mine Drainage on a Watershed Scale for TMDL Calculations. JAWRA, Vol. 39, No. 2, April, 2003.
7. Keller, A. 2000. Peer review of WARMF – an evaluation of WARMF for TMDL applications by independent experts using USEPA guidelines. Technical Report 2000.1000252, EPRI, Palo Alto, CA.
8. Kiehl, J. T., Hack, J. J., Bonan, G. B., Boville, B. A., Williamson, D. L., Rasch, P. J. 1998. The National Center for Atmospheric Research Community Climate Model: CCM3. Journal of Climate, Vol.11 , No. 6, pp. 1131-1149

9. Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R. 2001. Soil and Water Assessment Tool Theoretical Documentation. Version 2000. BASINS 3.0, EPA-823-C-01-003, USEPA, Office of Water and Office of Science and Technology, Washington, D.C.
10. Rich, P.M., L.H.Z. Weintraub, M.E. Ewers, T.L. Riggs, and C.J. Wilson. 2005. Decision Supoort for Water Planning: the ZeroNet Water-Energy Initiative, Proceedings of the American Society of Civil Engineers - Environmental & Water Resrources Institute (ASCE-EWRI) "World Water and Environmental Resources Congress 2005: Impacts of Global Climate Change", May 15-19, Anchorage, AK. LA-UR-05-1068.
11. Strezepek, K.M., D. N. Yates. 1997. Climate Change Impacts on the Hydrologic Resources of Europe: A Simplified Continental Scale Analysis, Climatic Change, Volume 36, Issue 1 - 2, May 1997, Pages 79 - 92
12. Thomson, A.M., R.A. Brown, N.J. Rosenberg, R. Srinivasan, R.C. Izaurralde. 2005. Climate Change Impacts for the Conterminous USA: An Integrated Assessment. Part 4: Water Resources. Climate Change, Volume 69, Pages 67-88. 2005.
13. Weintraub, L.H.Z., C.W. Chen, J. Herr. 2001. Demonstration of WARMF: a decision support tool for TMDL Development. Proceedings of WEF TMDL Science Issues Conference, March 4-7, 2001. St. Louis, MO.
14. Zhu, T., M.W. Jenkins, J.R. Lund. 2005. Estimated Impacts of Climate Warming on California Water Availability Under Twelve Future Climate Scenarios. Journal of the American Water Resources Association (JAWRA). 41(5):1027-1038.

Table 1. Scenario Matrix for Drought and Climate Simulations

Scenario	Temp. +/- (°C)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
1 – d3t0	0	Normal	Normal	Dry	Dry	Dry	Normal	Normal	na	na
2 – d3t1	1	Normal	Normal	Dry	Dry	Dry	Normal	Normal	na	na
3 – d3t2	2	Normal	Normal	Dry	Dry	Dry	Normal	Normal	na	na
4 – d5t0	0	Normal	Normal	Dry	Dry	Dry	Dry	Dry	Normal	Normal
5 – d5t1	1	Normal	Normal	Dry	Dry	Dry	Dry	Dry	Normal	Normal
6 – d5t2	2	Normal	Normal	Dry	Dry	Dry	Dry	Dry	Normal	Normal

Table 2. Projected Water Shortages for Drought / Climate Scenarios

Scenario	Reservoir Release Adjustment	Volume Held Back in Reservoir (AF)	Number of Years with Reservoir Release Adjustment	Total Shortage Downstream of Reservoir During Drought Period (AF)	Average Shortage Downstream of Reservoir (AF/yr)[1]
D3T0	18%	86,786	1	266	266
D3T1	65%	314,010	1	45,050	45,050
D3T2	70%	689,548	2	129,173	64,586
D5T0	45%	656,699	3	27,767	9,256
D5T1	62%	896,268	3	109,713	36,571
D5T2	70%	1,358,127	4	248,282	62,071

[1]Averaged for years when reservoir release adjustment was implemented.

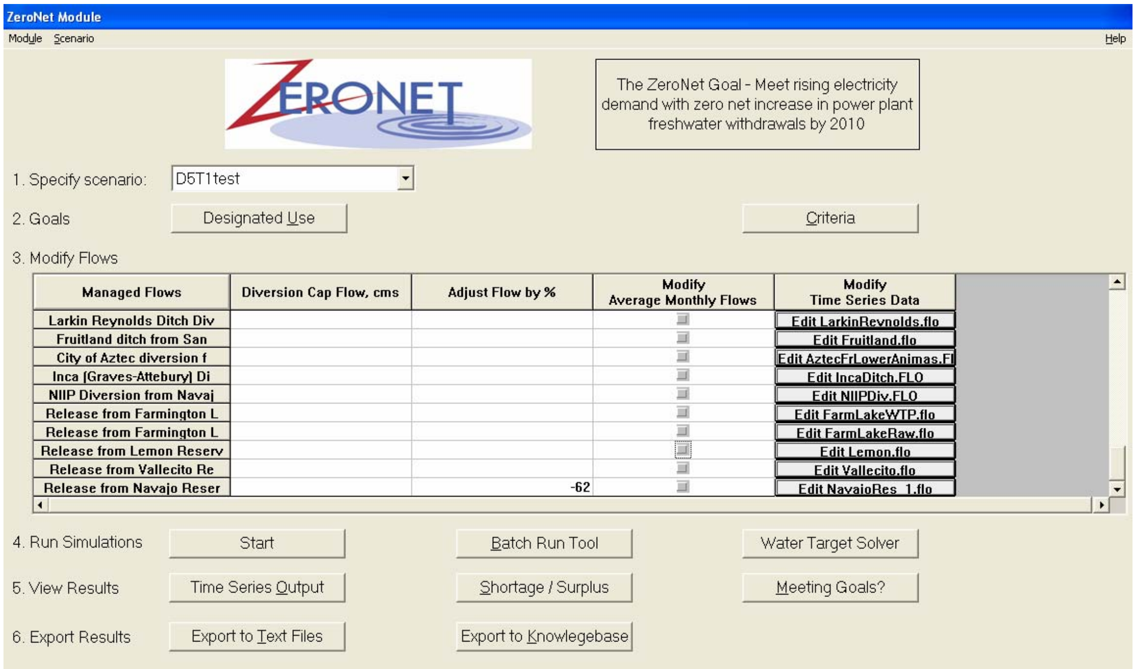


Figure 1. ZeroNet Module of WARMF

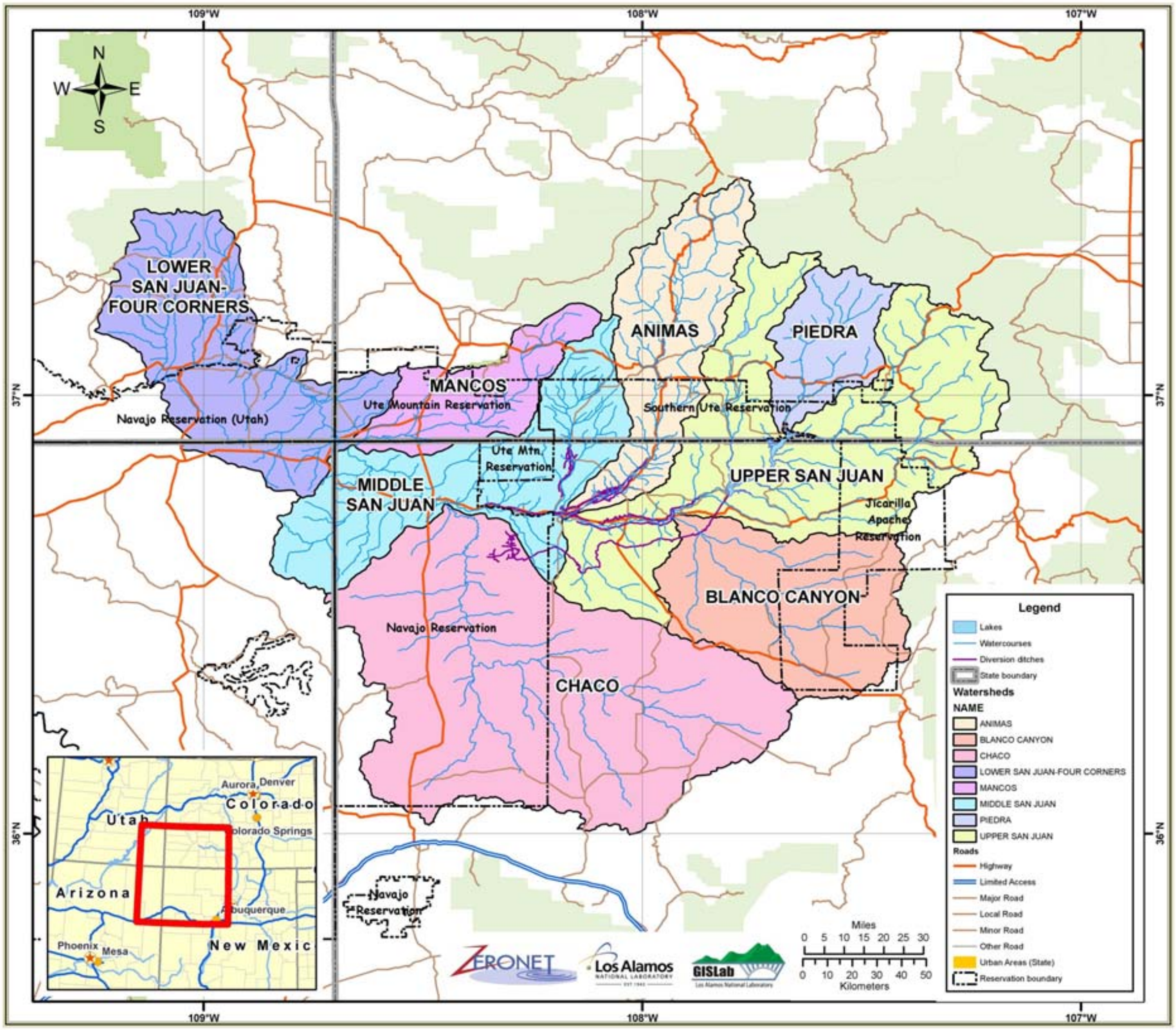


Figure 2. The San Juan Basin is located in the Four-Corners area where New Mexico, Colorado, Utah, and Arizona meet.

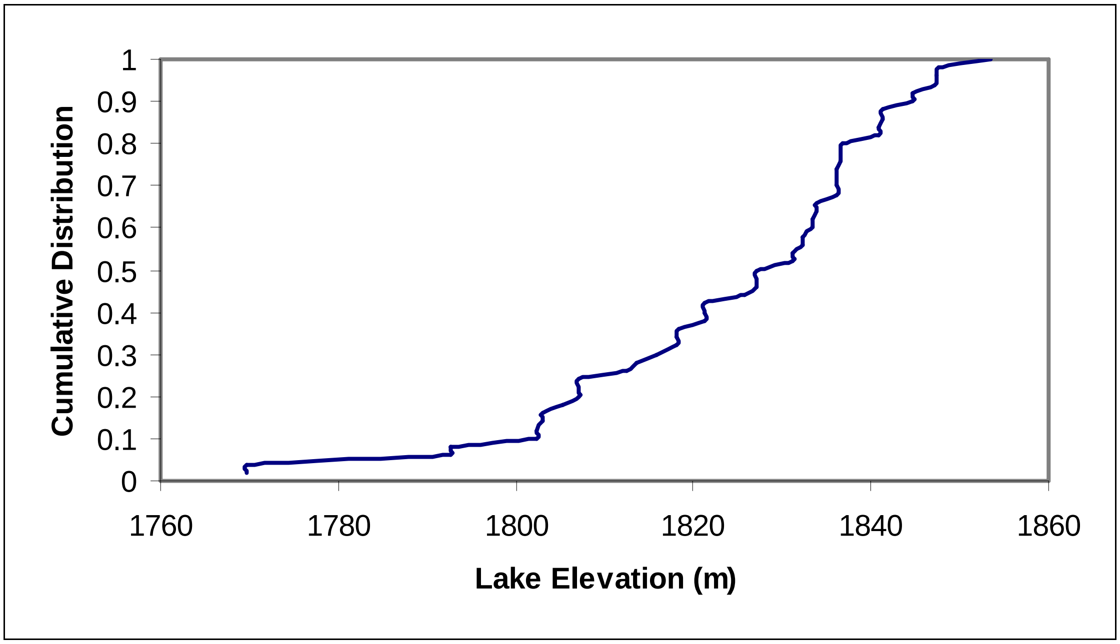


Figure 3. Projected cumulative distribution of surface elevation of Navajo Reservoir at the end of year 5 for a 3-year drought and 1-degree temperature increase (D3T1).

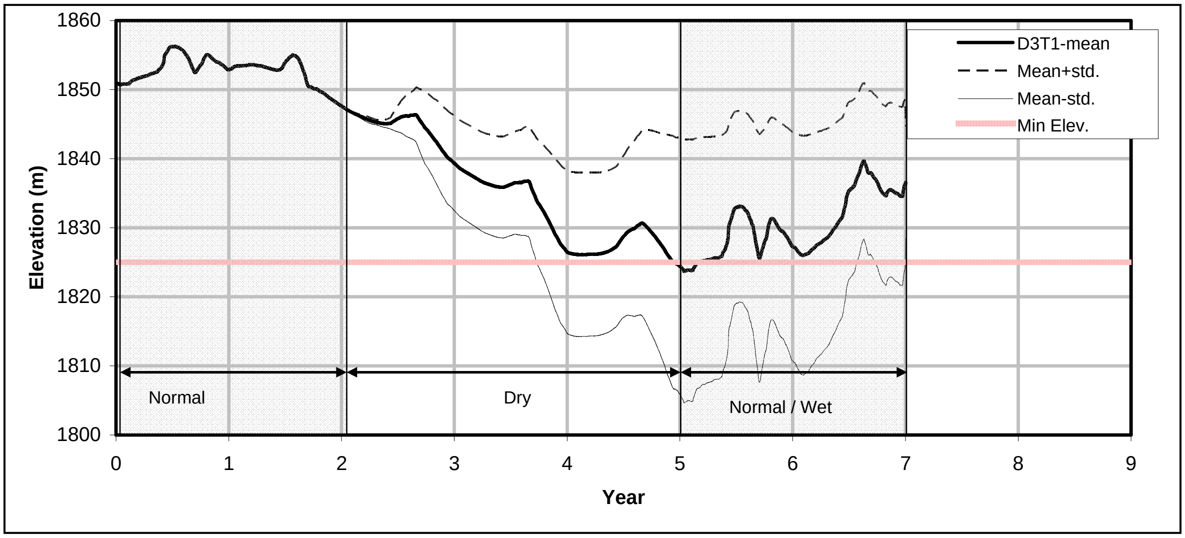


Figure 4. Projected mean surface elevation of Navajo Reservoir under a 3-year drought and 1-degree temperature increase (D3T1) with ± standard deviation.

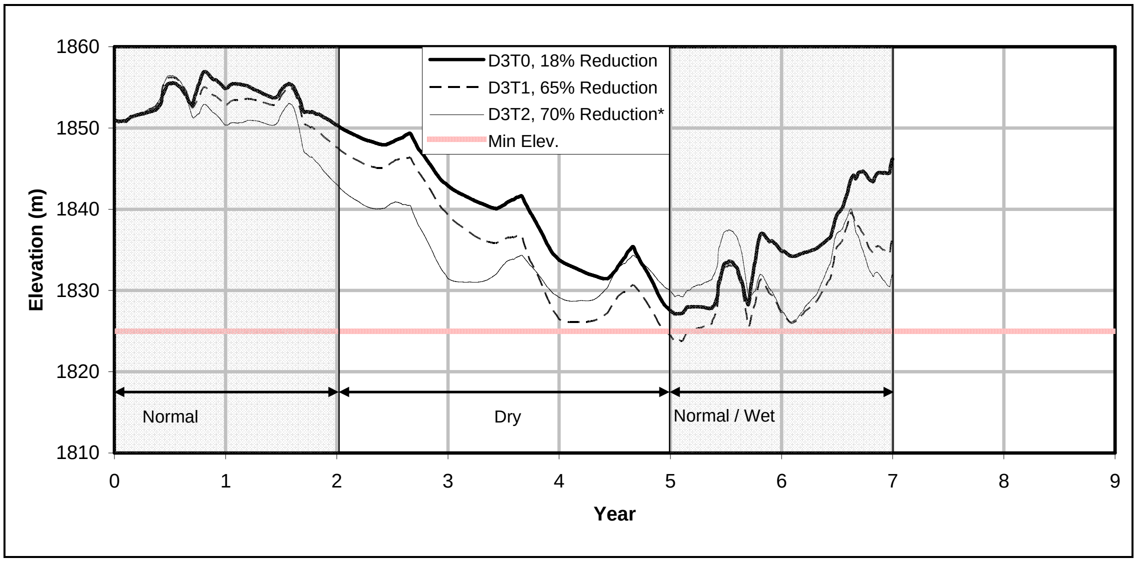


Figure 5a. Projected Mean Surface Elevation of Navajo Res. for 3-Yr Drought Scenarios. Note: Reservoir release reduction was implemented for years 4 and 5 for scenario D3T2 and for year 5 only for scenarios D3T0 and D3T1.

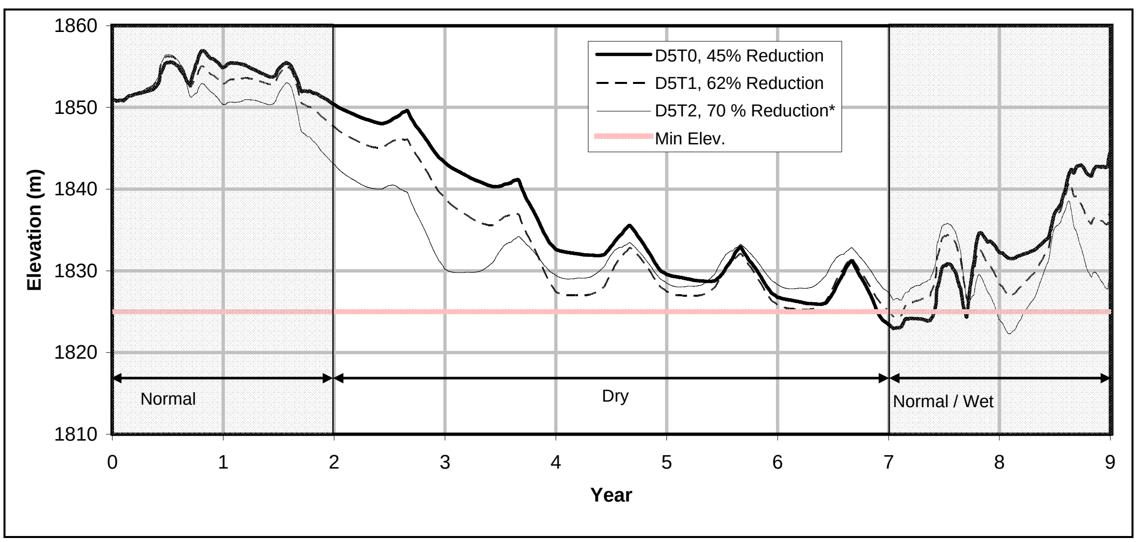


Figure 5b. Projected Mean Surface Elevation of Navajo Res. for 5-Yr Drought Scenarios. Note: Reservoir release reduction was implemented for years 4, 5, 6, 7 for scenario D5T2 and for years 5, 6, 7 for scenarios D5T0 and D5T1.