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SECTION 2.0

HYDRAULIC STUDIES

INTRODUCTION

The purpose of the hydraulic studies section of this report is to summarize and assess the hydraulic data collected at the Sacramento Constructed Wetlands Demonstration Project (SCWDP) site over the five years of operation. Each of the hydrologic components that make up the wetland water balance is discussed. The hydrologic components are used to conduct a water balance for the wetland system. In addition, the results of tracer studies and Manning's flow studies are presented. All tables and figures are presented at the end of the text.

HYDROLOGIC COMPONENTS

The hydrologic components of the wetland system include inflow, outflow, precipitation, evaporation and transpiration (considered together as evapotranspiration), and infiltration. Inflow and precipitation represent water inputs to the wetland system, and outflow, evapotranspiration, and infiltration represent water outputs from the wetland system. The hydrologic elements of the wetland system are depicted in Figure 2-1.

When all water inputs and outputs are measured over a given time period, a water balance can be conducted to test the accuracy of the measurements. If measurements for a single hydrologic component are not available, the water balance can be used to estimate the missing values. During the five-year history of the Sacramento Constructed Wetlands Demonstration Project (SCWDP), measurements of all of the hydrologic components were collected. A summary of the hydrologic data collected at the SCWDP is presented in Table 2-1.

As shown in Table 2-1, significant amounts of hydrologic data were not collected until 1996. No hydrologic data are provided in the 1994 Annual Report, and only a few measured values (for October and November) are presented in the 1995 Annual Report. After 1996, inflow to all of the wetland cells except Cells 8 and 10 was measured. Outflow was measured in Cells 3, 5, 7, and 9. Infiltration was not measured directly until 1998. Each component of the water balance is discussed separately below. Following the discussion of each of the hydrologic elements, a water balance for the wetland system is presented.

Inflow

UV-disinfected secondary effluent from the Sacramento Regional Wastewater Treatment Plant (SRWTP) is pumped to the wetland facility standpipe, where it flows by gravity through a distribution main to each cell inlet. Inflow to the wetland cells is measured by propeller flow meters installed in the pipelines that convey flow to each cell. The meters contain a flow rate indicator, and a totalizer gage to record the cumulative flow volume. Although influent flow meters were installed during construction of the wetland, the original meters were replaced in the fall of 1995 due to faulty operation. Proper operation of the new meters was confirmed by comparing measured flow values to the flow meter at the wetland pump station. However, the new meters also require appreciable maintenance, and have had to be replaced periodically.

The design inflow value for the wetland cells is a constant 70 gal/min, with the exception of half-cells 6A and 6B (less water is applied to the half-cells, as water is alternately discharged to each half-cell for twelve hours per day). As seen in Table 2-1, the average monthly inflow generally approaches and occasionally exceeds 70 gal/min. However, the average annual flows to each cell have become less uniform (generally lower) with time. In 1996, the wetland cell annual average inflow ranged from 65 to 71 gal/min (excluding Cells 6A and 6B), while the range was 61 to 71 gal/min and 38 to 62 gal/min in 1997 and 1998, respectively. Because inflow totalizer data are collected approximately every week, lower monthly averages may reflect treatment plant shutdowns, meter malfunctions, or wetland cell downtime (for vegetation removal or other maintenance).

Because wetland hydrologic data for 1998 are not provided in previous annual reports, and because 1998 is the first year when all hydrologic components were measured (for Cells 3, 5, 7, and 9), particular attention will be given in this report to the 1998 hydrologic data for Cells 3, 5, 7, and 9. Average monthly and daily inflow values for Cells 3, 5, 7, and 9 in 1998 are presented graphically in Figure 2-2. As shown in Figure 2-2, inflow values varied appreciably during 1998. It is not known whether these flow variations are due to faulty flow-measuring equipment (some of the flow meters were replaced in 1998 when it was observed they were not operating properly), or to unrecorded plant shutdowns. Low inflow values recorded for Cell 9 during the months of March, April, and May have been replaced by the design inflow value of 70 gal/min, because it is known that significant outflow occurred from Cell 9 during these months. The daily inflow values presented in Figure 2-2 appear to be constant between each flow measurement recording date, because the intermediate (non-recorded) values are interpolated between the recorded flow values.

Outflow

Effluent flow meters were not installed until 1996. Before 1996, wetland cell outflow was estimated on a volumetric basis using the concrete effluent structures. Because the effluent flow pipes are inaccessible, inline flow meters (like those used to measure wetland cell inflow) were not installed. Instead, V-notch weirs and calibrated ultrasonic level detectors were installed to measure outflow. The water elevation behind the weir is measured every 15 minutes, and the corresponding flow is calculated and stored on a datalogger. Effluent flows are highly variable, as they are influenced by several factors including inflow, precipitation, evapotranspiration, and infiltration. In addition, it has been observed that faulty flow measurements have been caused by debris such as leaves and spiderwebs collecting in the effluent structures, causing the ultrasonic level detectors to give artificially high results. Low outflow values are most often related to plant shutdowns.

In Table 2-1, it can be seen that the average annual effluent values for 1996 and 1997 range from 40 to 46 gal/min, or about sixty percent of the influent flow. The average monthly outflows for 1998 range from 0 to 63 gal/min, with yearly values ranging from 18 to 44 gal/min. Monthly and daily 1998 outflow values are presented graphically in Figure 2-3. As with inflow, variation in outflow values is more apparent when presented on a daily basis. It is assumed that some of the irregular values are due to faulty measurement of outflow, as it has been observed that the flow logging stations are frequently out of calibration. Flows over 400 gal/min, recorded in late March and early April, have been replaced with interpolated values between more reliable results.

Precipitation

The SCWDP is located immediately south of Sacramento, in the California Central Valley. Typical precipitation for the Sacramento area is seventeen to eighteen inches per year, mostly occurring in the winter months. Average annual precipitation values for the Sacramento area are presented in Table 2-2. As shown in Table 2-2, the long-term weather station closest to the SCWDP is located at the Sacramento Executive Airport, about 4.5 miles northwest of the SCWDP.

During the five-year study period, annual rainfall for the Sacramento area was lower than normal during the first year, about average during the fourth year, and higher than normal during the remaining years. The average annual precipitation at the Sacramento Executive Airport during the five-year study period was 21.3 inches, with a high of 27.8 inches during 1998. Precipitation values from local weather stations for 1994-1998 are presented in Table 2-3. Included among the precipitation values are data from California Irrigation Management Information System (CIMIS) stations, located on four sides of the SCWDP. The CIMIS station data are included for comparison.

Precipitation is measured at the wetland site by a Texas Weather Instruments (TWI-WR-25) weather station. The onsite weather station precipitation values are also presented in Table 2-3. It can be seen that the onsite weather data show inconsistent agreement with the values from the other weather stations. Therefore, values from the Sacramento Executive Airport weather station will be used in the 1998 water balance presented later in this section.

Evapotranspiration

Wetland water losses to the atmosphere occur from water surfaces and moist soil surfaces (evaporation) and from the interior of the emergent portions of plants (transpiration). Both processes involve the passive evaporation of moisture, which is absorbed by unsaturated air moving through the wetland. The primary difference between evaporation and transpiration (evaporation from plants) is that plants have the ability to limit water losses by closing their pore openings when not actively photosynthesizing. However, because the period of most active photosynthesis occurs during the period of highest evaporation (i.e., daylight hours during summer), the transpiration rate is practically the same as the evaporation rate.

When water surfaces and photosynthesizing plants are present together, as in a wetland, unsaturated air acquires moisture from both sources. However, the combined amount of moisture taken by the air from both sources is no greater than would be lost by either source alone, if it were isolated. In other words, the air carries away a finite amount of water dependent on temperature, relative humidity, and other physical conditions. Whether the amount of water carried away comes from the open water, or from plants, or from a combination of the two, the amount lost is roughly the same. For this reason, and because it is difficult to separate the processes of evaporation and transpiration, reference evapotranspiration (ET) rates can be used to calculate wetland water losses.

In the scientific literature, several attempts to quantify wetland evapotranspiration rates can be found. Most researchers have concluded that ET rates from wetland vegetation are not significantly different from that of well-watered terrestrial vegetation in similar climates. Although narrow stands of wetland vegetation will experience higher ET rates, large areas of emergent aquatic plants are not expected to have ET:pond evaporation ratios greater than one. The general consensus is that pond water losses are not increased measurably by the introduction of wetland vegetation (research titles and authors are included in the list of references at the end of this section).

A summary of long-term reference evapotranspiration and pan evaporation values for the Sacramento area is included in Table 2-4. Reference ET values refer to water losses from well-watered pasture, and are comparable to pond evaporation values. As shown in Table 2-4, typical ET for the Sacramento area is about 52 inches. Pan evaporation values are measured in Class A evaporation pans (four feet in diameter). Due to the relatively small size of the pans, pan rates typically are higher than reference ET or pond evaporation rates, and must be multiplied by a pan coefficient (typically 0.7 to 0.8) to represent lake evaporation or crop ET (conversely, pan rates may be divided by reference ET rates to yield a pan coefficient). As shown in Table 2-4, pan evaporation values for the Sacramento area are about 65 inches. For the Davis and Lodi stations, the pan coefficients are 0.71 and 0.79, respectively. Long-term reference ET values for the closest CIMIS station (Fair Oaks) are relatively low, probably because the Fair Oaks station has only been in operation for the last two years, which were unusually cool and wet. The Fair Oaks CIMIS station is located about sixteen miles northeast of the SCWDP.

Reference ET values measured at local CIMIS stations from 1994 to 1998 are presented in Table 2-5. It can be seen that ET values during the five-year operation of the SCWDP were lower than normal. For example Lodi CIMIS data (which agree well with long-term ET values for the Sacramento area) range from a high of 52.6 inches during 1997 (the fourth year of operation), to values of 48.8, 45.7, 49.0, and 42.9 inches in the other years. The Fair Oaks CIMIS annual ET value for 1998 is 43.6 inches.

At the Sacramento Demonstration Wetlands, pan evaporation measurements were made from two sets of pans, one set located in open water areas, and one set located in vegetated areas. The purpose of the study was to quantify and compare evaporation rates in both areas. The data would be used to estimate water losses from the wetland. Pans were installed in Cells 3, 5, and 7, and measurements were made on a semi-weekly basis (more often in the summer, and less frequently in the winter). The results of the evaporation pan measurements made in 1998 are presented in Table 2-6. It can be seen in Table 2-6 that average monthly pan evaporation values for the open water area range from 0.4 to 8.3 in/month, with an annual total of 52.5 inches. In the vegetated area, the average monthly pan evaporation values range from 0.2 to 3.3 in/month, with an annual total of 21.2 inches. For comparison, 1998 reference ET values from the Fair Oaks CIMIS station are also presented in Table 2-6. The monthly CIMIS reference ET values range from 0.5 to 7.9 inches, with an annual total of 43.6 inches, which falls between the wetland open water area and vegetated area annual evaporation values.

The evaporation values provided in Table 2-6 are presented graphically in Figure 2-4. As seen in Figure 2-4, the open-water pan evaporation results are higher than either the CIMIS or vegetated area values, presumably due to freer air movement and greater potential for heating due to sunlight. On the other hand, the vegetated area evaporation rates are lowest, presumably due to restricted air movement and greater shading. It can be seen in Figure 2-4 that the CIMIS values are intermediate.

The 1998 Fair Oaks CIMIS ET values will be used in the water balance. Although the wetland evaporation pan values generally are similar to the CIMIS values, the evaporation pan measurements were, in some cases, compromised by rain, pan dry-out, and interference from muskrats or waterfowl. It is worth noting that evapotranspiration is the air-conditioning system for the treatment wetland. Without the attendant loss of the latent heat of vaporization of water, the summer wetland temperature would increase considerably. Just as evaporation of perspiration helps keep a body cool, the evapotranspiration of wetland moisture helps moderate summer temperatures in the wetland.

An attempt to quantify the amount of moisture lost by transpiration was made in 1997. Wetland vegetation was established in 30-gallon tubs, which were then sealed with clear plastic allowing only the plant shoots to protrude, so that non-transpiration water losses could be prevented. Control tubs without vegetation were also used for comparison. As reported in the 1997 Annual Report, the measured total transpiration from June to October was 165 inches, ranging from a high of 41.8 inches transpired in August, to a low of 19.5 transpired inches in October. Although the measured transpiration values clearly exceed historical ET values (the transpiration values are approximately five times the ET values presented in Table 2-6), it is interesting to note that the ratio of monthly to total estimated transpiration values is similar to the ratio of monthly to total ET values.

Infiltration

Wetland infiltration is the loss of water from wetland cells into the soil. In this report, the term infiltration will be used to refer to the movement of water *into* the soil, whereas the terms percolation, permeability, and hydraulic conductivity will refer to the movement of water *through* the soil. Infiltration rates are controlled by soil porosity, soil particle size, and degree of soil compaction, as well as the degree of "sealing" due to the deposition of fine organic material on the wetland basin floor.

According to a 1954 USDA SCS soil survey of the area, the three dominant soil types identified at the wetland site are Alamo clay, San Joaquin loam, and Fremont clay. Soil permeability for the restricting layer of these soils is characterized as "very slow," less than 0.06 in/hr. In a more recent soil survey (1993), the dominant soils types at the wetland site are identified as Galt clay, Clear Lake clay, Madera loam, and San Joaquin silty loam. The infiltration rates associated with these soils under saturated conditions are presented in Table 2-7.

As shown in Table 2-7, infiltration rates range from under 0.06 in/hr to a maximum of 0.2 in/hr. The loam soils, while having a larger range of particle sizes than clays, are associated with underlying claypan layers that restrict movement of water. While it is difficult to predict the infiltration rate based solely on the soil survey data, it can be seen that, due to the presence of multiple soil types, infiltration can be expected to vary somewhat at the wetland site. Although the wetland basin bottoms were compacted during construction, planting operations included trenching, which probably led to increased percolation. However, due to the presence of clay and the effects of sealing due to deposition of fine organic matter, it was expected that infiltration rates would be relatively low.

In March and July 1998, a series of infiltration tests was conducted in wetland cells 3, 5, 7, and 9. No inflow or outflow to the cells occurred during the test period, so water losses were limited to infiltration and evapotranspiration. The water level in the test cells was monitored for nearly two weeks. The results of the March infiltration test are presented in Figure 2-5. As shown in Figure 2-5, the infiltration rates for each cell are nearly constant (a slight rise in water level occurs initially due to rainfall). After correcting for ET losses (0.0036 in/hr during March 1998), the average wetland cell infiltration rate is estimated to be approximately 0.011 in/hr (rates of 0.008, 0.011, 0.015, and 0.011 in/hr for Cells 3, 5, 7, and 9, respectively). The value of 0.011 in/hr falls within the "very slow" category of infiltration, as identified in the SCS soil survey. It is believed that organic matter settling on the wetland floor helped to seal the bottom, further reducing infiltration rates. The average infiltration loss, when considered over an entire wetland cell, is equivalent to 7.2 gal/min, about 10 percent of the design inflow of 70 gal/min. The results of the July infiltration test confirmed the values measured earlier in the year.

HYDROLOGIC RESULTS

As described above, the sum of water inputs to the wetland system should equal the sum of water outputs over a given time interval. The quality of the hydrologic data can be evaluated by analyzing the percent error in the water balance.

Water Balance

Assuming that changes in storage are negligible over the long-term, the sum of wetland cell inputs can be set equal to the sum of cell outputs:

$$\text{Inflow} + \text{Precipitation} = \text{Outflow} + \text{Evapotranspiration} + \text{Infiltration} \qquad [1]$$

The hydrologic data collected in 1998 are used to calculate water balances for Cells 3, 5, 7, and 9 in Table 2-8. As seen in Table 2-8, monthly inflow and outflow volumes for each cell are converted to units of depth (inches) so the values can be compared to the other hydrologic components, also reported as depths (inches). For each of the cells, inflow is the dominant hydrologic element, ranging from 741 to 825 inches per year. The other input value, precipitation, accounts for only 28 inches per year. Total wetland cell output consists of outflow (241 to 588 in/yr), infiltration (69 to 135 in/yr), and ET (44 in/yr). However, for each of the cells considered, the total output makes up no more than 85 percent of the total input, for a minimum error of 15 percent (Cells 7 and 9). In Cells 3 and 5, the total output is only about half the total input, for errors of 56 and 44 percent, respectively.

The error in the water balance may be due to inflated inflow values or artificially low outflow values. Because precipitation does not play a dominant role in the water balance, it is unlikely that the error is the result of overly high rainfall values. Although the effect of ET is more significant, it is unlikely that the error is due to underestimated ET values (for example, ET values would have to be multiplied by ten to make up the difference in Cell 3). It is possible that the infiltration rate is underestimated, as infiltration losses in porous soils can be enormous. However, due to the uniformity of the infiltration test results, it is considered most likely that the errors in the water balance are due to faulty operation of the inflow and outflow measuring devices.

Hypothetical water balances for Cells 3, 5, 7, and 9 are presented in Table 2-9. To estimate wetland metals and nutrient loading, and conduct additional analyses of wetland operations, it is necessary to prepare a likely balanced scenario of hydrologic inputs and outputs to the wetland cells. In the hypothetical water balance, it is assumed that the cells receive the design inflow of 70 gal/min. Values for precipitation, ET, and infiltration are taken from Table 2-1, converted to units of flow. Outflow is assumed to equal the difference between inputs and outputs, or:

$$\text{Outflow} = \text{Inflow} + \text{Precipitation} - \text{Evapotranspiration} - \text{Infiltration} \quad [2]$$

The percent water loss (i.e., the difference between inflow and outflow, expressed as a percentage of inflow) is estimated for each cell. As shown in Table 2-9, the annual percent water losses range from 9 to 16 percent, with an average value of 12 percent water loss. The hypothetical water balance values from Table 2-9 for January, July, and average annual conditions are also presented in Figure 2-6. As shown in Figure 2-6, the precipitation contribution to total input is significant in winter (8.5 percent of total input) and negligible in summer, while the converse is true of ET (9.9 percent of total output in summer, and less than one percent in winter). Infiltration accounts for about 10 percent of total water output throughout the year.

To verify the assumed values used in the hypothetical water balance, a salt balance was performed. Although salt balances typically are calculated using TDS or chloride as the constituent under consideration, only a few TDS and chloride measurements were made at the SCWDP. However, thousands of electroconductivity (EC) measurements were made, so EC concentrations were used to conduct the salt balance. It can be seen in Table 2-10 that, for an average annual influent EC value of 613.8 μmho/cm (the annual average inflow concentration), the predicted outflow EC concentration is 638.2 μmho/cm, an increase of 4.0 percent. The predicted increase compares favorably to the measured average annual increase of 5.3 percent. For summer conditions, as shown in Table 2-11, an increase of 11.4 percent is predicted, which is relatively close to the measured increase of 9.0 percent. The results of the salt balance provide a measure of assurance that the hypothetical water balance values are reasonably accurate.

TRACER STUDY

Tracer studies were performed on cell 7B from 1995 through 1998, and cell 9B from 1995 through 1997. The tracer studies were conducted to analyze the flow patterns in the wetland cells, to estimate the actual hydraulic residence time, and to evaluate the accuracy of the proposed flow models.

Methods

Lithium chloride with 99 percent purity was used as the tracing element in the tracer studies. Lithium chloride was added to the cell as an evenly-distributed spike input.

Lithium concentrations were then measured at the culvert between the half cells. In 1995 and 1996, baffles were installed along the edges of the wetland cells to control short-circuiting. The baffles consisted of plywood sheets, drilled with holes to allow the movement of mosquitofish. The baffles were evenly distributed along the channels, on both sides of the wetland cells.

Twenty-four pounds of lithium chloride was introduced to Cell 7B in August 1998. Input flow rates were measured weekly, and ranged from 31.6 to 72.3 gal/min. The outflow rates were determined daily, and ranged from 16.8 to 54.9 gal/min.

Results and Discussion

The results of tracer study analyses over the last four years are shown in Table 2-12. An average flow rate was used in 1995-1997 for calculations, but large variations in 1998 flow data prompted using daily flow rates. Low flow rates at the end of the test caused the mean residence time to decrease from 3.7 to 3.5 days when daily flow rates are used. The mean residence time of 3.5 days is the lowest of the four-year study, but low flows also resulted in the highest nominal retention time. This discrepancy can be explained by the low recovery percentage of 41 percent. In the 1997 water balance, a yearly average water loss of 30 percent is computed, leaving 30 percent of the tracer unaccounted for.

In Figure 2-7, tracer data for Cell 7 are plotted as an E curve, the tracer concentration normalized by the amount of tracer recovered, with respect to time (Levenspiel, 1972). Further information on the analysis is presented in the 1995 Annual Report (Nolte and Associates, 1996). A t-test performed on sampling times weighted by the concentration shows, at a 90% confidence level, that the means for 1997 ($p = 0.08$) and 1998 ($p = 0.03$) are lower than for 1996. All the other comparisons were not significantly different. The difference may be attributed to the use of baffles in the 1996 study. The 1995 tracer study also used baffles and had a higher mean residence time, but it was not significantly higher.

Because the vegetation in Cell 7 was not harvested, it can be assumed that the plants have become progressively more dense. If a higher vegetative factor was used, it would increase the nominal retention time and move the plug flow model further from the actual curve. A conclusive statement regarding the effect of increased vegetation on the hydraulics of wetland cannot be made because of the other differences in the tests, such as use of baffles and varying flow rates, that do not allow the change in vegetative density to be isolated.

It is useful to model the flow of the wetland as a known type of bioreactor. Once a reactor model is found that represents the complex wetland system accurately, it is possible to apply properties of that model to the design and operation of the wetland. Two common reactors are the complete-mix reactor (CMR) and the plug flow reactor (PFR). For the CMR, it is assumed that constituent concentrations are homogeneous throughout the reactor. For the PFR, it is assumed that each unit of input progresses through the reactor without mixing, creating a gradient of concentrations along the reactor flow path. Neither of these bioreactor models represents wetland flow patterns exactly, so adaptations to the model must be made. To account for the decreasing concentrations along the flow path and the lag time in the peak concentration, CMRs in series may be considered as a model. The PFR model is adapted by adding a dispersion component.

Tracer study results for Cell 7B in 1998 are compared using several different models in Figure 2-8. Even if the flow models match the measured retention times, the model's relationship to the treatment process is not guaranteed. The wetland tracer studies each have a peak before the mean that matches the CMR in series model; however, the CMR in series model does not characterize the actual flow in the system. The PFR with small dispersion is more representative of the actual wetland conditions, but does not match the tracer output well. The discrepancy can be attributed to the edge effects of the wetland.

Dr. Brad Finney (Humboldt State University) has applied a finite stage model that allows the characterization of major flow features such as short-circuiting and relative dead zones, along with a basic plug flow model. The output of the finite stage model for 1997 and 1998 is shown in Figure 2-9. The close fit is obtained by adjusting the different parameters in the model to match the tracer data. The predictive power of this model is limited by the relationship of the model parameters to the wetland. There is a 20 percent decrease in the fitted value for porosity between 1997 and 1998, but there is no explanation for such a difference in the wetland.

A complex model like that used by Dr. Finney may be used to characterize the hydraulics of a constructed wetland, but further verification beyond HRT and tracer studies is required. True validation of a model requires matching the hydraulics with the treatment kinetics, and comparing the modeled effluent and actual constituent characteristics. This kind of validation requires measuring the wastewater characteristics while performing a tracer study.

DERIVATION OF MANNING'S ROUGHNESS COEFFICIENT

Surveys of wetland bottom surface and water elevations were performed in summer 1997 to identify the frictional characteristics of flow in the surface flow wetland cells.

Introduction

Analysis of flows in open channels has developed over the past century through the use of empirically-derived equations assumed to approximate actual conditions for a given set of assumptions. Open channel flow may be described as laminar or turbulent, steady or unsteady, uniform or varied. Conditions of steady, uniform, turbulent flow are common assumptions for open channel flow analysis and are therefore of greatest interest and applicability to hydraulic analysis (Vennard, 1967, White, 1986).

Flow velocity in steady, uniform, turbulent channel flow can be expressed as a function of the water surface height, the slope of the channel, and a factor for the channel roughness. The Manning equation (Equation 3) is often used to describe flow in an open channel. The Manning coefficient, n, provides a correlation to the channel roughness.

$$v = \frac{1}{n} h^{\frac{2}{3}} s^{\frac{1}{2}} \qquad [3]$$

where:

v = actual flow velocity (m/d)
u = vε = superficial flow velocity (m/d)
ε = volume fraction water (m^3/m^3)
n = Manning roughness coefficient ($s/m^{0.333}$)
h = depth of water within the wetland (m)
s = hydraulic gradient, or slope of the water surface (m/m)

The greatest difficulty in applying open-channel flow equations to natural systems lies in the determination of the coefficient n, for there is no exact method of selecting the n value. Consultation of tabular values of channels of various types yields a maximum open channel Manning n value of 0.29 $s/m^{1/3}$ (Chow, 1959). This value is approximately one order of magnitude less than values determined from actual wetland data (Kadlec, 1996b). The reason for this discrepancy is that for open channel flow equations, it is typically assumed that the frictional resistance occurs only at the bottom and sides of the channel, whereas significant additional flow resistance is present in wetlands due to emergent vegetation and litter. Therefore, in wetland systems the Manning n value is a function of the depth of water because of the resistance imposed by wetland vegetation. The resistance in turn depends on the density of the vegetation, which can vary with location and season. Consequently, there is a need for site-specific estimates of the Manning n value for a range of water depths and vegetation densities.

Although conditions within surface flow wetlands do not entirely satisfy conditions of steady, uniform and turbulent flow; the alternate hydraulic analyses available are considered less appropriate and of far less practical importance to the practicing engineer. The case of uniform flow, described by a constant depth and velocity, is not expected for surface flow wetlands due to the presence of microtopographical effects and internal mixing (Kadlec, 1996a).

There is a fundamental problem with the application of Manning's equation to wetland hydraulics, in that Manning's equation is a correlation for turbulent flows, while wetlands are nearly always in a laminar or transitional flow regime (Kadlec, 1996b). A turbulent flow estimation technique for laminar flow conditions is available; however, it is assumed that the entire frictional resistance is attributed to the channel surface and neglects the presence of plants and litter. The net result of this approach is similar to Equation 3 with the exponents relaxed, and returns flow resistance coefficients the same order of magnitude as derived from the Manning equation.

Steady flow exists when velocity and pressure do not change with time. Although conditions of unsteady flow occur with shutdowns in the delivery of treated effluent to the wetlands, inlet flow during the investigation was continuous. Wetland cells were allowed to equilibrate prior to measurement of elevations and the standard deviation of inlet flows over the entire week preceding the test remained less than seven percent of the average inlet flow during each event. As discussed in the water balance section of this report, the difference between inlet and outlet flows is the result of infiltration and evapotranspiration losses that occur uniformly along the length of the wetland cells.

Methodology

The friction experiments were conducted on wetland cells 3 and 7, as these two cells provide opportunities for a range of flow rates and water depths. The earliest experiment was conducted on April 30, 1997 when new plant growth was emerging, and the final experiment was conducted on September 22, 1997 at the peak of vegetation growth.

A continuous flow was provided to the cells during the experiments, and no shut-downs in delivery of secondary effluent occurred during the period of study. Initial experiments were performed at the typical influent flow rate of 382 m^3/d (70 gal/min). A second set of experiments was conducted at the maximum flow rate of 800 m^3/d (145 gal/min). The recycle pump station that returns Cell 3 effluent to the inlet half-cell was not in operation during the experiments. Surveys of wetland elevations were not conducted for a period of at least one week following adjustments to inlet flow to allow flow to achieve a steady state.

Measurements of both wetland bottom elevation and water depth were made at several locations along the profile of each cell. The influent half-cell was measured at the following locations: 0, 38, 64, 90 m (beginning of middle open water area), 102 m (end of middle open water area), 128, 154, and 192 m. The effluent half-cell was measured at the following locations: 193, 230, 256, 282 m (beginning of middle open water area), 294 m (end of middle open water area), 320, 346, and 384 m. Approximately four measurements of both wetland bottom elevation and water depth were made along the width of the half-cell at each location. The number of measurements taken at each location along the profile was reduced in later friction experiments as the accuracy of the methodology improved.

A Topcon RL-H laser level was used to collect measurements of the wetland bottom and water elevations with respect to a fixed location. A level fitted to the surveyor's rod was used to ensure that the rod remained vertical during the height and depth measurements.

An initial measurement of the outlet structure on the adjacent wetland cell was made to serve as a reference elevation, as the laser level was moved from location to location. The arrangement of surveying equipment utilized for the experiment is considered to be accurate to one-hundredth of an inch.

Wetland bottom elevations were measured by placing the surveyor's rod firmly on the bottom surface and recording the observed elevation. The rod was allowed to settle firmly on sediment bottom without being displaced by detritus or driving it into the sediment. The water depth was measured by marking the location at which the water surface intersected the surveyor's rod. This methodology is consistent with other research where the operative definition of ground level is defined as the location where a standard surveying rod stops when placed firmly on the wetland surface (Kadlec, 1990).

Flow discharged to each wetland cell is measured with a propeller flow meter configured with a flow rate indicator and flow totalizer. The influent flow meter totalizer value was recorded at the start and finish of each experiment to provide an average inflow. Measurement of outlet flow is made using V-notch weirs in combination with ultrasonic level detectors. Calibrated flow measurements are recorded on a datalogger every 15 minutes. Instantaneous outlet flow was recorded at the start and finish of each experiment. Measurements of pan evaporation and vegetation density were coordinated with each friction experiment.

Results

The wetland ground surface and water surface data collected during each survey event were adjusted relative to the reference point and offset by an arbitrary value to indicate positive elevations. If more than one measurement was taken at any one location along the profile, an average wetland ground surface elevation and an average wetland water surface were determined. This method of averaging was thought to reduce any errors in individual measurements. A typical profile of wetland survey data is presented in Figure 2-10 for the May 28, 1997 survey event in Cell 7. A linear regression was applied to determine the ground slope and water surface slope. Two sets of data (Cell 3 and 7 on 4/30/97) indicated discontinuities in the water slope that can only be explained by the wetland cell having not been in steady state when surveyed. Incongruous data of this nature were discarded.

A time averaged observed, or superficial, flow velocity was determined using a linear relationship between the average inlet and average outlet flow rate. An average water depth was used to convert the volumetric flow rate to velocity because of the wide variation in the ground surface elevation. An average water depth was determined from measurements of depth averaged over a 3.0 m grid. A depth of 0.46 m was determined for the typical inlet flow of 382 m^3/d (70 gal/min) and a depth of 0.61 m was determined for the inlet flow of 749 m^3/d (137 gal/min).

The use of a time averaged velocity is considered appropriate for the conditions of steady inflow and outflow, as it accounts for the wide distribution of surface velocities within the wetland (Kadlec, 1996a). However, this superficial velocity reflects the presence of obstructions within the flow path. An actual flow velocity that reflects the volume of the wetland absent litter and stems in the water column is determined by dividing the superficial velocity by the volume fraction of water estimated as described below.

Plant stems and litter occupy a significant fraction of the water column and contribute to frictional resistance to flow. Vegetation density was determined from the average of stem counts identified from nine quadrats located throughout the wetland cell. Vegetation density in Cell 3 was estimated to be approximately 55 stems per square meter when measured in early May. Vegetation density in Cell 7 ranged from approximately 100 stems per square meter in May to approximately 200 stems per square meter in September. An analysis of the volume fraction of water was conducted simultaneous to the collection of vegetation densities by measuring the volume of litter material removed from the quadrats and summing the litter volume with the volume estimated to be occupied by plant stems. Volume fraction estimates for May ranged from approximately 90 percent in Cell 3 to approximately 60 percent in Cell 7. The estimated volume fraction in Cell 7 increased to 86 percent by September as a result of litter decomposition. The difference in vegetation density and volume fraction of water results observed in Cells 3 and 7 in May 1997 reflect the impact of the harvest event conducted in Cell 3 in March.

Estimates of the Manning roughness coefficient n, determined using Equation 3, are presented on Table 2-13. Observed values of n range from 2.1 $s/m^{1/3}$ to 15.1 $s/m^{1/3}$. The head loss between inlet and outlet, determined from the linear regression of the water slope applied to the 384 m wetland length, was observed to range from 0.7 to 7.3 cm.

A comparison of the Manning n values for a variety of reported natural channels, natural wetlands, and treatment wetlands is presented in Table 2-14. The values calculated from the SCWDP are significantly higher than typical values reported for natural open channels, which typically are below 0.5 $s/m^{1/3}$. The values also exceed many values reported in the literature for natural wetlands, but are similar to values reported for densely vegetated treatment wetlands (Kadlec, 1996b).

Increases in flow result in decreased values of the Manning n value as expected; however, the resulting decrease is greater than that anticipated from the inverse relationship of n to flow. An increase in average flow by a factor of 2.3 between the May surveys conducted in Cell 7 at low flow and the June survey conducted at high flow resulted in a 3.2-fold decrease in the Manning n value from 11.4 $s/m^{1/3}$ to 3.6 $s/m^{1/3}$. The discrepancy between the anticipated and observed Manning n values is likely to be a result of the increase in the volume fraction of water at higher flows, as the percentage of the water column occupied by litter will decrease as the water level rises. Because the volume fraction of water estimates were only determined for the low flow condition, the relationship between depth and volume fraction of water is not incorporated into the analysis. A wide band of error in the vegetation measurements may also contribute to the discrepancy. No change was observed in the Manning value when flows were raised in Cell 3. This unexpected result may be due in part to the fact that the volume fraction of water estimates were significantly greater in this cell due to harvesting than observed in Cell 7, which has never been harvested.

The influence of increased flow on the roughness coefficient can be observed with comparison of the SCWDP results to those reported by Hall and Freeman. The latter research, conducted at significantly higher flow rates than those observed at Sacramento, resulted in Manning values an order of magnitude lower than those observed at Sacramento for similar vegetation densities.

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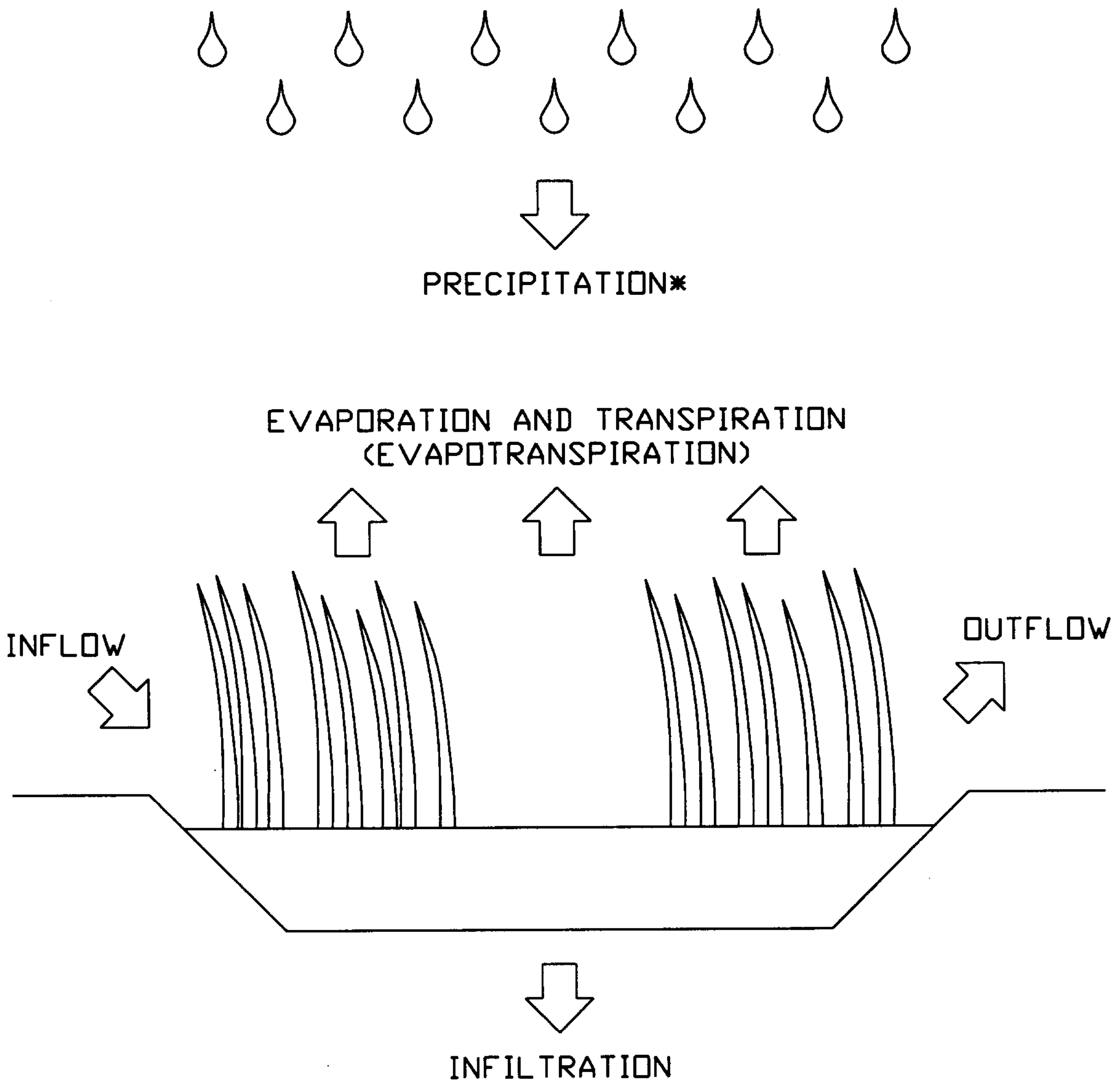
INFLOW + PRECIPITATION =

OUTFLOW + EVAPOTRANSPIRATION + INFILTRATION



* PRECIPITATION INCLUDES
DIRECT RUNOFF INTO CELL

FIGURE 2-1

WATER BALANCE COMPONENTS

SACRAMENTO CONSTRUCTED
WETLANDS DEMONSTRATION PROJECT

NOLTE
BEYOND ENGINEERING

PATH: N:\SA1185\03\5YR\TAB\WATER.DWG

TABLE 2-1
SUMMARY OF HYDROLOGIC DATA
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

	Inflow by Cell[a], gal/min											Outflow by Cell[b], gal/min											Precip.[c]	ET[d]	Infiltration by Cell[e], gal/min			
Month	1	2	3	4	5	6A	6B	7	8	9	10	11	1	2	3	4	5	6A	6B	7	8	9	10	11	gal/cell min	gal/cell min	3	5	7	9
Jan-96	68	70	-	69	68	42	46	65	-	65	67	68	-	-	-	-	-	-	-	41	-	-	-	-	4.1	-	-	-	-	-
Feb-96	68	70	70	68	68	40	46	64	-	66	68	68	-	-	-	-	-	-	-	41	-	-	-	-	5.8	-	-	-	-	-
Mar-96	71	70	59	70	51	41	45	68	-	66	65	65	-	-	-	-	-	-	-	41	-	-	-	-	1.7	-	-	-	-	-
Apr-96	72	71	72	70	-	38	43	70	-	70	71	69	-	-	-	-	-	-	-	41	-	-	-	-	1.3	-	-	-	-	-
May-96	71	74	73	70	-	37	43	67	-	67	70	69	-	-	-	-	-	-	-	41	-	-	-	-	0.8	-	-	-	-	-
Jun-96	74	68	75	73	-	33	42	72	-	70	75	73	-	-	-	-	-	-	-	41	-	-	-	-	0.0	-	-	-	-	-
Jul-96	70	72	70	70	-	26	40	68	-	65	71	70	-	-	-	-	-	-	-	41	-	-	-	-	0.0	-	-	-	-	-
Aug-96	74	74	73	71	70	26	43	71	-	70	73	74	-	-	-	-	-	-	-	41	-	-	-	-	0.0	-	-	-	-	-
Sep-96	72	72	72	72	69	0	0	70	-	68	-	75	-	-	-	-	-	-	-	41	-	-	-	-	0.0	-	-	-	-	-
Oct-96	74	74	74	71	67	49	32	69	-	67	-	72	-	-	-	-	-	-	-	40	-	-	-	-	0.7	-	-	-	-	-
Nov-96	-	-	-	-	-	-	-	70	-	-	-	-	-	-	-	-	-	-	-	34	-	-	-	-	2.0	-	-	-	-	-
Dec-96	-	-	-	-	-	-	-	70	-	-	-	-	-	-	-	-	-	-	-	46	-	-	-	-	6.3	-	-	-	-	-
96 Avg.	71	71	71	70	65	33	38	69	-	67	70	70	-	-	-	-	-	-	-	40	-	-	-	-	1.9	-	-	-	-	-
Jan-97	45	46	45	45	67	-	-	47	-	44	-	43	-	-	37	-	60	-	-	47	-	52	-	-	9.0	-	-	-	-	-
Feb-97	65	70	67	67	71	-	-	64	-	64	-	65	-	-	40	-	53	-	-	38	-	47	-	-	0.3	-	-	-	-	-
Mar-97	71	77	54	67	70	17	17	60	-	60	-	69	-	-	20	-	44	-	-	30	-	37	-	-	0.6	-	-	-	-	-
Apr-97	65	69	66	75	62	18	37	53	-	51	-	65	-	-	39	-	33	-	-	1	-	-	-	-	0.2	-	-	-	-	-
May-97	70	71	69	72	73	18	39	68	-	72	-	60	-	-	68	-	45	-	-	42	-	-	-	-	0.3	-	-	-	-	-
Jun-97	27	55	84	56	71	18	40	100	-	53	-	73	-	-	64	-	43	-	-	67	-	-	-	-	0.6	-	-	-	-	-
Jul-97	70	75	72	72	72	18	34	70	-	64	-	72	-	-	49	-	40	-	-	38	-	-	-	-	0.0	-	-	-	-	-
Aug-97	75	79	76	75	75	18	36	74	-	43	-	70	-	-	45	-	46	-	-	47	-	-	-	-	0.3	-	-	-	-	-
Sep-97	64	68	67	65	74	17	31	66	-	67	-	60	-	-	38	-	49	-	-	49	-	45	-	-	0.2	-	-	-	-	-
Oct-97	75	75	76	65	76	17	33	72	-	71	-	67	-	-	45	-	50	-	-	61	-	45	-	-	0.8	-	-	-	-	-
Nov-97	69	74	70	68	72	17	35	70	-	70	-	71	-	-	52	-	45	-	-	34	-	48	-	-	4.7	-	-	-	-	-
Dec-97	67	67	70	61	68	16	35	-	-	68	-	72	-	-	48	-	39	-	-	28	-	45	-	-	2.9	-	-	-	-	-
97 Avg.	64	69	68	66	71	17	34	68	-	61	-	66	-	-	45	-	46	-	-	40	-	46	-	-	1.7	-	-	-	-	-
Jan-98	50	54	52	48	49	45	124	50	-	53	-	47	-	-	31	-	35	-	-	30	-	50	-	-	6.3	0.4	5.2	6.9	10.1	6.9
Feb-98	52	73	60	69	67	67	165	51	-	72	-	71	-	-	2	-	52	-	-	33	-	53	-	-	10.9	0.8	5.2	6.9	10.1	6.9
Mar-98	26	33	43	33	43	31	85	52	-	70	-	38	-	-	7	-	14	-	-	31	-	35	-	-	2.4	2.3	5.2	6.9	10.1	6.9
Apr-98	64	74	83	81	69	57	165	53	-	70	-	84	-	-	13	-	47	-	-	62	-	46	-	-	1.1	3.4	5.2	6.9	10.1	6.9
May-98	67	59	46	72	71	0	74	54	-	70	-	75	-	-	0	-	19	-	-	45	-	63	-	-	3.0	3.8	5.2	6.9	10.1	6.9
Jun-98	65	47	65	69	61	0	113	55	-	61	-	70	-	-	0	-	41	-	-	38	-	50	-	-	0.6	5.7	5.2	6.9	10.1	6.9
Jul-98	39	14	40	45	44	0	78	56	-	45	-	43	-	-	8	-	17	-	-	19	-	24	-	-	0.0	7.0	5.2	6.9	10.1	6.9
Aug-98	30	42	46	48	60	0	121	57	-	46	-	45	-	-	12	-	12	-	-	21	-	27	-	-	0.0	6.5	5.2	6.9	10.1	6.9
Sep-98	19	37	78	79	71	0	197	58	-	73	-	75	-	-	36	-	18	-	-	44	-	44	-	-	0.2	4.4	5.2	6.9	10.1	6.9
Oct-98	2	9	49	48	68	0	86	59	-	46	-	47	-	-	26	-	18	-	-	32	-	37	-	-	0.8	2.9	5.2	6.9	10.1	6.9
Nov-98	0	19	73	1	68	0	188	60	-	69	-	76	-	-	42	-	18	-	-	47	-	50	-	-	2.9	1.0	5.2	6.9	10.1	6.9
Dec-98	42	65	66	-	65	0	95	61	-	66	-	76	-	-	39	-	16	-	-	28	-	50	-	-	0.6	0.7	5.2	6.9	10.1	6.9
98 Avg.	38	44	58	54	61	17	124	55	-	62	-	62	-	-	18	-	26	-	-	36	-	44	-	-	2.4	3.2	5.2	6.9	10.1	6.9
Total Avg.	57	61	65	63	66	22	69	64	-	63	70	66	-	-	32	-	36	-	-	39	-	45	-	-	2.0	3.2	5.2	6.9	10.1	6.9

[a] Erroneous low inflow values occuring in Cell 9 during March, April, and May 1998 have been replaced by the design inflow value of 70 gal/min.

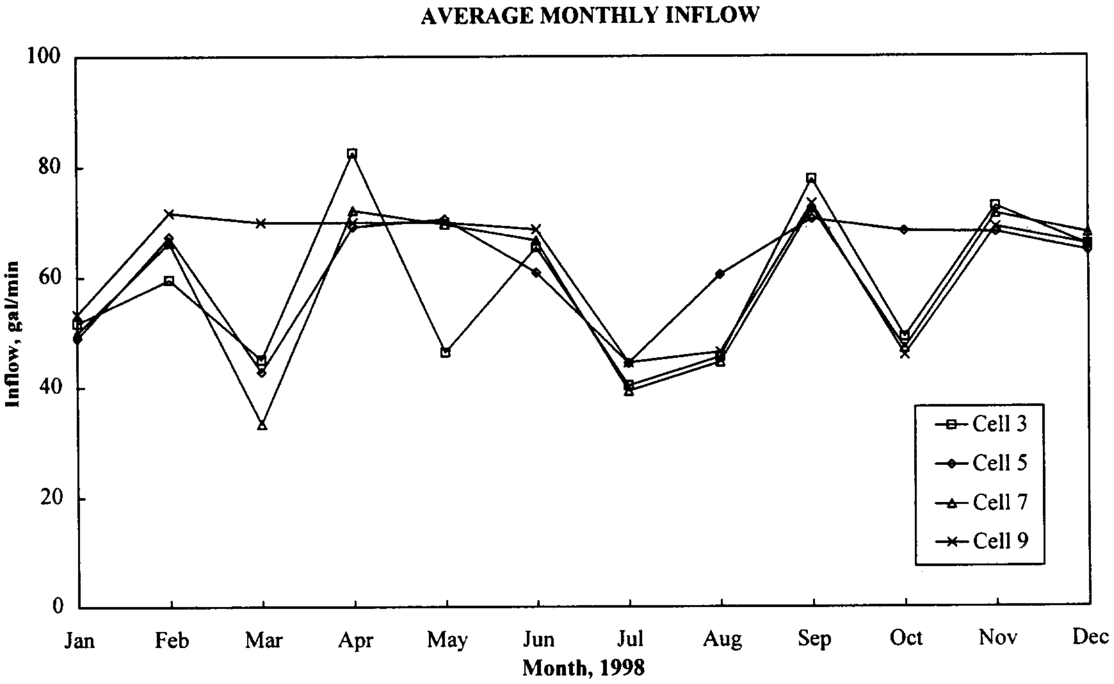
[b] Erroneous high effluent values occurring in 1998 have been replaced by values interpolated between reliable measurements.

[c] Precipitation flow based on precipitation data from Sacramento Executive Airport weather station (NOAA Climatological Data Annual Summary), using assumed wetland cell area of 1260 ft x 50 ft, plus 3 ft of catchment area around all four sides (i.e., total assumed cell area is 1266 ft x 56 ft).

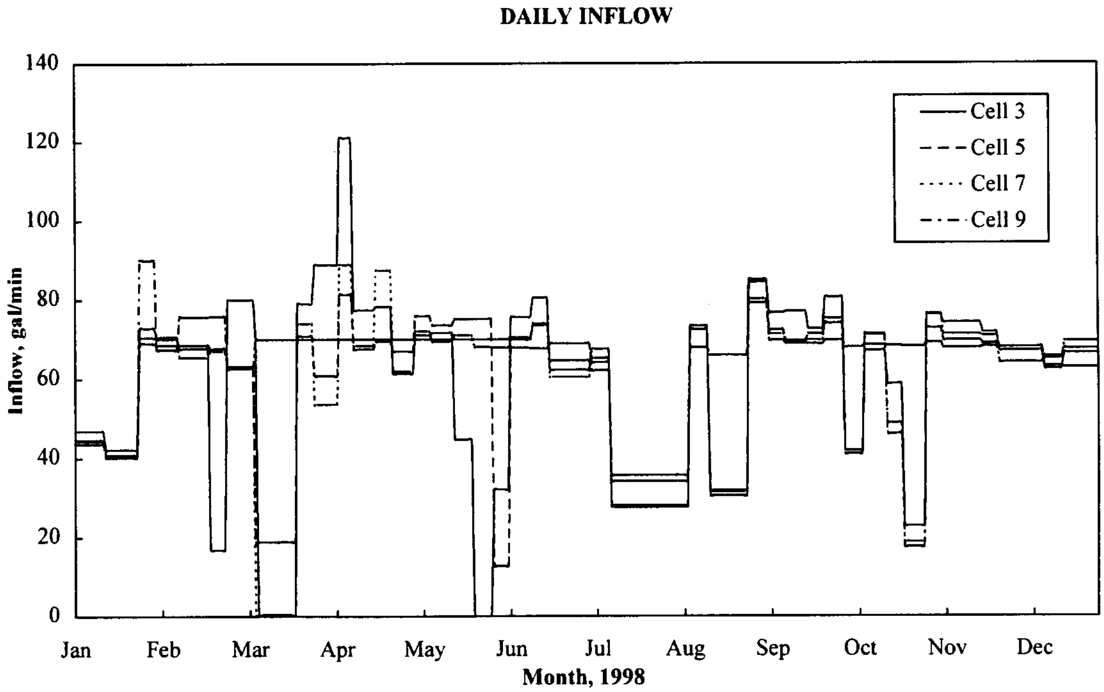
[d] Evapotranspiration flow based on reference evapotranspiration from Fair Oaks CIMIS station, using assumed wetland cell area of 1260 ft x 50 ft.

[e] Infiltration flow for cells 3, 5, 7, and 9 based on measured rates of 0.0079, 0.0105, 0.0154, and 0.0105 in/hr, respectively, using assumed wetland cell area of 1260 ft x 50 ft.

FIGURE 2-2
AVERAGE MONTHLY AND DAILY INFLOW FOR WETLAND CELLS 3, 5, 7, AND 9 IN 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

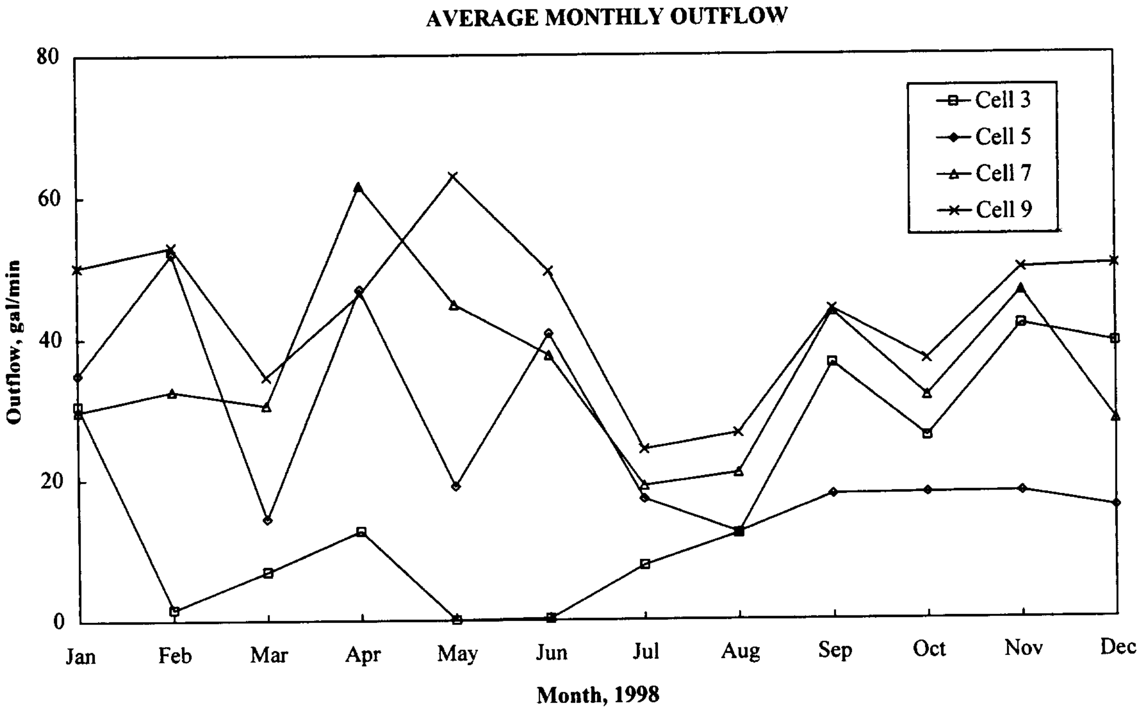


(a)

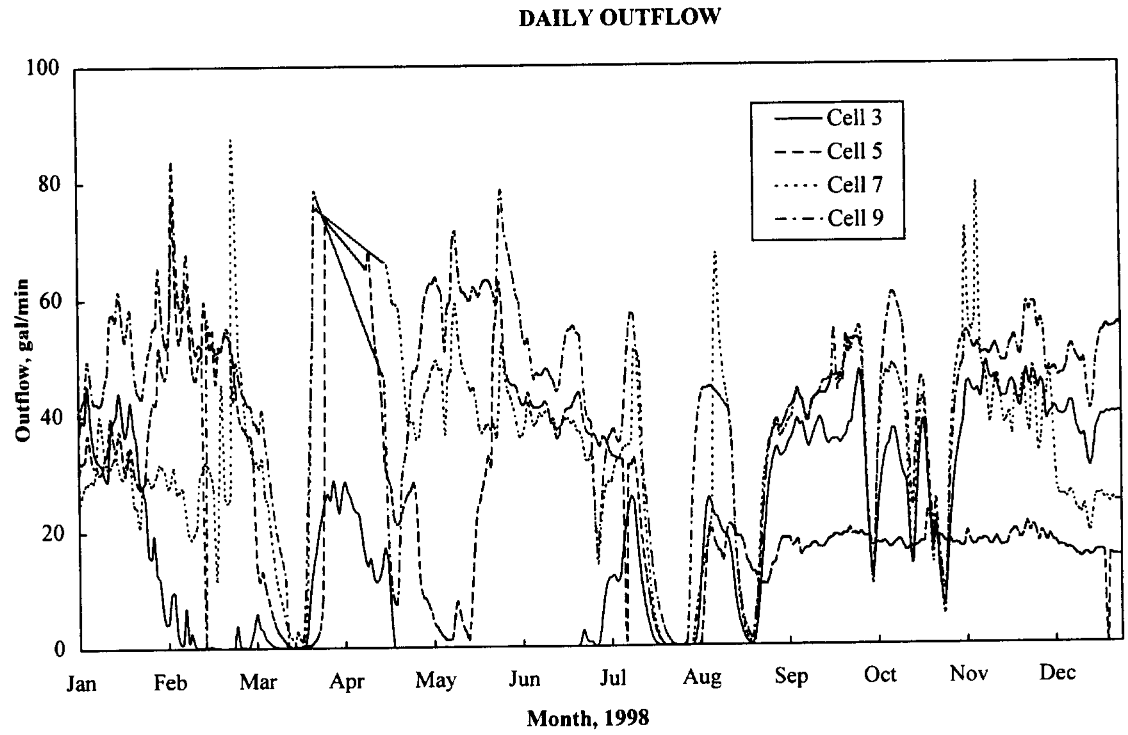


(b)

FIGURE 2-3
AVERAGE MONTHLY AND DAILY OUTFLOW FOR WETLAND CELLS 3, 5, 7, AND 9 IN 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT



(a)



(b)

TABLE 2-2

SUMMARY OF LONG-TERM PRECIPITATION DATA SACRAMENTO CONSTRUCTED WETLAND DEMONSTRATION PROJECT[a]

	Average Precipitation[b]		30-year Avg. Precip.[c]	
	Sac. Exec.	Sac. Dntn.	Sac. Exec.	Sac. Dntn.
Month	FAA Apt.[d]	WSO CI[e]	FAA Apt.	WSO CI
Years	56	120	30	30
Jan	3.60	3.66	3.73	3.85
Feb	2.85	3.13	2.87	2.98
Mar	2.44	2.66	2.57	2.79
Apr	1.15	1.41	1.16	1.24
May	0.40	0.59	0.27	0.29
Jun	0.15	0.16	0.12	0.12
Jul	0.03	0.01	0.05	0.05
Aug	0.06	0.03	0.07	0.07
Sep	0.33	0.31	0.37	0.37
Oct	0.91	0.91	1.08	1.12
Nov	2.12	1.99	2.72	2.97
Dec	2.91	3.16	2.51	2.76
Total	16.95	18.02	17.52	18.61

[a] SCWDP site located at 38.45 N, 121.45 W.

[b] Precipitation data from NCDC *Summary of the Day*, EarthInfo.

[c] Precipitation data from NCDC *Monthly Station Normals for 1961-1990.*

[d] Sacramento Executive FAA Airport station located at 38.52 °N, 121.50 °W, NW of SCWDP.

[e] Sacramento Downtown WSO station located at 38.58 °N, 121.50 °W, NW of SCWDP.

TABLE 2-3
SUMMARY OF PRECIPITATION DATA 1994 - 1998
SACRAMENTO CONSTRUCTED WETLAND DEMONSTRATION PROJECT

		NCDC stations		CIMIS stations			
Month	Wetland[a]	Sac. Exec. FAA Apt.[b]	Sac. Dntn. WSO CI[c]	Dixon[d]	Davis[e]	Lodi[f]	Fair Oaks[g]
Jan-94	-	2.12	3.17	-	2.20	1.93	-
Feb-94	-	3.15	3.17	-	3.15	4.09	-
Mar-94	-	0.05	0.07	-	0.08	1.69	-
Apr-94	-	0.67	0.80	-	0.75	0.98	-
May-94	-	1.68	1.65	-	1.02	1.65	-
Jun-94	-	0.00	0.00	-	0.00	0.00	-
Jul-94	-	0.00	0.00	-	0.00	0.00	-
Aug-94	-	0.00	0.00	-	0.00	0.00	-
Sep-94	-	0.00	0.00	-	0.24	0.12	-
Oct-94	-	0.00	0.45	0.30	0.63	0.63	-
Nov-94	-	0.71	3.96	3.81	3.90	2.32	-
Dec-94	-	2.68	3.54	2.58	2.24	1.54	-
Total	-	11.06	16.81	-	14.21	14.95	-
Jan-95	-	8.81	-	11.57	6.69	9.72	-
Feb-95	-	0.20	0.19	0.11	0.31	0.63	-
Mar-95	-	8.13	7.84	8.69	7.87	6.97	-
Apr-95	-	1.46	1.90	1.29	0.94	1.54	-
May-95	-	1.06	1.01	0.61	1.14	0.75	-
Jun-95	-	0.47	0.53	0.65	0.79	0.31	-
Jul-95	-	0.00	0.01	0.01	0.04	0.00	-
Aug-95	-	0.00	0.00	0.00	0.24	0.00	-
Sep-95	-	0.00	0.00	0.00	0.00	0.00	-
Oct-95	-	0.00	0.00	0.03	0.00	0.00	-
Nov-95	-	0.00	0.00	0.02	0.00	0.00	-
Dec-95	-	5.49	5.14	6.93	4.80	3.15	-
Total	-	25.62	-	29.91	22.82	23.07	-
Jan-96	5.73	4.16	3.30	5.41	4.65	5.12	-
Feb-96	6.66	5.49	6.09	6.04	6.10	4.06	-
Mar-96	2.52	1.73	2.30	1.73	2.24	2.68	-
Apr-96	2.40	1.25	1.93	1.53	1.69	1.46	-
May-96	0.92	0.79	2.22	2.11	2.48	1.77	-
Jun-96	0.00	0.00	0.00	0.00	0.04	0.20	-
Jul-96	0.03	0.00	0.00	0.00	0.08	0.00	-
Aug-96	0.00	0.00	0.00	0.00	0.12	0.00	-
Sep-96	0.00	0.00	0.00	0.00	0.12	0.00	-
Oct-96	0.39	0.67	0.76	1.08	1.42	1.65	-
Nov-96	1.26	1.97	1.49	1.73	1.46	2.40	-
Dec-96	7.10	6.39	5.83	7.85	5.04	5.98	-
Total	27.01	22.45	23.92	27.48	25.44	25.32	-

TABLE 2-3 (CONTINUED)
SUMMARY OF PRECIPITATION DATA 1994 - 1998
SACRAMENTO CONSTRUCTED WETLAND DEMONSTRATION PROJECT

		NCDC stations		CIMIS stations			
Month	Wetland[a]	Sac. Exec. FAA Apt.[b]	Sac. Dntn. WSO CI[c]	Dixon[d]	Davis[e]	Lodi[f]	Fair Oaks[g]
Jan-97	9.49	9.05	7.68	9.62	7.32	7.48	-
Feb-97	-	0.28	0.26	0.31	0.28	0.35	-
Mar-97	-	0.34	0.58	0.59	0.43	0.31	-
Apr-97	0.00	0.18	0.28	0.06	0.12	0.39	-
May-97	0.00	0.35	0.35	0.70	0.35	0.35	-
Jun-97	0.01	0.59	0.53	0.12	0.20	0.31	-
Jul-97	0.00	0.00	0.00	0.00	0.20	0.00	0.00
Aug-97	0.00	0.32	0.21	0.19	0.16	0.08	0.36
Sep-97	0.16	0.16	0.18	0.05	0.35	0.00	0.05
Oct-97	0.00	0.82	1.01	0.43	0.43	0.59	1.28
Nov-97	-	4.56	4.67	3.91	4.25	3.62	4.00
Dec-97	-	2.91	2.64	1.91	2.20	2.72	3.09
Total	-	19.56	18.39	17.89	16.29	16.20	-
Jan-98	1.26	6.40	6.79	5.15	4.88	6.73	7.69
Feb-98	10.23	9.95	9.43	10.18	11.73	11.38	11.85
Mar-98	3.30	2.47	2.55	1.83	1.85	3.15	3.44
Apr-98	1.56	1.05	1.44	0.80	1.26	1.69	2.00
May-98	1.03	2.98	3.04	2.46	2.32	3.31	4.49
Jun-98	0.35	0.58	0.29	0.12	0.08	0.16	0.06
Jul-98	0.03	0.00	0.00	0.00	0.04	0.00	0.00
Aug-98	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Sep-98	0.19	0.23	0.30	0.43	0.47	0.04	0.30
Oct-98	0.45	0.76	0.81	0.55	0.67	0.98	0.83
Nov-98	3.04	2.84	3.60	2.76	2.44	3.46	4.19
Dec-98	0.26	0.58	0.65	0.72	0.63	0.67	0.81
Total	21.72	27.84	28.90	25.00	26.37	31.57	35.66

[a] SCWDP site located at 38.45 N, 121.45 W.

[b] Sacramento Executive FAA Airport station located at 38.52 °N, 121.50 °W, NW of SCWDP.

[c] Sacramento Downtown WSO station located at 38.58 °N, 121.50 °W, NW of SCWDP.

[d] Dixon CIMIS station located at 38.42 N, 121.79 W, SW of SCWDP.

[e] Davis CIMIS station located at 38.54 N, 121.78 W, NW of SCWDP.

[f] Lodi CIMIS station located at 38.11 N, 121.35 W, SE of SCWDP.

[g] Fair Oaks CIMIS station located at 38.65 N, 121.22 W, NE of SCWDP.

TABLE 2-4

SUMMARY OF LONG-TERM EVAPOTRANSPIRATION AND PAN EVAPOTRANSPIRATION DATA SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT[a]

	CIMIS ETo				NCDC/EarthInfo (pan)				ETo maps (UC 21426)	
Month	Dixon[b]	Davis[c]	Lodi[d]	Fair Oaks[e]	Walnut Grove[f]	Davis[g]	Lodi[h]	Folsom Dam[i]	Sacra-mento	Rose-ville
Years	5	17	16	2	6	49	49	39	NA	NA
Jan	0.65	1.08	0.86	0.56	1.53	1.43	1.24	0.92	1.0	1.1
Feb	1.38	1.80	1.68	1.05	2.90	2.33	1.94	1.90	1.8	1.7
Mar	3.23	3.49	3.36	2.78	4.74	4.41	3.85	3.47	3.2	3.1
Apr	5.23	5.54	5.29	4.37	5.73	7.01	5.99	5.21	4.7	4.7
May	6.27	7.22	6.80	6.05	7.76	10.04	8.64	7.95	6.4	6.2
Jun	7.68	8.38	7.65	7.00	10.04	12.11	9.96	9.91	7.7	7.7
Jul	8.24	8.55	7.91	7.97	10.22	12.74	10.66	11.12	8.4	8.5
Aug	7.18	7.63	6.94	6.96	8.81	11.23	9.08	9.93	7.2	7.3
Sep	5.43	5.86	5.21	5.12	6.40	9.04	6.77	7.45	5.4	5.6
Oct	4.04	4.29	3.39	3.26	3.60	6.23	4.20	4.89	3.7	3.7
Nov	1.61	2.09	1.54	1.06	2.10	2.89	1.87	2.06	1.7	1.7
Dec	0.89	1.17	0.83	0.85	1.32	1.43	1.06	1.25	0.9	1.0
Total	51.83	57.09	51.47	47.00	65.15	80.89	65.26	66.06	52.1	52.3

[a] SCWDP site located at 38.45 N, 121.45 W.

[b] Dixon CIMIS station located at 38.42 N, 121.79 W, SW of SCWDP.

[c] Davis CIMIS station located at 38.54 N, 121.78 W, NW of SCWDP.

[d] Lodi CIMIS station located at 38.11 N, 121.35 W, SE of SCWDP.

[e] Fair Oaks CIMIS station located at 38.65 N, 121.22 W, NE of SCWDP.

[f] Walnut Grove pan evaporation station located at 38.23 N, 121.52 W, SW of SCWDP.

[g] Davis pan evaporation station located at 38.53 N, 121.77 W, NW of SCWDP.

[h] Lodi pan evaporation station located at 38.12 N, 121.28 W, SE of SCWDP.

[i] Folsom Dam pan evaporation station located at 38.70 N, 121.17 W, NE of SCWDP.

TABLE 2-5
SUMMARY OF REFERENCE EVAPOTRANSPIRATION DATA 1994 - 1998
SACRAMENTO CONSTRUCTED WETLAND DEMONSTRATION PROJECT[a]

	CIMIS stations			
Month	Dixon[b]	Davis[c]	Lodi[d]	Fair Oaks[e]
Jan-94	-	1.06	0.65	-
Feb-94	-	1.65	1.39	-
Mar-94	-	4.04	3.61	-
Apr-94	-	5.31	4.85	-
May-94	-	6.41	6.03	-
Jun-94	-	8.75	7.89	-
Jul-94	-	8.19	7.58	-
Aug-94	-	7.57	7.08	-
Sep-94	-	5.40	4.84	-
Oct-94	4.01	4.05	3.20	-
Nov-94	1.87	1.76	1.34	-
Dec-94	0.53	0.42	0.33	-
Total	-	54.61	48.79	-
Jan-95	0.68	0.51	0.51	-
Feb-95	0.92	0.94	0.83	-
Mar-95	2.61	2.59	2.22	-
Apr-95	4.66	4.89	4.31	-
May-95	5.80	5.94	5.85	-
Jun-95	7.70	7.86	7.22	-
Jul-95	8.37	8.13	7.42	-
Aug-95	7.76	7.48	7.05	-
Sep-95	5.46	5.24	4.96	-
Oct-95	4.68	4.80	3.21	-
Nov-95	2.19	2.24	1.65	-
Dec-95	0.63	0.57	0.48	-
Total	51.46	51.19	45.71	-
Jan-96	0.72	0.68	0.54	-
Feb-96	1.24	1.12	1.12	-
Mar-96	3.58	3.37	3.18	-
Apr-96	5.16	5.16	4.81	-
May-96	6.31	6.90	6.40	-
Jun-96	7.84	8.38	7.67	-
Jul-96	8.55	8.75	8.38	-
Aug-96	7.33	7.70	7.11	-
Sep-96	5.36	5.83	4.93	-
Oct-96	3.94	4.37	3.22	-
Nov-96	1.59	1.64	1.11	-
Dec-96	0.82	0.87	0.49	-
Total	52.44	54.77	48.96	-
Jan-97	0.73	0.79	0.55	-
Feb-97	2.51	2.57	2.10	-
Mar-97	4.20	4.55	4.13	-
Apr-97	6.02	6.52	5.96	-
May-97	7.45	7.80	7.47	7.18
Jun-97	8.09	8.18	7.45	7.27
Jul-97	7.93	8.27	7.84	7.87
Aug-97	6.82	7.33	6.68	6.65
Sep-97	5.97	6.35	5.35	5.43
Oct-97	3.57	4.14	3.23	3.18
Nov-97	1.21	1.26	0.99	1.04
Dec-97	1.17	1.20	0.80	0.87
Total	55.67	58.96	52.55	-
Jan-98	0.27	0.35	0.30	0.51
Feb-98	0.75	0.81	0.74	0.87
Mar-98	2.79	2.96	2.69	2.65
Apr-98	4.27	4.58	4.02	3.69
May-98	4.14	4.30	4.31	4.32
Jun-98	6.89	7.02	6.48	6.25
Jul-98	7.95	8.15	7.72	7.91
Aug-98	6.97	7.24	7.03	7.41
Sep-98	4.94	5.23	4.72	4.80
Oct-98	4.02	4.21	3.14	3.33
Nov-98	1.21	1.20	0.96	1.07
Dec-98	1.28	1.22	0.83	0.83
Total	45.48	47.27	42.94	43.64

[a] SCWDP site located at 38.45 N, 121.45 W.

[b] Sacramento Executive FAA Airport station located at 38.52 °N, 121.50 °W, NW of SCWDP.

[c] Sacramento Downtown WSO station located at 38.58 °N, 121.50 °W, NW of SCWDP.

[d] Dixon CIMIS station located at 38.42 N, 121.79 W, SW of SCWDP.

[e] Davis CIMIS station located at 38.54 N, 121.78 W, NW of SCWDP.

[f] Lodi CIMIS station located at 38.11 N, 121.35 W, SE of SCWDP.

[g] Fair Oaks CIMIS station located at 38.65 N, 121.22 W, NE of SCWDP.

TABLE 2-6

MONTHLY EVAPOTRANSPIRATION AND EVAPORATION IN 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

		Evaporation, in													
	CIMIS	Wetland Cell (Open Water Area Pans)							Wetland Cell (Vegetated Area Pans)						
Month	ET[a], in	3A	3B	5A	5B	7A	7B	Avg	3A	3B	5A	5B	7A	7B	Avg
Jan	0.51	0.3	0.6	0.5	0.5	0.2	0.6	0.4	0.0	0.3	0.4	0.0	0.0	0.1	0.2
Feb	0.87	1.2	1.7	1.6	1.6	1.3	1.8	1.5	0.3	1.2	1.5	0.4	0.8	0.5	0.8
Mar	2.65	3.4	3.5	4.0	3.8	3.7	3.7	3.7	1.2	2.5	1.8	1.2	2.3	1.3	1.7
Apr	3.69	6.2	4.6	7.7	6.3	7.3	7.5	6.6	2.6	3.3	3.9	2.7	2.6	2.3	2.9
May	4.32	5.8	6.9	6.8	5.9	7.4	6.4	6.5	1.7	2.7	4.0	3.0	1.7	2.7	2.6
Jun	6.25	6.4	7.3	8.2	6.1	7.2	5.9	6.8	1.6	4.8	3.3	2.7	1.9	2.8	2.8
Jul	7.91	8.2	9.6	9.8	7.4	9.2	5.7	8.3	1.9	5.0	4.2	3.0	2.4	3.0	3.3
Aug	7.41	6.7	9.5	9.7	5.9	7.6	5.4	7.5	1.5	4.3	5.2	2.1	1.8	2.5	2.9
Sep	4.80	4.5	6.0	6.3	4.1	4.1	3.3	4.7	2.0	2.5	4.1	1.5	1.0	1.9	2.2
Oct	3.33	3.1	4.8	3.8	3.3	3.7	3.4	3.7	1.4	1.6	1.0	1.4	0.8	1.0	1.2
Nov	1.07	0.8	2.8	1.0	1.2	1.9	1.9	1.6	0.5	0.5	0.0	0.6	0.6	0.5	0.5
Dec	0.83	0.2	1.9	0.7	0.7	1.5	1.5	1.1	0.3	0.2	0.0	0.2	0.1	0.3	0.2
Total	43.64	46.9	59.1	60.0	46.8	55.2	47.1	52.5	15.0	29.1	29.4	18.9	16.0	18.9	21.2

[a] ET data from Fair Oaks CIMIS station, located approximately sixteen miles northeast of the wetland site.

FIGURE 2-4
MONTHLY EVAPOTRANSPIRATION AND EVAPORATION IN 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

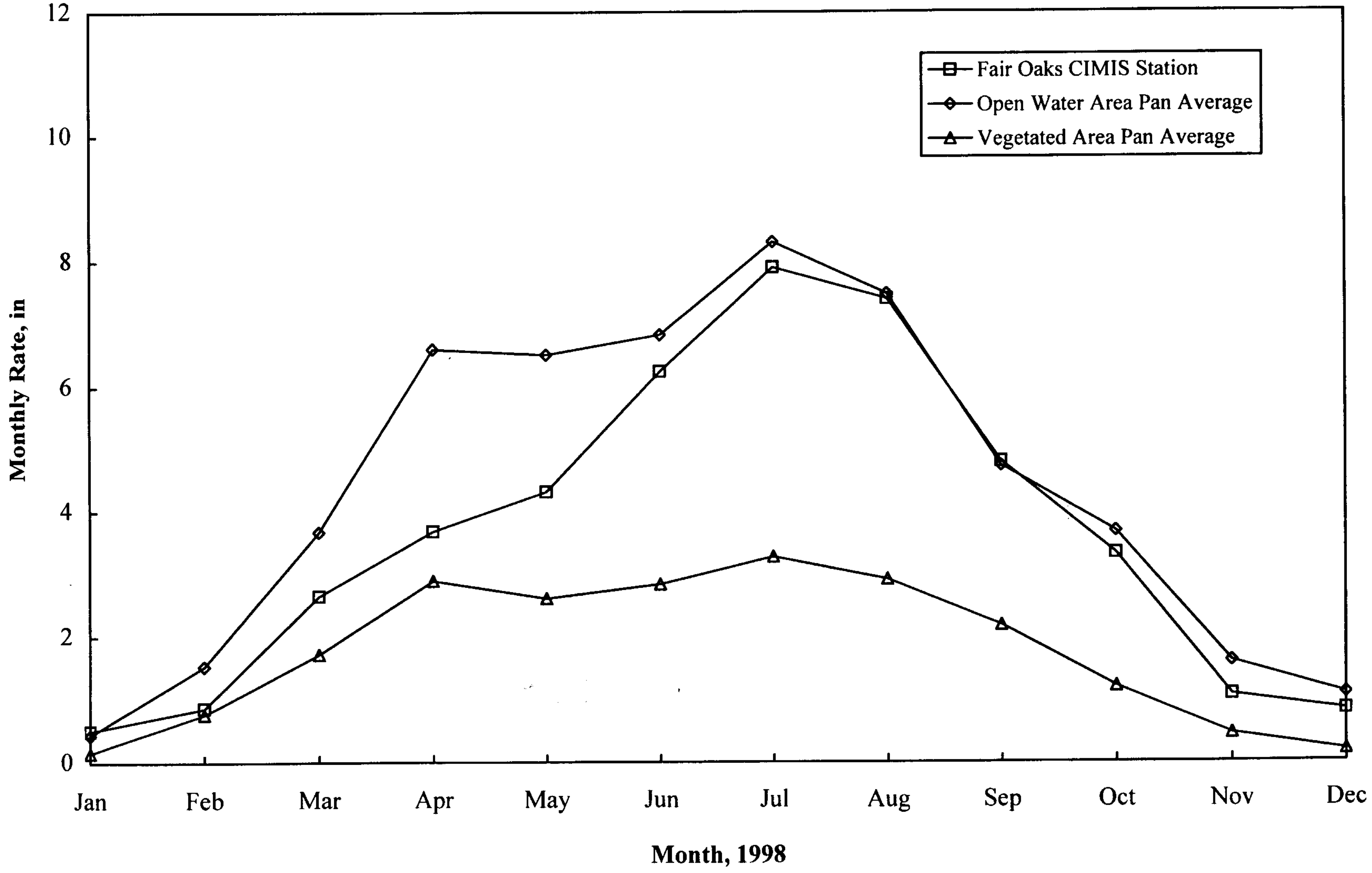


TABLE 2-7

INFILTRATION RATES FOR SOILS AT WETLAND SITE SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

Soil type[a]	Permeability	Rate, in/hr
Galt Clay	slow	0.2 - 0.06
Madera Loam	very slow	< 0.06
San Joaquin Silt Loam	very slow	< 0.06
Clear Lake Clay	slow	0.2 - 0.06

[a] Values from 1993 Soil Conservation Service Soil Survey of Sacramento County.

[b] In 1954, the Soil Conservation Service Soil Survey of Sacramento Area identified the site soils as Alamo Clay, San Joaquin Loam, and Freeport Clay.

FIGURE 2-5
RESULTS OF WETLAND CELL INFILTRATION TEST CONDUCTED MARCH 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT
(WATER LEVEL MEASURED AT NORTH END, SOUTH END, AND MIDDLE OF EACH CELL)

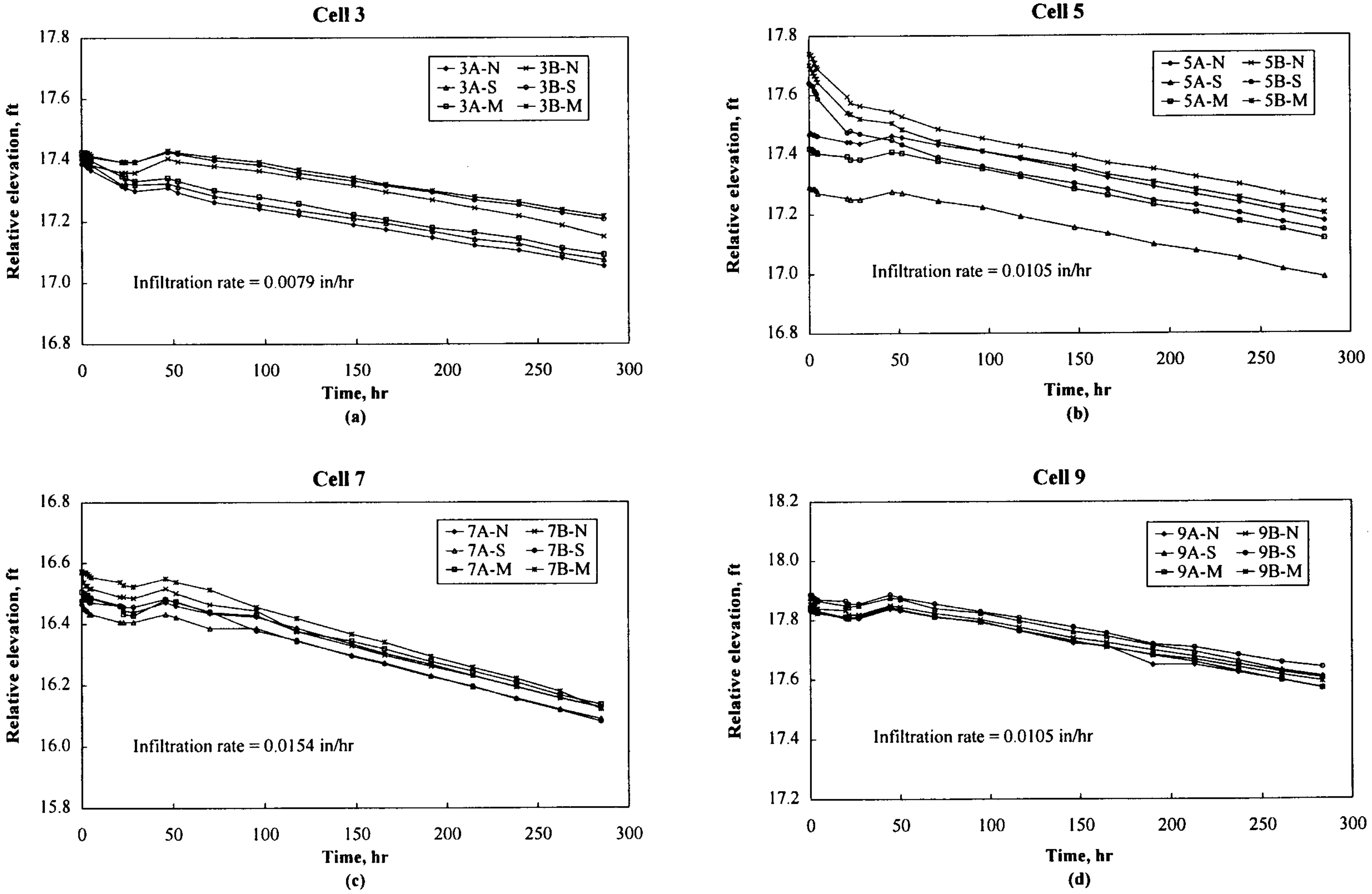


TABLE 2-8
WATER BALANCE FOR CELLS 3, 5, 7, AND 9 IN 1998[a]
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

CELL 3

	Inflow		Outflow		Precipita-tion, in	ET, in	Infiltra-tion, in	Σ In, in	Σ Out, in	Error, percent
Month	Mgal	in	Mgal	in						
Jan	2.31	58.7	1.36	34.7	6.40	0.51	5.9	65	41	-37
Feb	2.40	61.2	0.06	1.6	9.95	0.87	5.3	71	8	-89
Mar	1.91	48.6	0.31	7.9	2.47	2.65	5.9	51	16	-68
Apr	3.57	90.9	0.55	13.9	1.05	3.69	5.7	92	23	-75
May	2.07	52.7	0.00	0.0	2.98	4.32	5.9	56	10	-82
Jun	2.83	72.0	0.01	0.2	0.58	6.25	5.7	73	12	-83
Jul	1.80	45.8	0.35	8.8	0.00	7.91	5.9	46	23	-51
Aug	2.03	51.8	0.55	13.9	0.00	7.41	5.9	52	27	-47
Sep	3.36	85.6	1.58	40.1	0.23	4.80	5.7	86	51	-41
Oct	2.19	55.9	1.16	29.5	0.76	3.33	5.9	57	39	-32
Nov	3.15	80.1	1.81	46.0	2.84	1.07	5.7	83	53	-36
Dec	2.94	74.8	1.75	44.5	0.58	0.83	5.9	75	51	-32
Total	30.56	778.0	9.48	241.3	27.84	43.64	69.2	806	354	-56
Average	2.55	64.8	0.79	20.1	2.32	3.64	5.8	67	30	-56

CELL 5

	Inflow		Outflow		Precipita-tion, in	ET, in	Infiltra-tion, in	Σ In, in	Σ Out, in	Error, percent
Month	Mgal	in	Mgal	in						
Jan	2.18	55.5	1.56	39.7	6.40	0.51	7.8	62	48	-22
Feb	2.72	69.1	2.10	53.4	9.95	0.87	7.1	79	61	-22
Mar	1.91	48.6	0.64	16.4	2.47	2.65	7.8	51	27	-47
Apr	2.99	76.1	2.03	51.7	1.05	3.69	7.6	77	63	-18
May	3.15	80.2	0.85	21.6	2.98	4.32	7.8	83	34	-59
Jun	2.63	67.0	1.76	44.8	0.58	6.25	7.6	68	59	-13
Jul	1.98	50.4	0.77	19.5	0.00	7.91	7.8	50	35	-30
Aug	2.70	68.7	0.55	14.0	0.00	7.41	7.8	69	29	-57
Sep	3.05	77.6	0.77	19.5	0.23	4.80	7.6	78	32	-59
Oct	3.05	77.7	0.80	20.4	0.76	3.33	7.8	78	32	-60
Nov	2.94	75.0	0.78	19.9	2.84	1.07	7.6	78	28	-63
Dec	2.89	73.6	0.71	18.0	0.58	0.83	7.8	74	27	-64
Total	32.19	819.7	13.31	338.9	27.84	43.64	92.0	847	475	-44
Average	2.68	68.3	1.11	28.2	2.32	3.64	7.7	71	40	-43

[a] Hydrologic data from Table 2-1.

TABLE 2-8 (CONTINUED)
WATER BALANCE FOR CELLS 3, 5, 7, AND 9 IN 1998[a]
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

CELL 7

	Inflow		Outflow		Precipitation, in	ET, in	Infiltration, in	Σ In, in	Σ Out, in	Error, percent
Month	Mgal	in	Mgal	in						
Jan	2.22	56.6	1.33	33.8	6.40	0.51	11.5	63	46	-27
Feb	2.05	52.2	1.32	33.5	9.95	0.87	10.3	62	45	-28
Mar	2.31	58.9	1.37	34.8	2.47	2.65	11.5	61	49	-20
Apr	2.28	58.1	2.66	67.8	1.05	3.69	11.1	59	83	40
May	2.40	61.2	2.00	51.0	2.98	4.32	11.5	64	67	4
Jun	2.37	60.3	1.63	41.4	0.58	6.25	11.1	61	59	-4
Jul	2.49	63.5	0.85	21.6	0.00	7.91	11.5	63	41	-35
Aug	2.54	64.6	0.93	23.7	0.00	7.41	11.5	65	43	-34
Sep	2.50	63.6	1.89	48.1	0.23	4.80	11.1	64	64	0
Oct	2.63	66.9	1.42	36.1	0.76	3.33	11.5	68	51	-25
Nov	2.59	65.8	2.01	51.2	2.84	1.07	11.1	69	63	-8
Dec	2.72	69.1	1.26	32.1	0.58	0.83	11.5	70	44	-36
Total	29.10	740.9	18.66	475.1	27.84	43.64	134.9	769	654	-15
Average	2.42	61.7	1.55	39.6	2.32	3.64	11.2	64	54	-14

CELL 9

	Inflow		Outflow		Precipitation, in	ET, in	Infiltration, in	Σ In, in	Σ Out, in	Error, percent
Month	Mgal	in	Mgal	in						
Jan	2.38	60.5	2.24	57.0	6.40	0.51	7.8	67	65	-2
Feb	2.89	73.6	2.14	54.4	9.95	0.87	7.1	84	62	-25
Mar	3.12	79.6	1.55	39.3	2.47	2.65	7.8	82	50	-39
Apr	3.02	77.0	2.00	50.9	1.05	3.69	7.6	78	62	-20
May	3.12	79.6	2.81	71.5	2.98	4.32	7.8	83	84	1
Jun	2.65	67.4	2.14	54.5	0.58	6.25	7.6	68	68	0
Jul	1.99	50.6	1.08	27.5	0.00	7.91	7.8	51	43	-15
Aug	2.07	52.8	1.18	30.1	0.00	7.41	7.8	53	45	-14
Sep	3.17	80.7	1.90	48.5	0.23	4.80	7.6	81	61	-25
Oct	2.05	52.1	1.65	42.0	0.76	3.33	7.8	53	53	1
Nov	2.99	76.0	2.15	54.7	2.84	1.07	7.6	79	63	-20
Dec	2.94	74.9	2.24	57.1	0.58	0.83	7.8	76	66	-13
Total	32.39	824.8	23.08	587.7	27.84	43.64	92.0	853	723	-15
Average	2.70	68.7	1.92	49.0	2.32	3.64	7.7	71	60	-14

[a] Hydrologic data from Table 2-1.

TABLE 2-9
WATER BALANCE FOR TYPICAL WETLAND CELL
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

	Inflow[a], gal/min	Precip.[b]	ET[c]	Infiltration[d], gal/min				Outflow[e], gal/min					Percent loss[f], %				
Month	all cells	gal/cell min	gal/cell min	3	5	7	9	3	5	7	9	avg.	3	5	7	9	avg.
Jan	70	6.5	0.4	5.2	6.9	10.1	6.9	70.9	69.1	65.9	69.1	68.8	-1.2	1.2	5.8	1.2	1.8
Feb	70	5.7	0.8	5.2	6.9	10.1	6.9	69.7	68.0	64.7	68.0	67.6	0.5	2.9	7.5	2.9	3.5
Mar	70	1.6	2.3	5.2	6.9	10.1	6.9	64.1	62.4	59.2	62.4	62.0	8.5	10.9	15.5	10.9	11.4
Apr	70	0.8	3.4	5.2	6.9	10.1	6.9	62.3	60.6	57.4	60.6	60.2	11.0	13.4	18.0	13.4	13.9
May	70	1.4	3.8	5.2	6.9	10.1	6.9	62.4	60.7	57.5	60.7	60.3	10.9	13.3	17.9	13.3	13.8
Jun	70	0.4	5.7	5.2	6.9	10.1	6.9	59.5	57.8	54.6	57.8	57.5	14.9	17.4	21.9	17.4	17.9
Jul	70	0.0	7.0	5.2	6.9	10.1	6.9	57.9	56.2	53.0	56.2	55.8	17.3	19.8	24.3	19.8	20.3
Aug	70	0.1	6.5	5.2	6.9	10.1	6.9	58.4	56.7	53.5	56.7	56.3	16.6	19.0	23.6	19.0	19.5
Sep	70	0.1	4.4	5.2	6.9	10.1	6.9	60.6	58.9	55.7	58.9	58.5	13.4	15.9	20.4	15.9	16.4
Oct	70	0.7	2.9	5.2	6.9	10.1	6.9	62.6	60.9	57.7	60.9	60.6	10.5	12.9	17.5	12.9	13.5
Nov	70	3.2	1.0	5.2	6.9	10.1	6.9	67.1	65.3	62.1	65.3	65.0	4.2	6.6	11.2	6.6	7.2
Dec	70	3.3	0.7	5.2	6.9	10.1	6.9	67.4	65.7	62.4	65.7	65.3	3.8	6.2	10.8	6.2	6.7
Average	70	2.0	3.2	5.2	6.9	10.1	6.9	63.6	61.9	58.7	61.9	61.5	9.2	11.6	16.2	11.6	12.2

[a] Inflow rate assumed to equal design inflow value of 70 gal/min.

[b] Precipitation flow based on 3-year (1996-98) precipitation data from Sacramento Executive Airport weather station.

[c] Evapotranspiration flow based on 1998 reference evapotranspiration from Fair Oaks CIMIS station.

[d] Infiltration flow for cells 3, 5, 7, and 9 based on rates of 0.0079, 0.0105, 0.0154, and 0.0105 in/hr, respectively, measured in 1998.

[e] Outflow = inflow + precipitation - evapotranspiration - infiltration.

[f] Percent loss = difference between inflow and outflow, expressed as a percent of inflow.

FIGURE 2-6
SUMMARY OF HYDROLOGIC INPUTS AND OUTPUTS FOR A TYPICAL WETLAND CELL IN 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

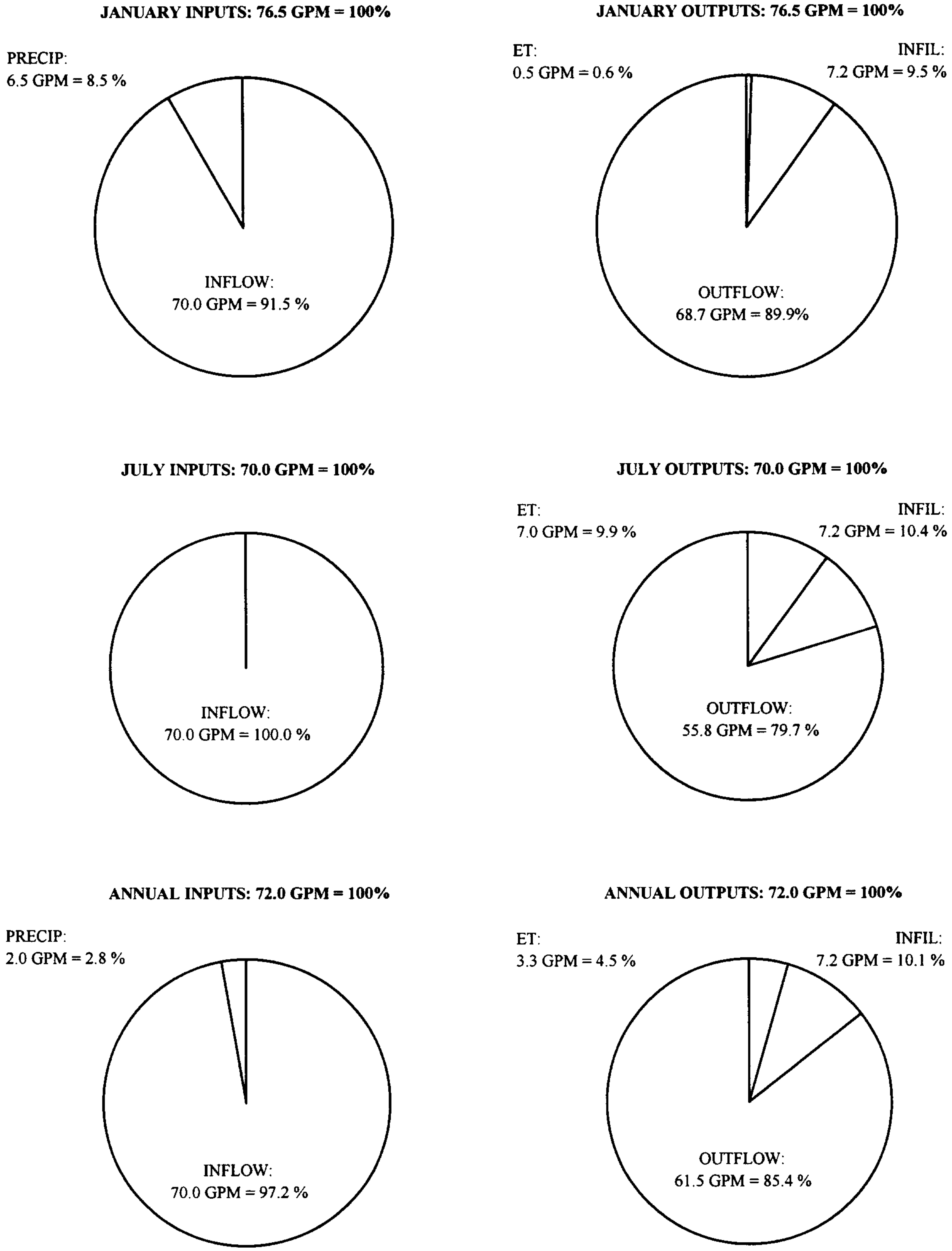


TABLE 2-10

ANNUAL BALANCE FOR WATER AND ELECTROCONDUCTIVITY FOR TYPICAL CELL

SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT[a]

Parameter	Units	Value
Cell area	ft^2	63,000
Inflow	gal/min	70.0
Precipitation	in/yr	17.5
Evapotranspiration	in/yr	51.5
Infiltration	in/hr	0.011
Inflow EC	μmho/cm	613.8
Precipitation	gal/min	1.3
Evapotranspiration	gal/min	3.8
Net evapotranspiration[b]	gal/min	2.5
Net ET as percent of inflow	percent	3.6
Infiltration	gal/min	7.2
Outflow[c]	gal/min	60.3
Flow loss	percent	13.9
Outflow EC[d]	μmho/cm	638.2
EC increase	percent	4.0

[a] Average annual values used.

[b] Net ET = ET - Precipitation.

[c] Outflow = Inflow + Precipitation - ET - Infiltration.

[d] $C_{out} = (Q_{in}C_{in} - Q_{inf}C_{in}/2)/(Q_{out} + Q_{inf}/2)$.

TABLE 2-11

SUMMER-MONTH BALANCE FOR WATER AND ELECTROCONDUCTIVITY FOR TYPICAL CELL

SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT[a]

Parameter	Units	Value
Cell area	ft^2	63,000
Inflow	gal/min	70.0
Precipitation	in/month	0.0
Evapotranspiration	in/month	7.5
Infiltration	in/hr	0.011
Inflow EC	µmho/cm	628.5
Precipitation	gal/min	0.0
Evapotranspiration	gal/min	6.8
Net evapotranspiration[b]	gal/min	6.8
Net ET as percent of inflow	percent	9.7
Infiltration	gal/min	7.2
Outflow[c]	gal/min	56.0
Flow loss	percent	20.0
Outflow EC[d]	µmho/cm	700.4
EC increase	percent	11.4

[a] Average summer month values used.

[b] Net ET = ET - Precipitation.

[c] Outflow = Inflow + Precipitation - ET - Infiltration.

TABLE 2-12
SUMMARY OF TRACER STUDY RESULTS
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

	Cell 7B					Cell 9B		
Parameter	1995	1996	1997	1998	98 w/flow	1995	1996	1997
Nominal Half Cell Residence Time, d	4.7	5.0	4.6	5.7	5.7	4.8	4.6	5.1
Tracer (Mean) Residence Time[b], d	4.4	5.3	4.3	3.7	3.5	5.0	6.0	8.3
Extrapolated Tracer (Mean) Residence Time[c], d	5.0	NA	NA	4.0	3.6	5.4	6.0	8.6
Estimated Whole Cell Residence Time[d], d	10.0	10.7	8.6	7.5	6.9	10.8	12.1	17.2
Nominal:Mean Residence Time Ratio, %	93%	93%	108%	153%	165%	89%	77%	60%
Mode, d	2.9	3.5	2.7	3.0	3.0	1.9	4.0	6.1
Mode:Mean Ratio, %	57%	66%	62%	80%	87%	35%	66%	71%
Mode:Nominal Ratio, %	61%	70%	58%	52%	52%	40%	86%	119%
Variance, d^2	5.2	7.1	4.8	3.1	2.2	7.8	7.0	11.1
Normalized Variance	0.207	0.251	0.256	0.191	0.172	0.314	0.197	0.151
Inlet Flowrate, gal/min	70.0	70.0	73.5	57.1	57.1	69	70	62.5
Half Cell Mean Flowrate, gal/min	66.3	62.3	66.8	54.3	54.3	64.5	66.9	60.5
Half Cell Outlet Flowrate, gal/min	62.5	54.6	60.0	51.5	51.5	60.0	63.9	58.5
Initial LiCl, lb LiCl	16	24	16	24	24	16	16	16
Recovered LiCl, lb LiCl	10.6	19.6	12.9	8.4	9.8	8.7	14.9	13.8
Recovery, %	66%	82%	80%	35%	41%	55%	93%	86%
Extrapolated Recovery (Exponential), %	76%	NA	NA	37%	42%	59%	94%	90%
Peclet Number, μL/D	8.06	6.77	6.65	9.35	10.54	6.32	9.23	12.17
Number of Well-Mixed Sections	4.8	4.0	3.9	5.2	5.8	3.8	5.2	6.6

[a] Based on 630 ft x 50 ft x 1.5 ft cell with 70% vegetation density and three 45 ft x 5 ft deep unvegetated open water areas. Flow rate estimated as average of influent and effluent flow.

[b] Observed residence time at the west sampling station (inside culvert).

[c] Estimated residence time based on observed data extrapolated to zero tracer concentration using exponential decay.

[d] Extrapolated half-cell residence time multiplied by two.

FIGURE 2-7
CELL 7 NORMALIZED TRACER CURVES
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

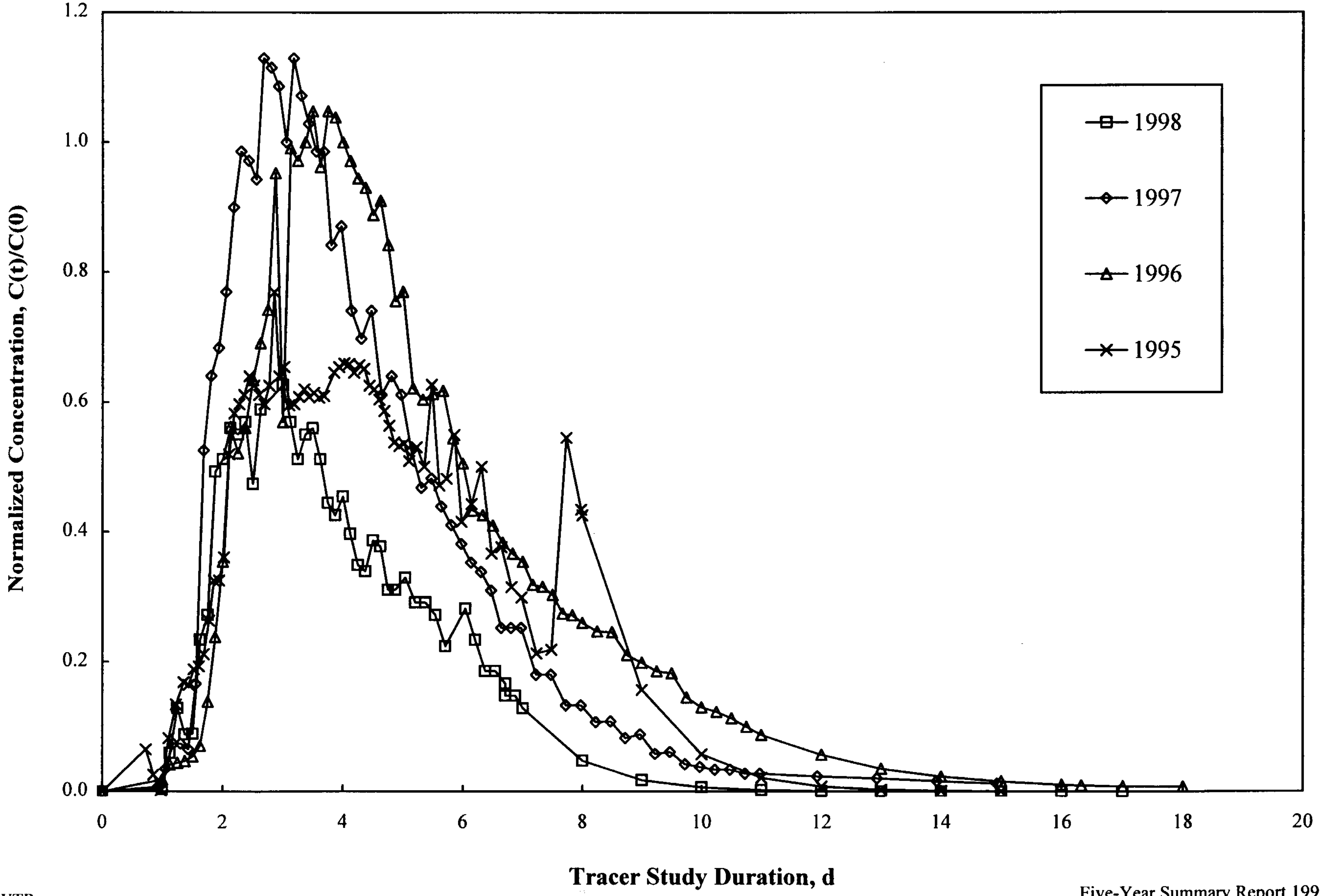


FIGURE 2-8
1998 TRACER STUDY AND MODELING FOR CELL 7B
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATON PROJECT

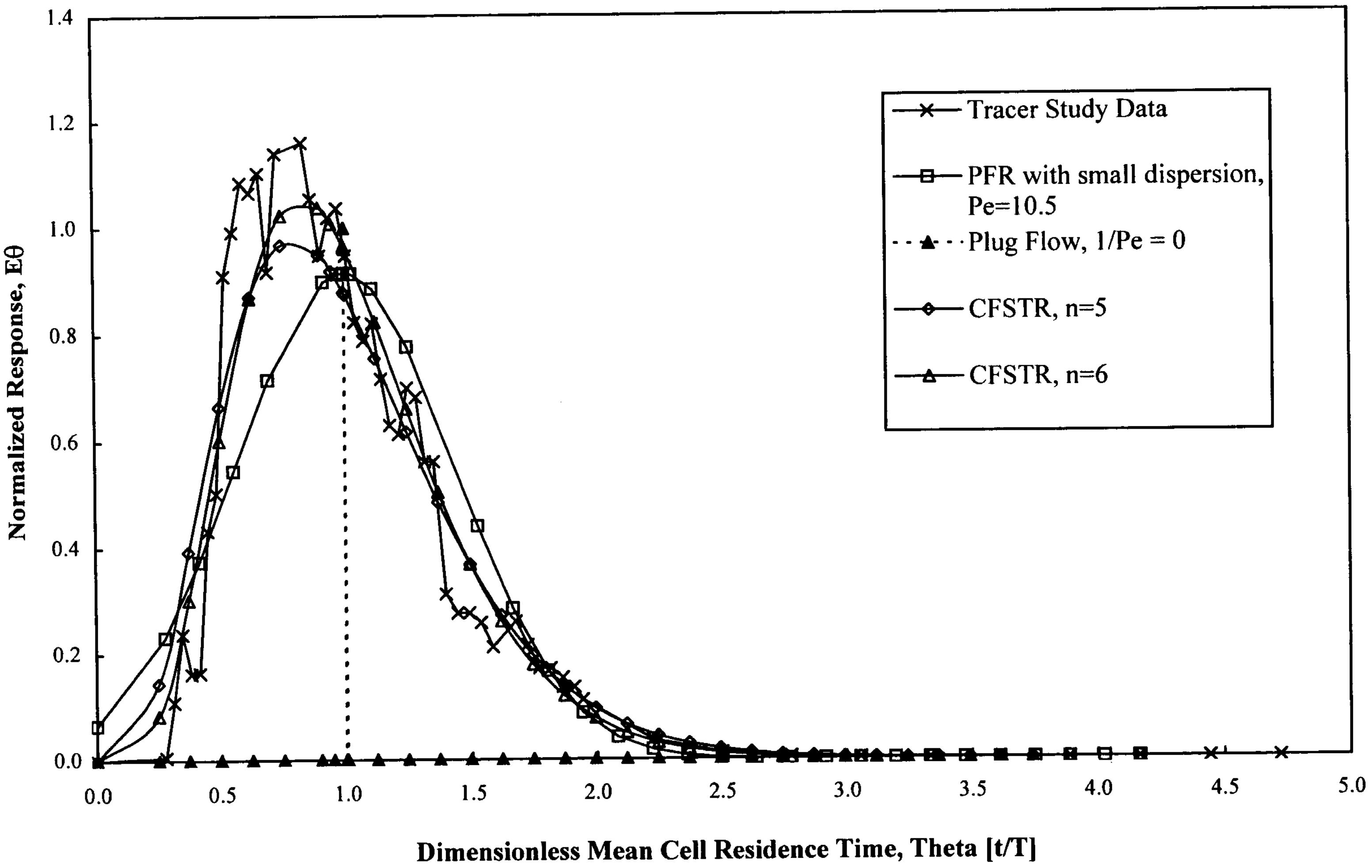
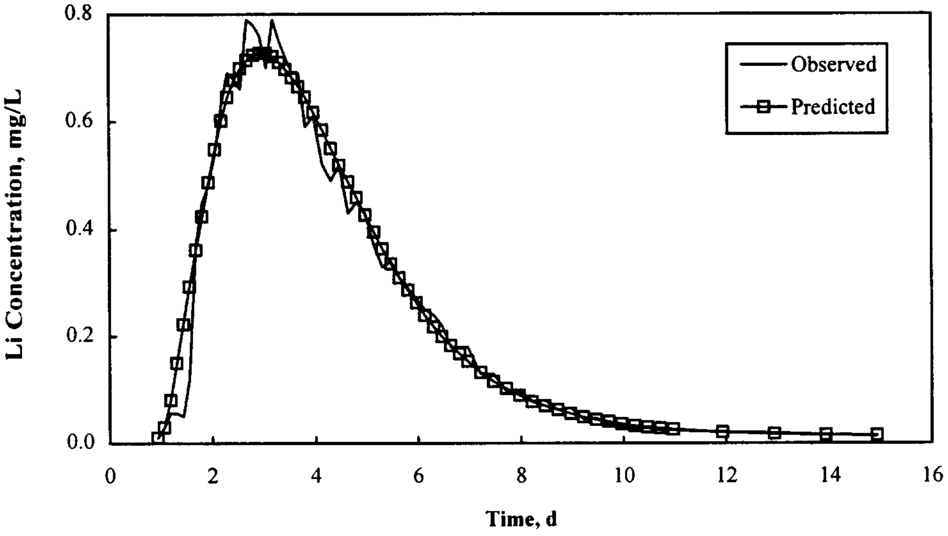
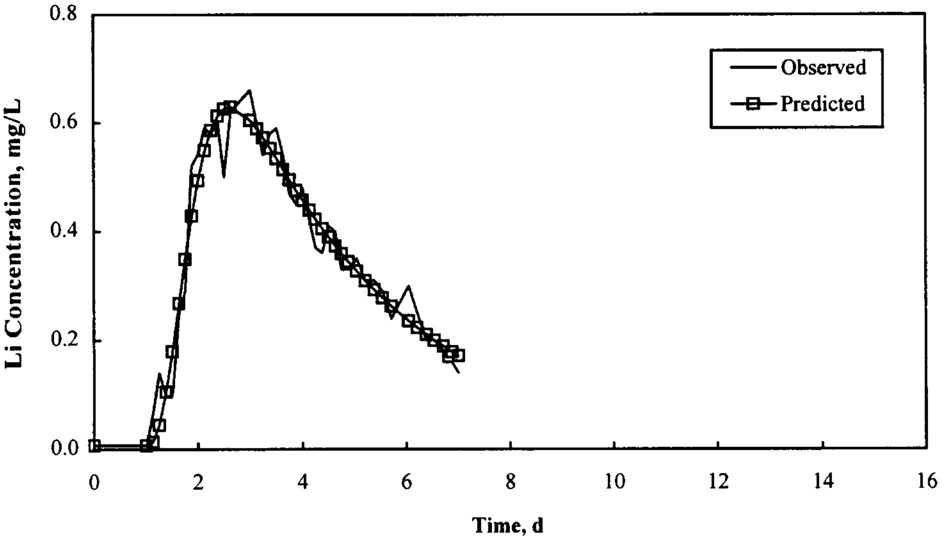


FIGURE 2-9
FINITE STAGE MODEL FOR 1997 AND 1998
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT



1997 FINITE STAGE MODEL

1997 Model Parameters	
Ncompart =	4
f =	0.25
Va =	0.72
p =	0.64
Plug flow volume (ft^3) =	9818



1998 FINITE STAGE MODEL

1998 Model Parameters	
Ncompart =	4
f =	0.28
Va =	0.63
p =	0.81
Plug flow volume (ft^3) =	11551

Note:
Ncompart=number of sequential compartment pairs
f = fraction of flow going to "off-line" compartment
Va = fraction of volume that is in "on-line" compartment
p = porosity

FIGURE 2-10
PROFILE OF CELL 7 WATER ELEVATIONS AND BOTTOM SLOPE (MAY 28, 1997)
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

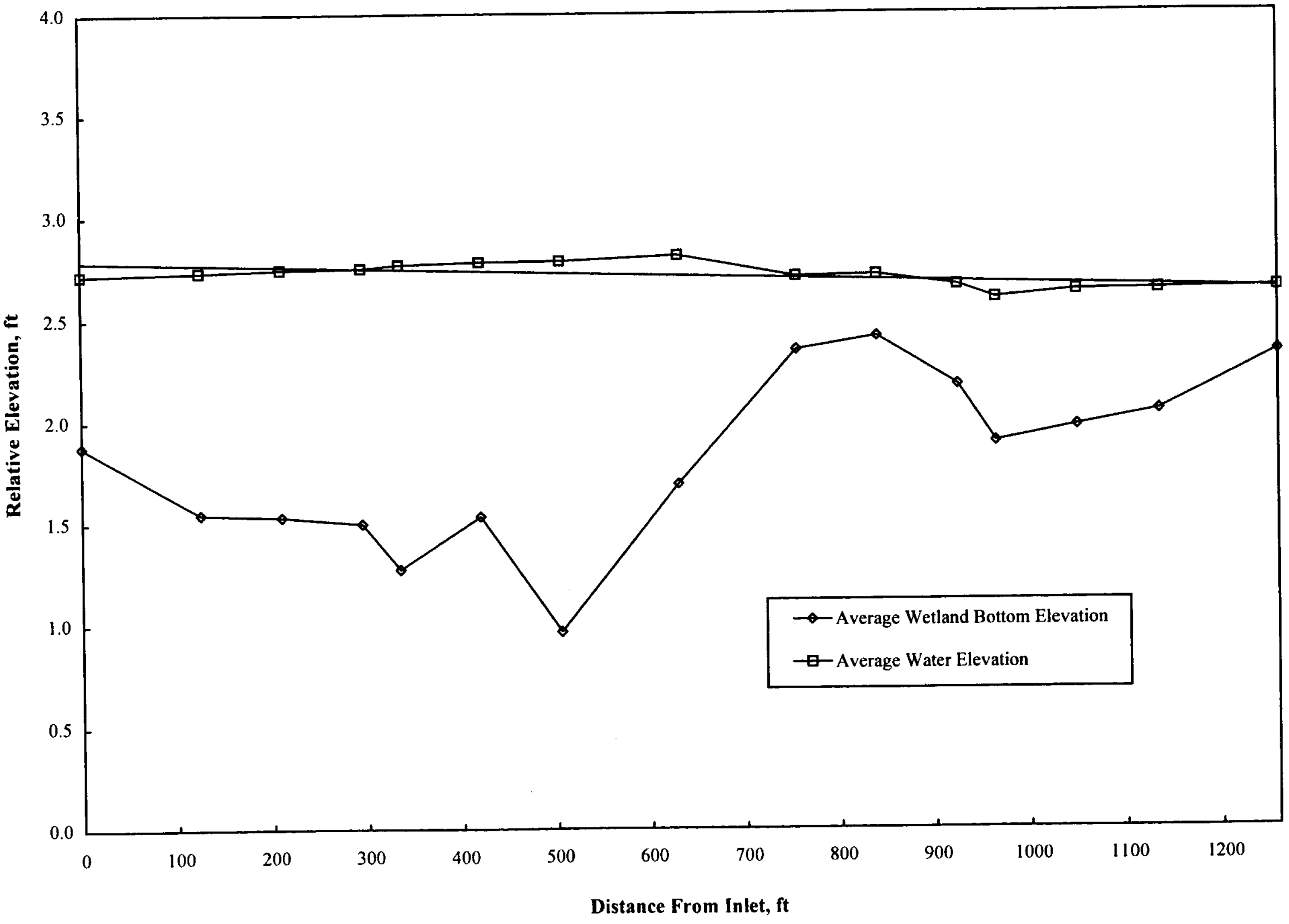


TABLE 2-13
SUMMARY OF WETLAND CELL FRICTION EXPERIMENTS
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

		Cell 3		Cell 7			
Parameter	Units	5/1/97	6/20/97	5/8/97	5/28/97	6/6/97	9/22/97
Inlet Flow	m^3/d	360	748	379	383	801	801
Outlet Flow	m^3/d	316	431	207	236	598	598
Average Flow	m^3/d	338	590	293	309	699	699
Depth	m	0.46	0.61	0.46	0.46	0.61	0.61
Vegetation Density	$stems/m^2$	55	57	93	199	199	NA
Volume Fraction Water[a]	%	86	95	61	61	57	86
Superficial Velocity	m/d	48.5	63.5	42.1	44.4	75.3	48.4
Actual Water Velocity[b]	m/d	56.4	67.2	69.3	73.2	131.6	56.7
Water Slope	m/m	0.000042	0.000052	0.000070	0.000117	0.000019	0.000190
Manning n	$s/m^{1/3}$	5.9	6.7	6.2	7.6	2.1	15.1
Observed Head Loss[c]	cm	1.6	2.0	2.7	4.5	0.7	7.3

[a] Volume fraction of water measured in Cell 3 on April 16, 1997 and in Cell 7 on April 21, 1997 from estimates of stem density and litter occupying water column within representative quadrats.

[b] Actual water velocity determined as superficial velocity divided by volume fraction water.

[c] Head loss determined from average water slope over 384 m wetland length.

TABLE 2-14
SUMMARY OF MANNING ROUGHNESS COEFFICIENT VALUES
SACRAMENTO CONSTRUCTED WETLANDS DEMONSTRATION PROJECT

Research	Flow, m^3/d	Depth, m	Water Slope, m/m	Vegetation Density, $stems/m^2$	Vegetation Type	Manning n Value, $s/m^{1/3}$
Sacramento Constructed Wetlands Demonstration Project						
Cell 3 (5/1/97)	360	0.46	0.000042	55	*Scirpus*	5.9
Cell 3 (6/20/97)	749	0.61	0.000052	57	"	6.7
Cell 7 (5/8/97)	379	0.46	0.000070	93	"	6.2
Cell 7 (5/28/97)	383	0.46	0.000117	199	"	7.6
Cell 7 (6/6/97)	801	0.61	0.000019	199	"	2.1
Cell 7 (9/22/97)	373	0.46	0.000190	NA	"	15.1
Benton[a]						
Benton 1	NA	NA	NA	NA	NA	1 - 10
Benton 2	NA	NA	NA	NA	NA	10 - 30
Hall and Freeman[a]						
Experimental Channels	778	NA	NA	400	bulrush	0.35
" "	778	NA	NA	800	"	0.70
" "	4,925	NA	NA	400	"	0.25
" "	4,925	NA	NA	800	"	0.50
Chandler Slough[b]						
Chandler Slough (6/79)	NA	0.16	NA	dense, sprayed	bulrush	0.12
Chandler Slough (7/79)	NA	0.25	NA	dense, non-sprayed	*P. lancelotata,* *C. occidentalis*	0.51
Everglades Nutrient Removal Project[c]						
ENR Cell 1	NA	0.46	NA	NA	*Typha*	1.10
ENR Cell 2	NA	0.91	NA	NA	"	0.27
Open Channels[d]						
Straight stream on plain	NA	NA	NA	NA	NA	0.030
Densely vegetated stream	NA	NA	NA	NA	NA	0.100
Earthen channel	NA	NA	NA	NA	NA	0.022
Cement-lined channel	NA	NA	NA	NA	NA	0.015

[a] As reported in Kadlec, 1996b.

[b] As reported in Shih and Rahi, 1982.

[c] As reported in Brown and Caldwell, 1996.

[d] As reported in Chow, 1959.