proportional to the availability of corroborating evidence and is indicated, when appropriate, throughout the text.

In summary the NADB was viewed as an overview inventory of wetland technology but not sufficient in itself to provide loading data and discharge data to be statistically analyzed. Individual sites and entries do provide data that can be used to predict performance and to extrapolate performance to other sites.

Role of Aquatic Plants in Controlling Treatment Processes

Aquatic macrophytes play an important role in the treatment processes active within FWS constructed wetlands. The plants, unique to the wetland environment, both control the pollutant removal processes and act as sources and sinks of certain dissolved and particulate water quality constituents. Wetland plants also play an important role in preventing incoming radiation from entering the water column. Interception of incoming radiation significantly reduces algae growth, which can add carbon back to the system via photosynthesis. The shading of the water surface also moderates the water temperature of a wetland. A distinguishing characteristic of FWS constructed wetlands is that the water temperature profile is buffered from the changes in the ambient temperature. The cooling potential for any one site is dependent upon the range of temperatures found at that site, the ET rate, and the extent of the canopy. While the magnitude of thermal buffering is unique to a site, in certain locations this effect can be taken advantage of to meet instream temperature standards.

Well-developed stands of vegetation also reduce the natural reaeration process by controlling the micrometeorology within the wetland and limiting wind induced turbulent mixing. Lower rates of oxygen transfer, combined with low algal concentrations and the dissolved oxygen consumed within the water column to satisfy BOD, usually results in low dissolved oxygen concentrations in FWS constructed wetlands. Surface level dissolved oxygen concentrations at 20 to 40 percent of saturation are commonly observed. Low dissolved oxygen concentrations are mitigated somewhat by the contribution of oxygen to the water column by common wetland plants.

While debate surrounds the potential for in-situ reaeration via emergent macrophytes, no debate exists concerning the ability of submergent plants to contribute dissolved oxygen. In most cases, emergent and submergent plants are not found in the same wetland zones. Submergent aquatic macrophytes thrive in the unshaded regions of FWS constructed wetlands. These plants contribute dissolved oxygen directly to the water column while affording a physical substrate for periphytic bacteria and algae. Plants such as *Potamogeton pectinatus*, sago pondweed, are commonly planted in FWS constructed wetlands to support the nitrification of ammonia and serve as a food source for aquatic waterfowl. Floating aquatic macrophytes are subject to being moved by the wind over the surface of the open water. It is not uncommon to have plants such as *Lemna spp.* windrowed amongst and against emergents or a berm, resulting in nearly complete inhibition of normal photosynthetic reaeration processes. Proprietary processes have been developed to keep floating aquatic macrophytes from being redistributed by the wind through various anchoring mechanisms. Significant solids handling problems can exist with dredged or harvested aquatic plants. Storage of these materials can result in odors.

The wetland vegetation is also a source of dissolved and particulate material that combines with the influent wastewater to produce a mixture of biodegradable compounds. A wide range of heterotrophic and autotrophic organisms degrade these compounds, similar to the production of BOD via algal growth and degradation in an oxidation pond.

Many of the biochemical transformations that occur in treatment wetlands are mediated by a variety of microbial species residing on solid surfaces such as those provided by plant leaves, stems, and litter. Examples of these processes include the decomposition of organic matter, periphyton fixation, nitrification-denitrification, and sulfate reduction. For example, maximum biofilm production of 1500 $mg/m^2 \cdot d$ has been measured in wastewater treatment wetlands at 60% of maximum sunlight (Tojimbara 1986). In turn, these processes are directly responsible for the water quality improvement potential of treatment wetlands.

Wetland vegetation also has an effect on the hydraulic characteristics of the wetland, which directly influences water quality constituent removal processes. Wetland vegetation can

- increase water losses through plant transpiration,
- decrease evaporation water losses by shading water surfaces and cooling water temperatures,
- create friction on the flowing water and, thereby, creating headloss and flocculation of colloids,
- provide wind blocks, thus promoting quiescent water conditions and protection for floating plants such as duckweed,
- provide complex water column flow pathways, and
- occupy a portion of the water column, thus decreasing detention time

In summary, it is the vegetation, specifically the emergent and submergent vegetation, that gives a FWS constructed wetland its capability to treat wastewater effectively in a passive manner. Free water surface constructed wetlands are unique in that they grow their own physical substrate for periphytic microorganisms while minimizing incoming radiation addition. The fact that a sedimentation process coupled with an anaerobic digester and fixed film reactor is possible in a shallow aquatic system is due to the ecosystem created by aquatic macrophytes. Without the aquatic macrophytes, the same physical conditions would result in an oxidation pond producing a large amount of total suspended solids (algae) in the effluent.

Summary of Wetland Treatment Performance

The performance evaluation of FWS constructed wetlands has been analyzed at three different levels. The first level includes a summary analysis of all the data for the systems listed in Table 4, determining the mean influent and effluent concentrations and their range of values. The mean and range of loadings for each water quality constituent are given in Table 5. This first level of assessment is useful only in the context of summarizing the range of operating conditions of FWS constructed wetlands and their range of response in terms of effluent concentration. At this level of analysis, only the wide range of application and expected performance for operating FWS treatment wetlands are summarized. No accounting for differences in upstream waste treatment processes, geometric configuration, planting strategy, inlet/outlet works, climate, etc. has been made at this level of analysis. Each of the factors listed above can significantly affect the effluent quality of a FWS constructed wetland.

In the second level of performance data analysis, the performance of those systems with the most extensive monthly influent/effluent data for the constituents of interest are compared. This level of analysis is displayed in terms of cumulative probability over the period of data collection. The third level of analysis is designed to determine how individual systems perform in terms of effluent concentrations over the range of their loadings. In the third level of analysis, monthly loading versus effluent concentrations for a single site are compared, thus demonstrating the expected variability within a single system.

Table 5. Summary of performance data and loadings for systems analyzed in this assessment.

Influent (kg/ha/d)				Influent (mg/L)			Effluent (mg/L)		
Constituent	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Biological Oxygen Demand (BOD)	0.04	31	183	1.7	70	438	1.2	15	69
Total Suspended Solids (TSS)	0.07	22	92	1.0	69	588	1.1	15	40
Ammonia (NH4-N)	0.02	3.5	16	0.63	8.7	29	0.07	6.8	23
Total Kjeldahl Nitrogen (TKN)	0.04	5.8	20	1.3	18	51	0.82	11	32
Nitrate (NO3-N)	0.05	0.9	3.5	0.31	3	13	0.01	1.2	3.5
Total Nitrogen (TN)	0.12	3.0	9.9	2.1	12	32	0.85	4.0	9.8
Organic Nitrogen (OrgN)	0.02	1.8	5.7	0.74	5.6	18	0.71	2.1	3.2
Total Phosphorus (TP)	0.01	1.2	4.4	0.27	4.1	11	0.09	2	4.2
Dissolved Phosphorus (DP)	0.01	0.6	1.3	0.23	2.6	5.7	0.04	1.5	3.7
Fecal Coliform (FC) (col/100mL)				1.7	73,000	360,000	47	1,320	9,800

BOD Performance

The relationship between average BOD loading and average BOD effluent concentration for systems in Table 4 shown in Figure 6. There is a general linear trend between increased BOD loading and increased effluent concentration over the loading range of 0.1 to 180 kg/ha·d. Considering the wide range of conditions, wetland design, and data quality, a general trend exists between increasing loading and increased effluent quality. Specific systems have BOD effluent versus BOD loading curves which are better correlated and predict lower effluent quality compared to the general trend observed in Figure **Error! Reference source not found.**. As shown in Figure 6, considerable effluent variation exists for a given BOD loading. For example, at a BOD loading of 25 kg/ha·d, the effluent concentrations vary from 9 to 35 mg/L. Considerable variation in effluent quality at the lower BOD

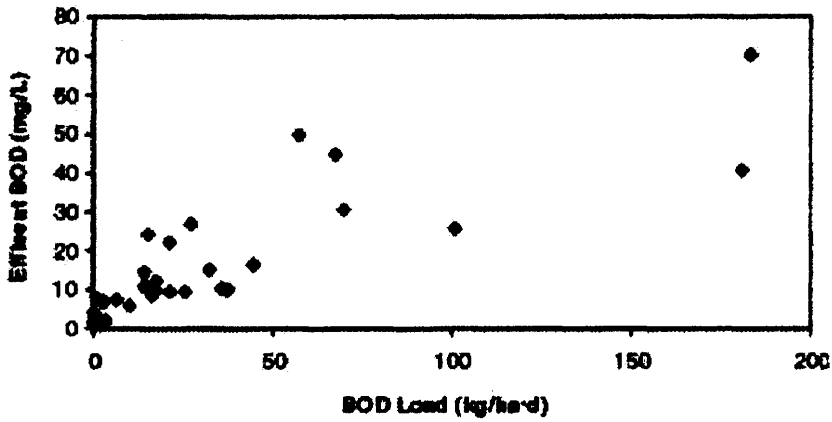
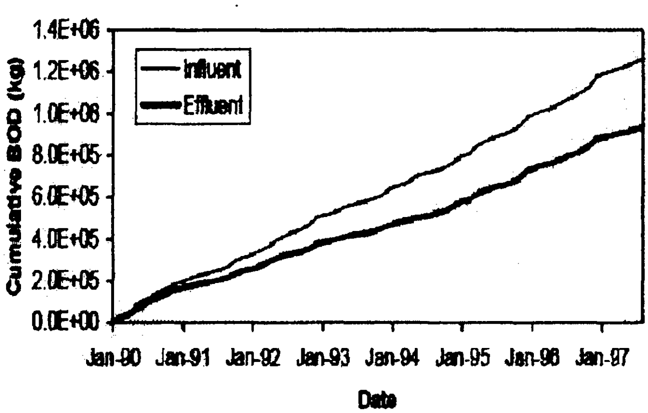


Figure 6. Average BOD loading rate versus effluent BOD concentration for TADB sites.

FIGURE 7 Cumulative monthly mass influent and effluent BOD for the Arcata Treatment Wetland.



loading rates is evident in Figure 6. For example, the effluent BOD varied from 1 to 8 mg/L within the BOD loading rate of 0.1 to 8 kg/ha·d. The effect of the background BOD due to plant decomposition is evident in systems with low loading rates. In addition to plant decomposition, relatively small changes in the inlet/outlet region, levels of animal activities, or weir location and operations, can all significantly affect the effluent BOD concentration under low loading rates. Cumulative BOD removal for Arcata's Treatment Wetland is shown in Figure 7, where the removal rate has remained constant for nearly 10 years.

TSS Performance

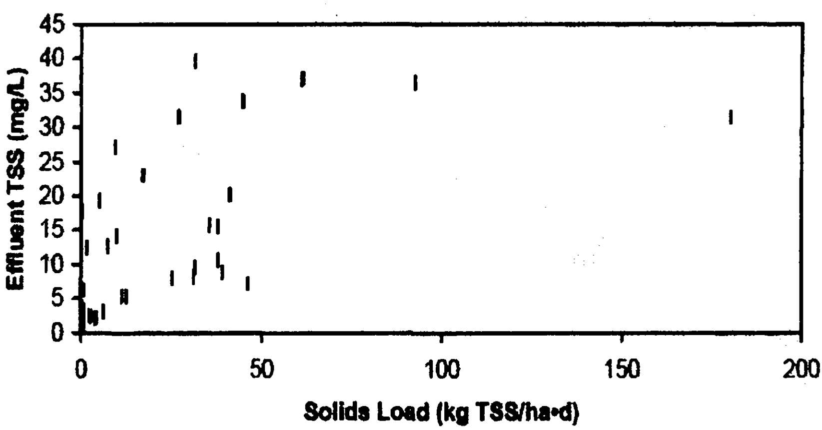
The effectiveness of FWS treatment wetlands to remove TSS is recognized as one of their principal advantages. The relationship between TSS loading and effluent TSS levels for the entire data set is shown in Figure 8. Over a range of loadings from 0.5 to 180 kg/ha·d, there does not appear to be any relationship between loading and effluent quality with this data set. What is apparent is that under a fairly wide range of solids loadings, relatively low effluent TSS concentrations can be attained. Because physical processes dominate the removal of TSS, it is expected that, to a point, TSS effluent levels are not affected by hydraulic or solids loading rates. The dominant TSS removal processes occur within the first 1 to 2 day HRT period. This effect can only be seen in transect data with 1 to 2 day increments. Most of the wetlands in the wetland database have detention times in excess of 2 days, which allows the removal of TSS to be masked by subsequent internal generation of TSS. The variation in the effluent TSS shown in Figure 8 is most likely related to internal TSS sources such as algal growth, sloughed epiphytes, animal sources, resuspension, or detrital particles. Based on the data from these sites, it can be concluded that wetlands generally will not reduce TSS concentrations below 3 mg/L, and in cases where the influent TSS is less than 10 mg/L, little if any additional TSS removal should be expected.

The removal of TSS is most pronounced in the inlet region of a FWS constructed wetland. Transect data from pilot project studies at Arcata show this pattern of removal (Figure 9). Generally 50-60 percent of the TSS from oxidation pond systems are removed in the first 2-3 days of nominal hydraulic detention time. Gravity settling processes account for most of this removal, and the overall removal efficiency is a function of the terminal settling velocity of the influent biosolids. Within the TSS loading range of 50 to 200 kg/ha·d, the removal of the settled total suspended solids does not require any routine solids handling operation. The separated solids undergo anaerobic decomposition, releasing soluble dissolved organic compounds and gaseous by-products, carbon dioxide and methane gas, to the water column.

Long term studies from individual sites have shown low and stable effluent concentrations from a relatively wide range of TSS loading rates. The TSS effluent concentrations rates from the Arcata Enhancement Wetland are consistently low, less than 5 mg/L, 90 percent of the time, with an annual average loading of 16 TSS kg/ha·d. The Arcata enhancement marsh has continued to remove TSS at a constant rate of approximately 90% for the last six years.

Thirteen FWS constructed wetland systems with permit and effluent data were available in the NADB that could be used to evaluate permit compliance. Effluent TSS permit limits varied from 10 to 30 mg/L on a monthly average basis In general, the FWS constructed wetlands were able to meet effluent TSS limits. The cases where limits were exceeded resulted from poor vegetative cover and the subsequent

FIGURE 8 Monthy TSS loading versus effluent TSS concentration for TADB wetland systems.



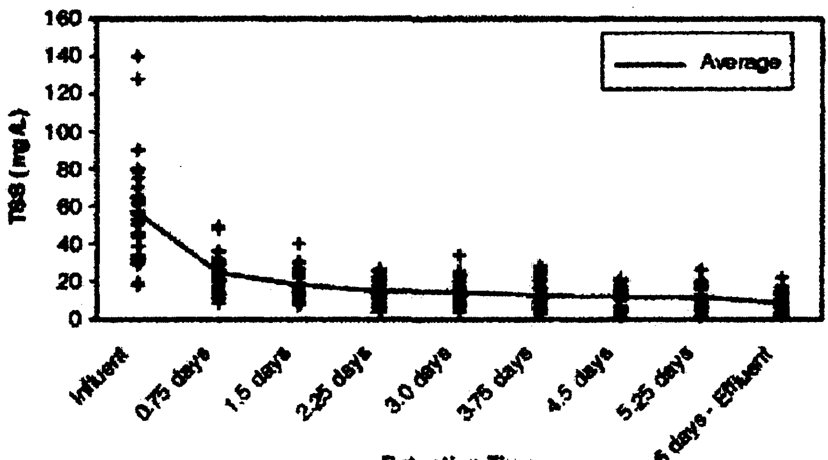


Figure 9. Weekly transect TSS concentration for Arcata's Cell 8 Pilot Project, with theoretical retention time of 6 days, receiving oxidation pond effluent.

growth of phytoplankton or solids resuspension. Of the thirteen systems in the

NADB, eight had 100 percent compliance with TSS effluent limits.

Nitrogen Performance

Effluent concentration data for nitrogen species shows considerable variation in response to the nitrogen loading. Total nitrogen (the sum of all nitrogen species) and total Kjeldahl nitrogen (organic plus ammonia nitrogen) effluent concentrations are generally correlated to their respective loadings. However, the other forms of nitrogen, ammonia, nitrate, and organic nitrogen, may exhibit very little correlation between effluent concentrations and influent loadings. This latter set of nitrogen species has both sources and sinks within FWS wetlands and a speciated nitrogen balance for a specific system is necessary to analyze removal performance.

In a number of cases, effluent concentrations of ammonia or nitrate N have been found to be higher than influent concentrations. This concentration increase is rarely the case for organic or total N. The conclusion from these observations is that the sequential nitrogen transformation processes result in an overall uni-directional conversion of elevated total and organic nitrogen forms to oxidized or gaseous nitrogen forms in treatment wetlands. However, these processes can also lead to increasing concentrations of intermediate nitrogen forms due to temporal, spatial, denitrification support (alkalinity/carbon, and redox potential. Distribution of various species of nitrogen within a wetland indicates that the nitrogen dynamics are affected by the influent loading, the degree of plant coverage and maturity of emergent vegetation (Sartorius et al. 1999).

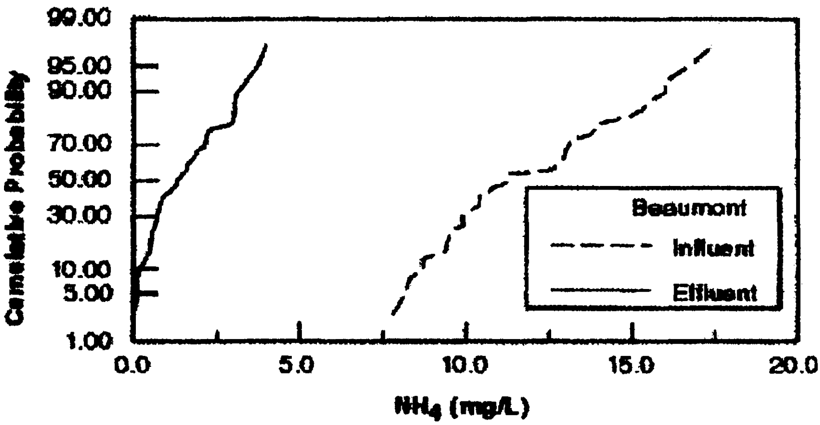


Figure 10. Cumulative probability distribution of monthly influent and effluent ammonia nitrogen from Beaumont, Texas.

Presentation of ammonia loading versus effluent concentration data for a number of different systems tends to mask the relationship between the various forms of nitrogen, the influent concentrations of ammonia, the water temperature, and the detention time of the wetland. The Beaumont, Texas FWS constructed wetland is an example of a system that showed very consistent ammonia nitrogen removal (Figure 10). Over a four year period, the 8 cell system of the Beaumont wetland had an average hydraulic detention time of 17.4 days, an average water temperature of 22.5 }C, and an average ammonia loading of 4.3 kg/ha}d. As shown in Figure **Error! Reference source not found.**, the average ammonia removal was nearly 90 percent. As shown in Figure 11, 60 percent of the ammonia removal occurs in the first five days of the total of 17 day retention time.

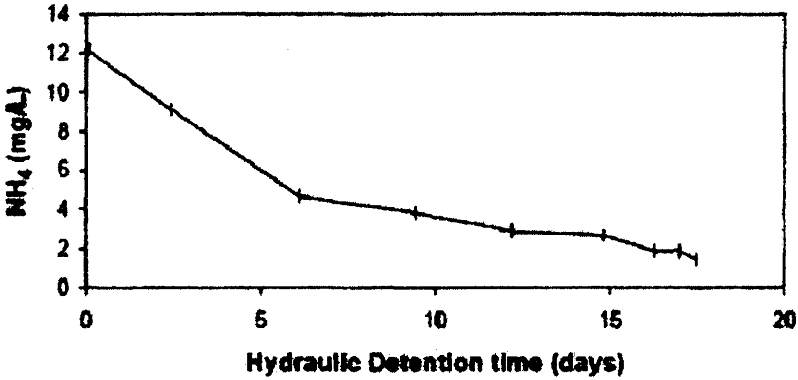


Figure 11. Ammonia nitrogen removal for Beaumont, Texas through 8 cells with a total HRT of 17 days.

From an analysis of the data, there does not appear to be any general relationship between the influent and effluent concentrations of fecal coliform from the TADB systems. In general, the correlation between influent and effluent conditions was better for specific sites (Gersperg et al. 1989). For example, as shown in Figure 12, a consistent 2 to 3 log removal with a 6 day hydraulic residence time was measured in Cell 8 in the Arcata Pilot Project. The mean influent (from an oxidation pond) fecal coliform was 5,000 cfu/100 mL and the mean effluent concentration was 35 cfu/100 mL. Fecal coliform removal was also found to be correlated with TSS removal in this system

Only four FWS constructed wetlands had fecal coliform permit limits and associated data in the NADB. In each case, monthly effluent permit limits were 200 colony forming units (cfu)/100 mL; only one system met this limit 100 percent of the time (Apalachicola, Florida, with only 2 months of data). Percent compliance for the other four systems ranged from 22 to 83 percent. A maximum value of 27,000 cfu/100 mL was reported for one month from the Benton, Kentucky, constructed wetland, and maximum values of 2,600 to 5,800 cfu/100 mL were reported for Central, South Carolina, and Pembroke, Kentucky, respectively. Based on this review of limited data, it appears that most FWS constructed wetlands will have problems consistently meeting fecal coliform limits of 200 cfu/100 mL.

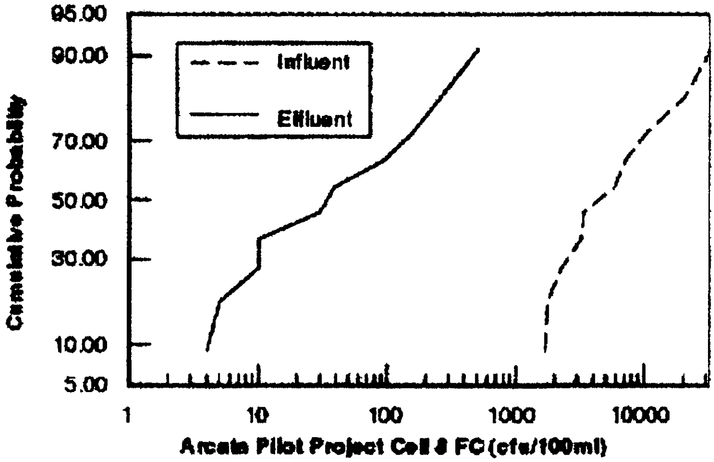


Figure 12. Cumulative probability distribution of influent and effluent fecal coliform from Arcata Pilot Project Cell 8, CA (Gearheart et al. 1986).

Other Performance Considerations

Wetland Background Concentrations

Wetland ecosystems typically include diverse autotrophic (primary producers such as plants) and heterotrophic (consumers such as microbes and animals) components. Most wetlands are more autotrophic than heterotrophic, resulting in a net surplus of fixed carbonaceous material that is buried as peat or is exported downstream to the next system (Mitsch and Gosselink 1993). This net production results in an internal release of particulate and dissolved biomass to the wetland water column, which is measured as non-zero levels of BOD, TSS, TN, and TP. Enriched wetland ecosystems are likely to produce higher background concentrations than oligotrophic wetlands because of the increased biogeochemical cycling that result from the addition of nutrients and organic carbon.

Background concentrations are not constant, but have a cycle of release that is a function of the biogeochemical cycle rates and external (other than wastewater inputs) factors. An example of this cycling can be seen in Figure **Error! Reference source not found.** from the Arcata Enhancement Wetland. Six years of weekly BOD measurements show that for this system the background concentration varies between 1.3 and 4.0 mg/L. The higher values of 3.5 to 4.0 mg/L occur in the fall and the lower values occur in the summer. This variation is attributed to the accelerated decomposition of the vegetative material and to increased bird activity in the fall. The lower values in the summer are correlated with low decomposition rates (low recent litter production) and decreased bird activity.

Water Balance Effects on Wetland Hydraulics and Water Quality

The variability inherent in wastewater flowrates and the stochastic nature of meteorological events controls wetland hydraulics, which in turn affects wetland water quality. The impacts to wetland hydraulics can best be described by noting the increases and decreases to the wetland hydraulic detention time caused by water gains and losses in the wetlands water balance. Likewise, the wetland hydraulic detention time can also be used to explain water balance impacts to wetland water quality.

Precipitation to a wetland increases inflow, which impacts wetland hydraulics by decreasing the hydraulic detention time, and affects water quality by diluting constituent concentrations. The combination of these two influences can provide either poorer or better performance of the wetland with regard to water. In systems receiving low influent constituent concentrations, concentration reduction is likely to be poorer with precipitation additions; in heavily loaded systems concentration reductions may be higher. Evapotranspiration has the effect of increasing hydraulic detention time and increasing constituent concentrations. The combination of precipitation and evapotranspiration can improve concentration reduction in very lightly loaded systems, but generally decreases concentration reduction in heavily loaded systems. The effect of exfiltration is similar to evapotranspiration by increasing the hydraulic detention time and increasing the potential for constituent removal. Constituent load reduction can further be enhanced by the loss of constituents with the water as it infiltrates into the soil.

Thermal Effects in Wetlands

The temperature of wetland waters influences both the physical and biological processes within a FWS constructed wetland. Under winter conditions, ice formation may also alter wetland hydraulics and limit oxygen transfer. Under severe conditions, freezing may even result in system failure. Decreased temperatures are known to reduce the rates of biological reactions. The extent of temperature effects, however, varies with the constituent. In FWS constructed wetlands, BOD removal does not always appear to exhibit a temperature dependence. Temperature dependent BOD removal may be masked by other processes such as internal loads due to decomposition that are also temperature dependent, or the removal may be primarily due to non-biological mechanisms. Nitrogen removal has consistently been observed to decrease with temperature, indicating that it is controlled by biological mechanisms.

Predicting and understanding the influence of water temperature within a FWS wetland is an essential step in identifying the limits of its operation. Temperatures can be estimated using an energy balance which accounts for the gains and losses of energy to the wetland over time and space. The important gains and losses in the energy balance will vary seasonally. At minimum, a winter and summer energy balance will be needed to predict the range of operating water temperatures, and thus the corresponding range in temperature dependent pollutant removal rates.

In summer, large amounts of energy are supplied by solar radiation. A small portion of this recharges the soil energy storage, but most is lost via evaporation and