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Review

A feasibility analysis of discharge of non-contact, once-through industrial cooling water to forested wetlands for coastal restoration in Louisiana

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ABSTRACT

Louisiana has had a high rate of coastal wetland loss due mainly to the isolation of the Mississippi River from the deltaic plain. We conducted a feasibility analysis of using once-through, non-contact industrial cooling water for restoring subsiding forested wetlands in coastal Louisiana. We considered the impacts of heated water and high nutrient and sediment concentrations. River diversions introduce sediments and nutrients to stimulate the productivity and accretion of coastal wetlands. Since increases in sediments and nutrients can cause water quality problems, we analyzed the assimilative capacity of the swamp. Based on a loading rates analysis, we estimated that the following nutrient reductions would occur: 75% for NO_3, 50% for TN, 60–75% for TP, and 100% for suspended sediments. Because of the concern of impacts from heated water, it is likely that the temperature of the cooling water will have to be decreased before discharge. Altering the duration and location of the discharge are ways to minimize the impact of temperature. We recommend that a pilot study be carried out to determine the effects of heated water on the functioning of the system, the retention of sediments and nutrients, and the impacts of different discharge scenarios.

1. Introduction

Wetland loss is a global problem worldwide. There are approximately 8.6 million km^2 of wetlands that cover about 6% of the land surface (Mitsch and Gosselink, 2000). Wetland loss is most severe in highly populated or developed regions. Over the past two centuries, the United States has lost more than 53% of the original 900,000 km^2 of wetlands (Dahl, 1990). Coastal wetland loss is an especially critical problem in the Mississippi delta. The state of Louisiana has about 40% of the total U.S. area of coastal wetlands but has suffered greater than 80% loss of its coastal wetland (loss of 4920 km^2 since 1930s; Field et al., 1991; Dunbar et al., 1992; Barras et al., 1994; Dahl, 2006). The main causes of wetland loss in the Mississippi delta region are isolation of the river from the deltaic plain by levees, pervasive alteration of hydrology, enhanced subsidence due to removal

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of oil and gas, and loss of barrier islands (Boesch et al., 1994; Day et al., 2000; Morton et al., 2002).

In order to restore the Mississippi delta, the state of Louisiana and the Federal Government have begun a massive restoration program that includes reintroduction of river water to the deltaic plain, hydrologic restoration, creation and nourishment of marshes with dredged sediments, and barrier island restoration (Penland et al., 1990; Mendelssohn and Kuhn, 2003; USACE, 2004). Reconnection of the river to the delta by reintroduction of river water via diversions (gated structures in levees or siphons over levees) is perhaps the major management tool for delta restoration (Boesch et al., 1994; Day et al., 2000; USACE and LADNR, 2003). In general, diversions are gated structures in levees or siphons over levees (e.g., Boesch et al., 1994; Lane et al., 1999, 2004; DeLaune et al., 2003).

A novel, and potentially important, approach to diverting river water into coastal wetlands is through the use of industrial cooling water. Many industries along the Mississippi River south of Baton Rouge pump river water for once-through, non-contact cooling (Schonberg et al., 2003). After passing through heat exchangers, the heated water is pumped back to the Mississippi River. An estimated 8.1 million m^3 (2300 million gal/day (MGD)) of water is used by various types of industrial plants in Louisiana (petrochemical 68%, refining 22%, paper products 5%, food products 2%, and other 2%) (Schonberg et al., 2003). Approximately, 93% of the water usage is from surface water and about 72% of all surface water withdrawn is from the Mississippi River. In 2002, a survey was conducted to determine the major uses of water by the petrochemical industry (Fig. 1). Cooling water accounted for 4.2 million m^3 (1100 MGD) or 67% of the 6.3 million m^3 (1657 MGD) of water withdrawn from the Mississippi River for industrial use.

In this paper, we report on a preliminary feasibility analysis of diverting once-through, non-contact industrial cooling water from the IMC Phosphates Company for the purpose of restoring subsiding forested wetlands in coastal Louisiana (Fig. 2). Currently, IMC Phosphates uses up to 5.2 m^3/s (82,000 gal/min, GPM) of water from the Mississippi River. This non-contact cooling water is used once and returned directly to the river. It has been suggested that this cooling water might serve as a source of river water for diversion into coastal wetlands. In a properly designed diversion project, the nutrients and sediments in river water can enhance wetland sustainability (DeLaune et al., 1990, 2003; Lane et al., 1999; DeLaune and Pezeshki, 2003). However, pumping heated water into a wetland can have serious detrimental impacts. In particular, we analyzed the potential impacts of diverting heated water with high nutrients and sediments on the adjacent forested wetland and developed a general design for a distribution system for delivering cooling water to the swamp. Because of the uncertainty of the impact of heated water on the forested wetland, a detailed assessment of this impact was carried out. Although recent research has demonstrated beneficial effects of river diversions (Lane et al., 1999, 2001, 2003; DeLaune et al., 2003, 2005; Wheelock, 2003), none of these diversions included heated water.

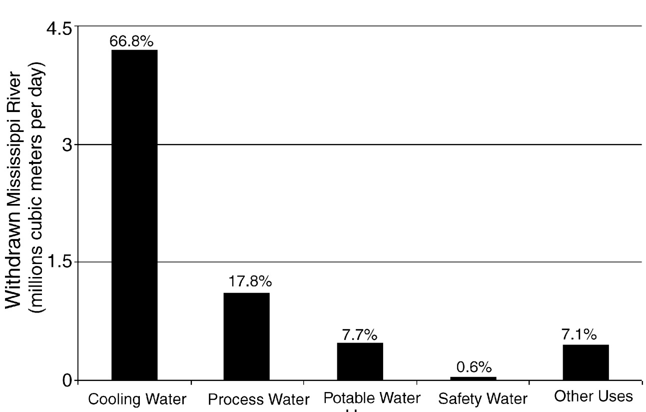

Fig. 1 – Categories and the relative importance of water usage withdrawn from the Mississippi River for industrial use (modified from Schonberg et al., 2003).

2. Area description

The IMC Phosphates plant is located on the east bank of the Mississippi River near Uncle Sam, Louisiana in St. James Parish (Fig. 2). The plant produces ammonia, diammonium phosphate, monoammonium phosphate, phosphoric acid, sulfuric acid, and urea fertilizer. The plant pumps up to 5.2 m^3/s

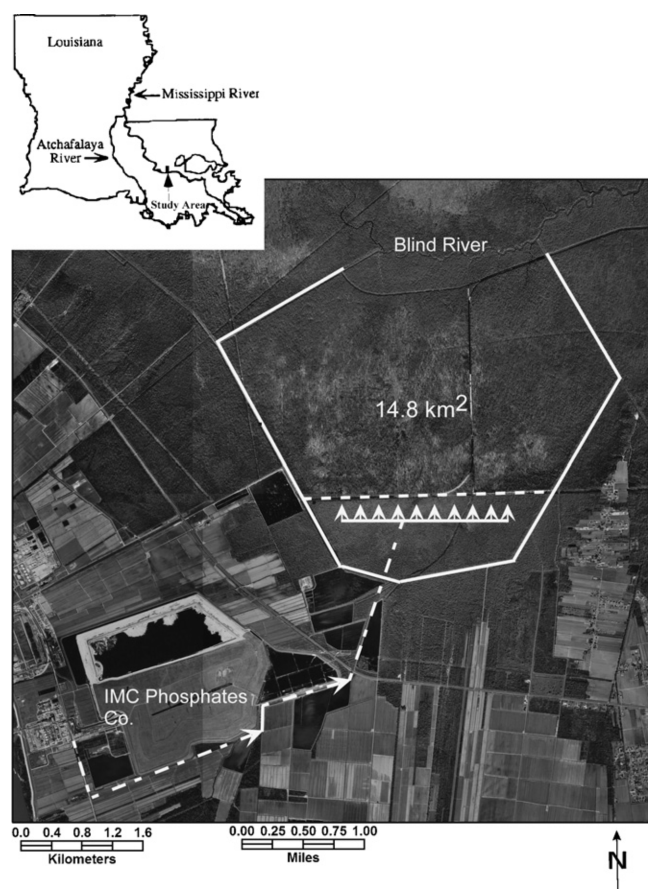

Fig. 2 – Map of the location of the IMC Phosphates Company. White arrows indicate the proposed dispersal path of cooling water. Solid white lines indicate projected forested swamp area to be influenced.

of Mississippi River water through heat exchangers for cooling and to condense steam from power generation units. The non-contact cooling water is returned uncontaminated to the Mississippi River at approximate water temperatures of 21 °C (70 °F) in the winter and 38 °C (100 °F) in the summer. There is a 5.2 m drop in elevation from the plant to the forested swamp over a 3.2–4.8 km distance. Like most swamps in the Louisiana coastal zone, the area has subsided and the swamp surface is flooded for most of the year. This prevents regeneration, and this swamp is slowly deteriorating. Vegetation consists primarily of maple (*Acer* sp.), elm (*Ulmus* sp.), bald cypress (*Taxodium distichum*), and water tupelo (*Nyssa aquatica*). Drainage in the area is eastward towards the Blind River and then into Lake Pontchartrain.

3. A review of the effects of thermal effluent on wetlands

Because of the potential negative effects of high temperatures on forested wetlands, we carried out a literature review to gain an understanding of these impacts. The maximum temperature of the cooling water after passing through heat exchangers is 21 °C in winter and 38 °C in summer. In the literature review, we focused particularly on the maximum discharge temperature that the ecosystem could sustain. The discharge of heated water to a wetland can have a number of potential impacts, both positive and negative. These include increased primary production, increased soil respiration, mortality of fauna and flora and changes in species composition (Parker et al., 1973; Gibbons and Sharitz, 1974; Sharitz et al., 1974b; McLeod and Sherrod, 1981; De Steven and Sharitz, 1997).

Literature on the impacts of heated water on forested wetlands is relatively scarce. One of the most intensively studied areas is the Savannah River Site in South Carolina. Forested wetlands on this site received high temperature cooling water from a nuclear reactor for over 35 years (Sharitz et al., 1974a; Gibbons and Sharitz, 1974). Water temperatures were commonly greater than 35 °C. Thus, results from the Savannah River Site provide a framework of possible outcomes of heated water on forested wetlands. Several factors were studied at the site in order to assess the effect of the discharge on the productivity and sustainability of the forested wetland. The major factors affecting swamp health were thermal loading, flooding and siltation associated with the reactor discharge (Sharitz et al., 1974a).

The addition of thermal effluent can alter the productivity and diversity of a forested wetland as well as the recruitment of new individuals (Gibbons and Sharitz, 1974; Sharitz et al., 1974b; Christy and Sharitz, 1980; McLeod and Sherrod, 1981; Donovan et al., 1988). The potential severity and extent of damage caused by the thermal effluent is dependent upon the duration and intensity of the temperature-change. Water temperatures in excess of 45 °C prohibited the growth of vascular plants at the Savannah River Site (Sharitz et al., 1974a, 1974b; Gibbons and Sharitz, 1974). At temperatures greater than 50 °C, only thermophilic bacteria and algae survived (Gibbons and Sharitz, 1974).

The introduction of thermal effluent at the Savannah River Site resulted in tree mortality of over two-thirds of the swamp (Sharitz et al., 1974a). Total (100%) tree mortality occurred in the 227 ha thermal delta while some tree mortality and stunting resulted in an open canopy forest in an additional 263 ha with moderate thermal impact. Downstream of the 263 ha area, a 1396 ha area with low thermal impact experienced minimal tree mortality (Sharitz et al., 1974a). The decrease in tree mortality with distance reflects decreasing temperature stress. In the thermal delta, water temperatures were >25 °C above ambient and there was increased inundation. There was increased siltation as a result of erosion of the banks due to the lack of vegetation (Sharitz et al., 1974a). Hardwood species were unable to tolerate the combination of increased flooding, high siltation, and high temperatures (Sharitz et al., 1974a; De Steven and Sharitz, 1997).

The disturbance in the study area extended beyond the areas of continually elevated water temperatures. Scott et al. (1985) concluded that episodic pulsing of thermal effluent during the growing season was the primary cause of the disturbance within the least and intermediate disturbed areas. Canopy tree density decreased with increasing disturbance. Within the undisturbed forest, tree density was 1060 trees/ha which was substantially higher than in the disturbed area. Tree density decreased measurably with increasing thermal and substrate disturbance. Tree density was 20 trees/ha in the most disturbed site (De Steven and Sharitz, 1997).

Sharitz et al. (1974b) studied the impacts of the thermal effluent on vegetative composition at the Savannah River Site. They compared three areas classified as unaffected, affected by the heated effluent, or as post-thermal recovery. The unaffected swamp was composed primarily of woody plant species, 40% were trees and 14% were woody vines and shrubs. The remaining 46% were annual and perennial herbaceous plants. In contrast, the affected swamp was comprised mostly of herbaceous perennials (60%) and herbaceous annuals (20%). Woody species and trees comprised the remaining 20%. The post-thermal area was in the early stages of succession with a vegetation composition of herbaceous annuals (33%), herbaceous perennials (46%), understory woody species (13%), and trees (8%; Sharitz et al., 1974b).

Succession in the affected area was monitored to determine the factors affected recovery of the forest. The impacted delta appeared to follow a prolonged succession from marsh to scrub–shrub to bottomland hardwood forest (Dunn and Sharitz, 1987). Some areas in the affected swamp had arrested succession, which was attributed to modified substrate conditions, competition, and limited seed availability (Dunn and Sharitz, 1987). Seed banks and living rootstock available for regeneration were killed by the long-term thermal stress of the heated effluent (De Steven and Sharitz, 1997). Downstream of areas with complete tree mortality, the only viable seed came from the surviving tree (Schneider and Sharitz, 1988). The potential for succession in the area was complicated by the thermal and hydrological alterations and the possible limitation of a seed source. The mortality of seed shed into thermally elevated water was high. Only 25% of bald cypress seed survived being submersed in 50 °C water for 72 h (McLeod and Sherrod, 1981). Locations with stream temperatures above 42 °C had limited bald cypress germination, and survivorship was very low (Sherrod et al., 1980). Water temperatures in the study area typically exceeded 45 °C, and vascular plants did not thrive in the water or the associated sediments (Sharitz et al., 1974b). Christy and Sharitz (1980) studied three populations of *Ludwigia leptocarpa* grown under three different thermal conditions (22, 32 and 42 °C). Seedlings from all three populations showed similar growth responses at 22 °C, whereas at 32 °C seedlings from the higher temperature locations grew more rapidly. At 42 °C, survivorship of seedlings from all three seed populations was low.

Donovan et al. (1988) showed that black willow (*Salix nigra*), water tupelo and bald cypress growth was unaffected with a 5 °C elevation in water temperature. However, an increase in height and diameter was noted in buttonbush (*Cephalanthus occidentalis*) at approximately 35 °C. With regard to flooding duration and temperature increase, stem diameter and height, biomass, and survivorship of water tupelo and bald cypress were all reduced by temperatures of 40 °C. By contrast, buttonbush was capable of tolerating high temperatures and increased flooding (Donovan et al., 1988). The 35 °C temperature range is representative of the water temperature of the cooling water being considered for discharge to the forested wetlands at Uncle Sam, Louisiana.

The species richness and diversity in ponds and wetlands at the Savannah River Site were affected by the change in hydrology and temperature range. Three pond systems (Pond C, Pond B and Par Pond) received different exposure to heated effluent (receiving thermal effluent, post-thermal, and no direct elevation of water temperature, respectively; Parker et al., 1973). The floral and faunal composition of each pond was directly related to the thermal impact. Par Pond had a higher species richness and diversity. Pond B had less species while Pond C had the fewest. Additionally, all species identified in Pond C were present in Pond B, and all species present in Pond B were present in Par Pond. Thus, the elevation of water temperatures in the ponds decreased overall diversity, but there was an increase in species richness of thermophilic or heat-tolerant flora and fauna.

4. Faunal aspects

Higher water temperatures have a significant impact on faunal composition, growth, and reproduction. At temperatures between 30 and 45 °C, about a dozen taxa at the Savannah River Site, including rotifers, cladocerans and cyclopoid copepods, thrived, at least occasionally. Zooplankton were eliminated entirely from areas where temperatures exceeded 45 °C (Leeper and Taylor, 1995). At temperatures greater than 50 °C, only thermophilic species of bacteria and blue-green algae survived (Gibbons and Sharitz, 1974). When the reactor was operating, zooplankton abundances were reduced by 1–3 orders of magnitude, and the number of taxa was typically halved. Biovolume of phytoplankton, which generally provide the main trophic resource for zooplankton, was reduced by 20–95% (Leeper and Taylor, 1995). In a related study in a thermally stressed reservoir in Central Texas, water temperatures above 30 °C for 4 months decreased macroinvertebrates abundance substantially. At temperatures of 38–42 °C, there was a complete elimination of macroinvertebrates in the reservoir (Wellborn and Robinson, 1996).

In summary, the introduction of thermally altered effluent into forested wetlands causes stress and alteration to the floral and faunal community. The degree of impact is directly related to the increase of water temperature. A decrease in species richness and diversity, decreased plant recruitment, and increased zooplankton mortality were recorded at the Savannah River Site when water temperatures were >35 °C. The thermal change can also affect the decomposition rate of organic matter in the forest floor (Slocum et al., submitted for publication).

5. Nutrient and sediment addition

In addition to heated water, we also considered the impact of other constituents in river water on the receiving wetlands. Mississippi River water contains high levels of nutrients, especially nitrate (1–2 mg/l), and relatively high levels of suspended sediments (100–300 mg/l). One of the goals of river diversions, including the site at Uncle Sam, is to use the sediments and nutrients in river water to stimulate the productivity and accretion of coastal wetlands and thus enhance their survival. However, nutrients and sediments also have the potential to cause water quality problems when discharged directly to open waters. Thus, diversion to wetlands addresses both water quality and wetland sustainability issues. Nutrients can lead to algal blooms and result in poor water quality (Lapointe, 1992; Justic et al., 1993; deJonge et al., 1995). Suspended sediments can cause turbidity and can potentially smother bottom dwelling organisms.

It has been shown in a number of studies of Mississippi River diversions and wetland treatment systems that wetlands can assimilate nutrients and thus improve water quality (Dortch, 1996; Zhang et al., 2000; Mitsch et al., 2001, 2005; Day et al., 2004). Since one of the main causes of wetland deterioration in the Mississippi delta is a lack of nutrient and sediment input (Day et al., 2000), the sediments and nutrients in river water can help offset this problem by enhancing accretion rates (DeLaune and Pezeshki, 2003; DeLaune et al., 2003).

Wetlands, however, cannot assimilate unlimited amounts of nutrients and sediments. It has been shown that the uptake of nutrients by a wetland is related to the loading rate (Richardson and Nichols, 1985; Mitsch and Gosselink, 2000; Mitsch et al., 2001). This is usually expressed in grams of nutrient per square meter per year, $g/m^2/yr$).

In order to determine the ability of the forested wetlands at Uncle Sam to assimilate nutrients and sediments in river water, we carried out a loading rate analysis. We first calculated the loading rates for nitrate (NO_3, the main form of inorganic nitrogen in river water), total nitrogen (TN), total phosphorus (TP), and total suspended sediments (TSS). We used average monthly concentrations for these constituents in river water (Lane et al., 1999). Based on a flow of $5.2\,m^3/s$, we calculated the total amount of each constituent per month and then summed these to obtain a total amount for the year. We used $14.8\,km^2$ for the area of the receiving basin (Fig. 2). The loading rates were based on these calculations and percent reductions were obtained from Mitsch and Gosselink (2000):

Constituent	Loading rate (g/m^2/yr)	Reduction (%)
NO_3	16.4	75
TN	27.7	50
TP	2.92	60–75
TSS	2289	100

Percent reductions reported for multiple study sites throughout coastal Louisiana follow the nutrient removal values reported by Mitsch and Gosselink (2000) (Lane et al., 1999; Zhang et al., 2000; Day et al., 2004).

These reductions assume that the discharge water is distributed evenly over the swamp, a requirement that can be achieved by proper design of the distribution system. Based on results of the river diversion at Caernarvon, Louisiana, we estimate that essentially all of the suspended sediments would be retained in the swamp (Lane et al., 1999). The sediment input to the area is equivalent to an elevation gain of about 2.3 mm/year due to mineral sediments alone. The actual elevation gain would likely be higher since much of the elevation gain in coastal wetlands is due to plant root growth leading to organic soil formation (DeLaune and Pezeshki, 2003). It has been shown in a number of studies that wetland plant productivity and accretion are both enhanced when sediments and nutrients are added (DeLaune et al., 1990, 2003; Day et al., 2004; Slocum et al., 2005).

6. Hydrology

An important consideration for a project such as this is hydrology. The loading rate calculations assume that the discharged water will flow over the entire surface of the wetlands. If the water were discharged directly into St. James Parish Canal, most would flow directly into Blind River, bypassing the swamp, resulting in minimal assimilation of nutrients and sediments. Thus, it will be necessary to ensure that discharged water flows through the swamp system as overland flow. This can be accomplished by the construction of a distribution system with multiple outlets that ensure distribution of the water over a broad area of the wetland (Fig. 2). An additional hydrological aspect that should be considered is the seasonality of the discharge. Under natural conditions, forested wetlands generally flood in the winter and spring and are dry in the summer and fall. Most coastal forested wetlands in Louisiana are now continuously flooded due to the combination of lack of riverine input, subsidence, and pervasive hydrological alteration (Chambers et al., 2005). Thus, addition of more water will not cause additional flooding. The maximum amount of cooling water pumped from the river is about 5.2 m^3/s. This is equivalent to 3.1 cm/day over the forested wetlands in question, but because the water is pumped, there is wide flexibility of both timing and amount of water that could be pumped to the swamp. Water could be discharged in the winter and spring but not in the summer and fall, at a constant rate or in pulses, or any combination of discharge schedules. The distribution system also allows the possibility of discharge to different parts of the swamp at different times.

7. Conclusions and recommendations

We analyzed the potential impacts of discharge of once-through, non-contact industrial cooling water on the ecological structure and function of a forested wetland system with special emphasis on the impact of elevated water temperatures. Much of the information on the effects of elevated temperatures on forested wetlands comes from studies of the Savannah River Site. The majority of the adverse conditions due to thermal effluent on the Savannah River Site occurred when water temperatures were greater than 35 °C. The temperatures of the cooling water of the IMC Phosphate Company are less than the high temperatures at the Savannah River Site in the winter (21 °C) but higher in the summer (38 °C). Sub-lethal effects including species shifts and increased metabolism could be serious problems. This may be most serious for increased soil respiration and oxidation of organic substrates. Loss of soil material would be a serious problem for subsiding coastal environments of coastal Louisiana. It is likely that the IMC cooling water would have to be cooled before it could be discharged to the swamp. This could be accomplished in a number of ways including mixing with ambient water, heat exchangers, aerial spraying, and cooling in transit to the swamp.

We also considered potential impacts on primary productivity of understory and canopy species, marsh elevation change, and soil biogeochemical processes. Increased temperatures could result in increased soil organic matter decomposition and soil nitrogen mineralization. Increased soil oxidation could lead to loss of soil elevation while nutrient mineralization might stimulate organic soil formation. The accelerated rate of decomposition can potentially contribute to subsidence. This could be particularly important in the subsiding environment of coastal Louisiana. Monitoring of soil oxidation will be necessary in any project where cooling water is diverted to wetlands in Louisiana. Thus, it is necessary to understand how increased temperature will affect the balance between these two processes. Based on the amount of water to be discharged and the area of the receiving wetlands, it is likely that the wetlands would be able to assimilate from 50 to 75% of the nutrients and sediments. This would stimulate wetland productivity and accretion.

In summary, our findings and recommendations are as follows:

1. Discharge of heated water is a concern because of the possibility of species shifts, mortality, and affects on metabolic rates, especially the potential for increased soil respiration and decomposition. It seems very likely that the temperature of the cooling water will have to be decreased before discharge, particularly if water is discharged in the summer. Discharge of the water to different parts of the swamp at different times and non-continuous discharge are ways to minimize the impact of temperature.
2. The swamp system will be able to retain essentially all suspended sediments and assimilate a large portion of the nutrients discharged, even at continuous discharge at the maximum rate of 5.2 m^3/s.

3. We recommend that a pilot study be carried out so that an optimal discharge regime can be developed. The pilot study should focus on the effects of different temperatures on the functioning of the system, the retention of sediments and nutrients, and the examination of different discharge scenarios.

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