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University of Alberta

Adaptive Management and Nutrient Retention in a Northern Prairie Wetland Restored with Agro-Industrial and Municipal Wastewater at Frank Lake, Alberta.

by

Jay Steven White ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of

Master of Science

in

Environmental Biology and Ecology

Department of Biological Sciences

Edmonton, Alberta

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Adaptive Management and Nutrient Retention in a Northern Prairie Wetland Restored with Agro-Industrial and Municipal Wastewater at Frank Lake, Alberta*, submitted by Jay Steven White in partial fulfillment of the requirements for the degree of Master of Science in Environmental Biology and Ecology.

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[illegible]

"The public should no more trust bureaucrats to assess their own environmental work than they should trust third-graders to design their own report cards."

--Andrew Nikiforuk "The Nasty Game"

Dedication

For my mom, Beatrice Francis White, whose tremendous support (both financial and otherwise) over my educational career made this whole project possible.

Abstract

Frank Lake, Alberta is a large (1 246 hectare) northern prairie wetland in southern Alberta, Canada, that was restored using secondary treated municipal and agro-industrial wastewater. Five years after restoration began, a one year study determined (1) spatial distribution of nutrients in marsh surface waters (2) surface water nutrient treatment efficacy and (3) the ability of sediments to retain added phosphorus. During the ice free seasons, NH_3-N, NO_3-N and TP surface water concentrations were decreased by 76%, 87% and 64% respectively, as waters flowed through the first basin of the marsh. February treatment was less successful, with surface water NH_3-N, NO_3-N and TP concentration reductions of 46%, -26% (export) and 26%, respectively, through Basin 1. Sediments near the inflow had a limited ability for additional P-sorption but had greater sedimentation and P- burial rates than all other sites. While the Frank Lake is presently providing effective nutrient retention, treatment efficacy may decrease as continued high loadings to the marsh lead to sediment saturation, eutrophication or phosphorus export from the marsh.

Acknowledgments

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Chapter 1: Introduction to the Frank Lake Study

Background

The Frank Lake wetland complex in southern Alberta, Canada, was restored in 1989 with river water, municipal wastewater and agro-industrial wastewater after a prolonged drought. The large northern prairie wetland was divided into three discrete basins, managed to both improve water quality and provide wildlife habitat. Outflow from the marsh to the Little Bow River began in 1993 after water levels became stabilized in the marsh and runoff exceeded marsh capacity. Recent water quality data from Alberta Environment Protection indicated that nutrients from Frank Lake could negatively impact the Little Bow River (Sosiak 1994).

History

Frank Lake, Alberta is a large (1 246 ha) northern prairie wetland in southern Alberta Canada subject to great variations in water level. The prairie pothole region is recognized as the principal waterfowl production area of North America. Ducks Unlimited Canada sought to establish permanent water levels in Frank Lake as far back as 1945, because of the importance of the marsh to waterfowl in southern Alberta. The Frank Lake ecoregion itself is considered to be of local, regional and provincial importance for breeding colonial waterbirds, migratory birds, staging geese, staging ducks, and for rare, threatened and endangered species (Poston *et al.* 1990; Wallis *et al.* 1996). However, attempts to maintain waterfowl habitat in the marsh failed in 1983 when the marsh dried completely (Howarth-Brockman and Smallwood 1989).

An opportunity arose in 1988 to restore Frank Lake with treated wastewater from an industrial beef packing plant. Ducks Unlimited agreed in principal to the arrangement but requested additional water to compensate for evaporative losses and to speed the filling of the marsh. In October of 1989, three new sources of water began to flow into Basin 1 of Frank Lake: (1) fresh water from the Highwood River, (2) secondary treated municipal sewage from the Town of High River and (3) secondary treated wastewater from the Cargill beef packing plant. Physical modifications were made to the existing wetland, which included dividing the marsh area into three discrete basins to better control water levels and maintain productive waterfowl habitat. However, no specific modifications were made to the marsh to optimize the Basins for nutrient assimilation. After completion, the Frank Lake wetland became the largest Canadian marsh to be restored with nutrient rich wastewater. The marsh is managed for the dual objectives of water quality improvement and provision of wildlife habitat. However, water quality data from Alberta Environment Protection indicated that nutrients in water from Frank Lake could negatively impact the downstream Little Bow River (Sosiak 1994).

This thesis deals with the adaptive management issues and nutrient retention ability shown by the Frank Lake marsh over a one year study period. Chapter 1 is an introduction to the thesis. Chapter 2 describes the adaptive management process of the Frank Lake Project and present the benefits of marsh restoration. Chapter 3 quantifies the treatment efficacy of Frank Lake to remove N and P from surface waters by: (a) determining the spatial and temporal nutrient concentrations in Basin 1 of the marsh, (b) quantifying historic P loadings to the marsh since restoration in 1989 and (c) comparing outflow nutrient concentrations from our marsh to those of nearby reference wetlands. The goal of Chapter 4 is to (a) determine the spatial distribution of P sedimentation in the two main basins of Frank Lake and (b) compare the sorption ability of Frank Lake sediments with nearby wetland sediments to identify sites of saturated P-sorption. Chapter 5 is a summary of the thesis work and outlines the main conclusions of the thesis work.

This research will help (1) guide managers of large scale wetland restoration projects (2) provide some of the benefits of wetland restoration (3) give an indication of the performance of a restored Canadian wetland to treat high nutrient loadings (4) give an indication of the impacts of high loadings on the marsh (5) provide an indication of the major mechanisms of nutrient storage (6) provide data on the nutrient assimilation capacity of a northern prairie wetland and (7) provide data to be used for comparison with other natural systems designed to treat wastewater and provide wildlife benefits.

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Chapter 2: Restoration of a Canadian prairie wetland using agricultural and municipal wastewater: Adaptive management and cooperative conservation at Frank Lake, Alberta

Introduction

The prairie pothole region of the mid-continent has long been recognized as the principal waterfowl production area of North America (Crissey 1969; Posphala et al. 1974). This region comprises 10% of the total continental waterfowl breeding area but produces more than 50% of the fall flight of ducks (Smith et al. 1964). Canadian prairie pothole wetlands have decreased 71% in area and American prairie pothole wetlands have diminished by 75% since settlement (Lands Directorate 1986; Jahn 1988). Wetland habitat loss is greatest where population, agriculture and development activities are the highest (Lands Directorate 1986). Climate, politics, economics and public attitudes influences these wetland losses (Leitch 1983).

Prairie wetland habitat loss has been directly linked to diminishing waterfowl populations (Crissey 1957; Gollop 1965; Stoudt 1969, 1971; Smith 1971, Henny et al. 1972; Posphala et al. 1974 and Reynolds 1987). The highly variable nature of temperature and precipitation in the area subject prairie pothole wetlands to wide annual fluctuations which may also decrease habitat. Both water and high quality upland cover are required for the success of many species of waterfowl. A Canadian study (1981-1989) revealed a 93.4% habitat degradation in the area responsible for producing more than two-thirds of Canada's ducks (Turner and Caswell 1989). Permanent re-establishment of high quality habitat in southern Alberta has become an important task for wildlife organizations in their efforts to restore waterfowl populations (Turner and Caswell 1989).

The Frank Lake wetland in the prairie pothole region of southern Alberta, Canada, has historically undergone considerable reduction in size due to climate influences and agricultural drainage. By the mid-1980s the marsh was dry. Ducks Unlimited Canada's main objective was to restore the failed Frank Lake wetland and bring back high quality habitat for waterfowl to help compensate for ongoing wetland losses in the prairie pothole region. Fresh water to restore the marsh was not available, so Ducks Unlimited had to employ other management strategies.

The opportunity arose in 1988 to restore Frank Lake with treated wastewater from a beef processing facility that Cargill Foods Ltd. had proposed in the Town of High River. Ducks Unlimited accepted Cargill's offer and negotiated additional water from the Highwood River and the Town of High River. Ducks Unlimited, on behalf of Provincial and North American Waterfowl Management Plan (NAWMP) partners, developed a project concept and outlined the goals and objectives for Frank Lake restoration. Management options considered long term loadings of nutrient rich wastewater into the marsh along with the previous goal of creation of high quality waterfowl habitat. Project implementation proceeded quickly after securing the participation of key stakeholders.

Frank Lake was reshaped from one large basin into four smaller basins. The original main basin was divided in two by a berm and two other basins were created on acquired lands within the Intensive Management Unit of Frank Lake. This allowed management of each basin separately based on their different morphology and state of development. This strategy allowed restoration one basin at a time as water availability would permit.

The purpose of this paper is to describe the development process of the Frank Lake Project and describe the management options that were assessed and implemented. Examples of wetlands restored using treated wastewater and examples of Canadian prairie wetlands used for wastewater treatment are given. The benefits of the Frank Lake restoration are briefly quantified and some of the key components for successful adaptive management projects are presented.

Wetland Restoration Using Treated Wastewater

Traditional arguments for the preservation or restoration of wetlands have included wildlife preservation, aesthetics, and the maintenance of biodiversity. In recent years, economic factors have spurred the restoration of wetlands. Jones et al. (1995) states that intrinsic values may be at the heart of our conservation effort, but the justifications may well be utilitarian. Some of the more sophisticated analyses of wetland values include reduction of flood damage, water quality improvement, recharging of ground water and fisheries production. Jordan et al. (1988) recognize that freshwater wetlands restored to create game and wildlife habitat for economic interests still have important implications for the conservation of biodiversity. Showing the economic benefits of wetland restoration can influence the public to support legislation that protects or restores lost wetlands.

Fog and Lampio (1982) stated that "few of the world's major habitat types have suffered as drastically from man's abuses of the environment as wetlands". The losses of prairie wetlands are among numerous quantified wetland losses throughout the world (Lands Directorate 1986, Dahl 1990, Dahl et al. 1991). Canada falls far behind the United States in statutes to protect wetlands. The social desire for ecological restoration in the United States is reflected in numerous regulations such as NEPA and Section 404 of the Clean Water Act. These regulations contain provisions for mitigation, rehabilitation, enhancement, and restoration of natural wetland systems (Tripp and Herz, 1988). Without legislation for ecological restoration of wetlands, Canadians rely heavily on two groups to reverse this trend: resource management agencies (such as non-governmental agencies) and private landowners. Unfortunately, many resource management agencies suffer from a lack of technical expertise to support wetland management and protection (Jones et al. 1995).

Municipal and Agricultural Effluent

There are at least 1500 documented examples of wetlands used to remove nutrients, sediments and biological oxygen demand (BOD) from treated municipal and agricultural effluent (Knight, 1993). Many small communities have agriculture-based industries within the town which use municipal waste treatment. The ability of wetlands to break down wastewater pollutants has been studied with increasing frequency in recent years. Wetlands are now being constructed for the sole purpose of treating effluent, while providing concurrent benefits to waterfowl. For example, government agencies in South Dakota have made a concerted effort to build prairie wetlands for tertiary treatment of nutrients from small municipal/agricultural treatment plants (Dornbush, 1993). Between

1987 and 1991, 40 wetland systems were engineered and installed in South Dakota. This method of wastewater treatment is land intensive, generally requiring one hectare of wetland for 104 people.

According to Bastian and Hammer (1993) there are three main approaches used to treat wastewater using wetlands:

1. systems designed to treat the maximum amount of wastewater in the smallest possible area (the wetland in Listowel, Ontario is the main Canadian example);
2. systems designed to provide tertiary treatment of relatively low to moderate volumes and loadings while at the same time enhancing wildlife potential; and
3. systems that use treated effluent as a source of water to restore or create wetlands for wildlife habitat.

Canadian prairie wetlands used for wastewater treatment

As many as 67 Canadian examples of wetlands receiving stormwater or municipal wastewater have been reported (Pries 1994). However, only three prairie wetlands receiving municipal treated effluent were documented: Brookhaven and Humboldt in Saskatchewan and Blue Quill, in Alberta.

(1) Brookhaven, Saskatchewan. Lakshman (1979), while comparing this marsh system to a modern wastewater treatment plant, found the wetland providing similar nitrogen removal and approximately 10% more BOD (biological oxygen demand) and COD (chemical oxygen demand) removal.

(2) Humboldt, Saskatchewan. The author concluded that wetlands were effective at treating phosphorus, nitrogen and BOD from municipal sewage, but presented no supporting data in the paper (Lakshman 1983).

(3) Blue Quills School, St. Paul, Alberta. This wetland removed total suspended solids (TSS), BOD, coliform, nitrogen and to some extent, phosphorus (Kent 1987). This wetland was successful in treating septic tank effluent, but significant impacts were noted at the point where effluent is discharged into the marsh. It was suggested that the soils in the immediate plume had become saturated with phosphorus (Kent 1987).

Impact on wetlands

While many of the wetlands that receive municipal and agricultural wastewater have shown fairly efficient removal of nutrients (Hammer et al. 1993) even in cold climates (Maehlum et al. 1995), the impacts of the added nutrients on wetland vegetation have varied (Brown and Stark 1989; Kadlec and Bevis 1990). Some wetlands have retained their natural vegetation, while in other wetlands the vegetation has changed. For example, a 179 ha natural wetland in St. Albans, Vermont which received treated municipal effluent exhibited a noticeable deterioration of water quality, a reduction in submersed aquatic macrophytes, an increase in phytoplankton populations, and a decrease in benthic invertebrates when compared to a nearby similar wetland (Schwartz and Gruendling 1985).

Frank Lake site description

The Frank Lake Conservation Area is located six kilometers east of the Town of High River, Alberta (50^0 33' N; 113^0 42' W) in the Frank Lake Plain sub-region of the Fescue Prairie Ecoregion (Poston et al. 1990) (Figure 2.1). Frank Lake lies in an arid region of Canada where net evapotranspiration exceeds net precipitation. Mean average rainfall and snowfall measured at the Town of High River is 316.3 and 172.0 mm year^{-1} respectively, totalling 488.2 mm year^{-1}(Environment Canada 1982). Mean calculated lake evaporation for the area is 522.9 mm year^{-1}, giving a mean annual water loss of 34.7 mm year^{-1}(Environment Canada 1984). Calcareous glacial till surrounds the area and the lake consists of lacustrine sediments of slightly alkaline pH. The major habitats of Frank Lake include upland native mixed grasslands, meadows and shorelines, wetlands, and human-modified habitats (Wallis et al. 1996). The main marsh is 1 246 ha (3 079 acres) with other seasonal potholes in the area totalling another 140 ha (350 acres). An additional 698 ha (1 725 acres) of uplands are intensively managed for wildlife benefits within the Management Unit. Completed in 1994, the Frank Lake Conservation Area has parking facilities for the public, a viewing blind and appropriate project signage.

The importance of the Frank Lake region to waterfowl and other wildlife

Ducks Unlimited and Alberta Environment have long recognised the importance of the Frank Lake region to nesting and staging waterfowl, marsh birds and shorebirds (Sadler et al. 1995). While important as a brood marsh, Frank Lake is also the only large permanent wetland in the area to provide habitat for staging and moulting waterfowl of the Pacific Flyway Corridor from the west. The Frank Lake ecoregion is considered of either local, regional or provincial importance for breeding colonial waterbirds, migratory birds, staging geese, staging ducks, and for rare, threatened and endangered species (Poston et al. 1990; Wallis et al. 1996).

Establishment of high quality habitat through land reclamation ensures wildlife production at Frank Lake. Up to 90% of the original landscape in the Frank Lake area has been altered by intensive agricultural production and the remaining grasslands and meadows are fragmented. Disturbance has been due to cultivation and repeated heavy grazing (Wallis et al. 1996) and several native plant and animal populations have been reduced or eliminated (Wallis et al. 1996). Fowler (1937) noted extirpation of wolf (*Canis lupus*), coyote (*Canis latrans*), badger (*Taxidea taxus*), swift fox (*Vulpes velox*), antelope (*Antilocapra americana*), sharp-tailed grouse (*Tympanuchus phasianellus*) and greater prairie chicken (*Tympanuchus cupido*) from the High River area. No mention was made of extirpated plant species, but the invasion of weedy species such as dandelions (*Taraxacum* spp.), Bladder Campion (*Silene latifolia*), Toadflax (*Linaria vulgaris*), and European Ox-eye Daisies (*Chysanthemum leucanthemum*) were noted by Fowler (1937).

Fragmented landscapes with non-contiguous habitats, and the absence of natural processes like grazing and fire may be responsible for the low species diversity of upland wildlife previously found at Frank Lake (Wallis et al. 1996). These disturbances commonly led to small populations with altered system dynamics. Because of the low species diversity previously found in this area, Patriquin (1993) gave Frank Lake restoration high priority for vertebrate species and habitats under the North American Waterfowl Management Plan (NAWMP). Wallis et al. (1996) identified several significant areas within Frank Lake that require special management considerations or that were noteworthy for other reasons. These areas included native grasslands, a large bulrush marsh and four shallow water wetlands along the bays and shores of Basins 1 and

2 (Figure 2.1).

Development of the Frank Lake project

In 1988 Cargill Foods Ltd., a privately owned multinational corporation, was looking to build a modern beef processing facility in southern Alberta close to both suppliers and markets. The Town of High River located south of Calgary was chosen for the plant site and the Highwood and Bow Rivers were proposed by Cargill as disposal sites for their secondarily treated wastewater. Alberta Environment rejected the use of either of these rivers for Cargill's nutrient-rich wastewater, as municipal wastewater from the Town of High River was already causing prolific weed growth and fish kills in the Highwood River (Alberta Environment 1990).

Alberta Environment was aware that Ducks Unlimited held a water licence for Frank Lake and suggested a joint meeting with Cargill Foods Limited. Cargill Foods and Alberta Environment approached Ducks Unlimited Canada in May 1988 and proposed restoration of Frank Lake with Cargill wastewater. The proposition provided a guaranteed water supply to the lake for Ducks Unlimited and an environmentally friendly means of wastewater disposal for Cargill Foods. Ducks Unlimited agreed to the concept of accepting wastewater from Cargill Foods, and requested additional fresh water from the Highwood River and wastewater from the Town of High River to compensate for evaporation. This action would both dilute Cargill's nutrient rich wastewater and speed lake restoration (Sadler et al. 1995). High River municipal wastewater would then be pumped to Frank Lake instead of the Highwood River, and this pleased environmentalists and supporters of the local trout fishery.

Goals and Objectives of the Frank Lake Project

The main goal of Frank Lake management was to reestablish the marsh on a permanent basis. Ducks Unlimited instituted an ecologically based adaptive management plan that maintained the natural habitat variability and provided habitat management for the full range of species that historically and recently occurred at the site (Sadler et al. 1995). The detailed project goals were broken down into immediate project goals and long term management goals (Table 2.1). Several stakeholder concerns were addressed within the immediate project goals. Stakeholders were assured that the wetland would not flood onto adjacent farmed land, and that the marsh itself would pose no problems such as odours, mosquitoes or groundwater contamination. Stakeholders also wanted to be assured that the marsh would be able to take up long term nutrient loadings and be able to accept additional wastewaters when Cargill Foods or the Town of High River expanded.

Project coordination

Ducks Unlimited (DU) Canada have managed Frank Lake since the 1940s and had gathered much information on the site. Biological reconnaissance of feasibility and potential productivity studies had been performed and engineering surveys of contours, slopes, soil stability and water tables were also available. These studies provided background information that was instrumental in rapid project implementation. The project cost to Ducks Unlimited Canada alone was over a million dollars and had to be approved by DU's joint Board of Directors. The cost/benefit ratio (cost per incremental duck versus man•day rates and cost recovery) was acceptable and the Board of Directors approved the project.

The Frank Lake Project Implementation Committee included DU, Cargill Foods, Alberta Environment, the Municipal District of Foothills, Alberta Transportation & Utilities, Alberta Fish & Wildlife and the Towns of High River and Okotoks. Membership on the implementation committee was not static and participation of interested parties changed as necessary including groups such as Trout Unlimited. The purpose of the committee was to oversee the five components of project development, which included:

1. tertiary wastewater treatment options
2. wetland development options and associated water needs,
3. finding an acceptable period for withdrawal of Highwood River water
4. evaluating locations for withdrawal of water from the Highwood River
5. evaluating pump station, pipeline and discharge options

Implementation schedules for the five components were drawn up by the committee in June, 1988 with final options and government approval scheduled for August 1988. Component number four was tabled to receive approval in October (Table 2.2). Thus, the project had a very short time frame from the initial planning in May 1988 to final approval of all components by October 1988.

Funding programs

Money for land purchase came from several funding programs including the North American Waterfowl Management Plant (NAWMP), Alberta Prairie CARE (Conservation of Agriculture, Resources and Environment) and DU's Ducks and More. The NAWMP is a multi-million dollar international cooperative effort to restore waterfowl populations through several initiatives including land purchase in Canada and the United States. Alberta Prairie CARE is the main landscape treatment activity of the NAWMP and offers technical and financial assistance to farmers and other landowners. Under Alberta Prairie Care, marginal cultivated lands are purchased and leased for grassland conversion to duck nesting cover, and agricultural techniques that protect soil resources are promoted. DU's Ducks and More program ensures that priority non-waterfowl groups such as colonial and other marsh birds, shorebirds, grassland birds, birds of prey and endangered species are considered and managed under the NAWMP.

Additional financing for the Frank Lake project came from Cargill Foods, a grant from Alberta Department of Transportation and Utilities, Alberta Forestry, Lands and Wildlife, and the Alberta Recreation, Parks and Wildlife Foundation (Haworth-Brockman and Smallwood 1989). Funding specifically for the pipeline construction came in the form of government grants to the Town of High River. With money secured, the land purchase around Frank Lake proceeded quickly. Some local landowners signed free easements and a land swap was negotiated with a local Hutterite communal farm to obtain particular sections. The speed at which land was purchased may have temporarily inflated land prices in the area. Total lands purchased were 1 083 ha (2 677 acres), of which 289 ha (713 acres) were flooded. These lands were retired from pasture and cultivation uses.

Legal Requirements of the Project

There was little public review necessary in 1988 for this project, and the application for a diversion license from the Highwood River was the only legal requirement. The application for a diversion license and the proposed diversion schedule were advertised in local newspapers in January of 1989 (Figure 2.2). Ducks Unlimited reduced concerns of the local trout fishery groups by avoiding water removal from the Highwood River in June or July when trout spawn and other irrigation requirements are high. The compromise was acceptable to both Trout Unlimited and Alberta Fish and Wildlife. Since DU already held a water diversion license for the Frank Lake site, their application requested a modification of the existing diversion license, and was not deemed a new water diversion project. The moratorium on water diversion projects on the Highwood River was temporarily lifted and the permit was issued to DU. No other public processes or Environmental Impact Assessments were necessary for the project. Today, a similar project would be reviewed by the Natural Resources Conservation Board (NRCB) and subject to Canadian Wildlife Service (CWS) rules on migratory and inland waterways.

Water Volumes and Flows

Water began to flow in the spring of 1989. By July of 1993, Basin 1 had been filled to its Normal Operating Level, and some water had spilled to the Little Bow River. The volumes of water piped into Frank Lake were approximately:

(1) 910 000 L (200 000 gallons) per day of secondarily treated municipal wastewater from the Town of High River,

(2) 2 275 000 L (500 000 gallons) per day of secondarily treated wastewater from the Cargill beef processing plant and

(3) approximately 455 000 L (100 000 gallons) per day of water from the Highwood River. The amount of water removed from the Highwood River in the spring for dilution was determined by Alberta Environment, and varied yearly. At the time of writing, no water from the Highwood River had been pumped into Frank Lake since the summer of 1993.

Management Strategies at Frank Lake

Waterfowl management at Frank Lake is focused on mitigating factors that limit waterfowl production in the area such as the lack of secure water supply, the lack of diverse wetland habitat and the shortage of upland nesting cover. Several upland and water management initiatives have been employed to overcome these problems. These initiatives include reclamation of cultivated lands to native grasses, weed eradication, grazing, backflood irrigation, and drawdowns. Other management strategies deal with the management of plant and animal wildlife, sewage water and visitors.

Upland management strategies

Properly managed upland habitats are critical for waterfowl production. Up to three times as much properly managed upland area may be required per unit area of wetland to support the wetland inhabitants (Haworth-Brockman and Smallwood 1989). Managers of Frank Lake are focusing on reclamation of cultivated lands to native species to produce cover for breeding waterfowl, birds and mammals. Almost 800 ha of upland cover have already been restored to native grasses and shrubs by seeding (Sadler et al. 1995). There is a zero tolerance weed policy in effect in seeded areas with spot spraying of noxious weeds elsewhere. Spraying of chemicals over water is not permitted.

Grassland areas are managed by selective grazing or mowing and fire strategies to encourage growth of keystone prairie species. These strategies are an effort to mimic the natural system and help control non-native species (Sadler et al. 1995). Cattle were allowed to graze around Basin 3 of Frank Lake in 1995 on an experimental basis, and the impacts of grazing are not yet known. Deferred grazing has been suggested for the native grassland areas north of Basin 1. Burning has not yet been employed at Frank Lake, but may be considered in future management to maintain and restore productive wildlife habitat (Anon 1996).

Water management techniques

An important wetland restoration technique is to restore water levels to appropriate seasonal depth variations (Jordan et al. 1988). A variety of techniques can be employed to manage water levels in wetlands such as the construction of dams and weirs, backflooding, drawdown, and the addition of wastewater such as municipal effluent. Maintenance of a permanent marsh at Frank Lake had to overcome the natural water level fluctuations that occur annually and those that occur over decades. The goals of the Ducks Unlimited project dictated that a minimum amount of water was to be retained in a core area of the marsh during the dry late summer months. Higher water levels to expand the marsh area during wetter periods of the year was also part of the management goals.

Control structures at Frank Lake

Physical modifications of the purchased lands around the Frank Lake marsh (berms, ditches and dykes) were made to control water levels and maintain productive waterfowl habitat. Wastewater is pumped 12 kilometers to Frank Lake from a common lift station through a 50 cm (20 inch) diameter underground pipe. Effluent is pumped into Basin 1 at a single point source through a 100 m (300 foot) long canal into Cargill bay (Figure 2.1). An internal ditch in Basin 1 channels water from the inflow canal to outflow weir at Basin 2. This ditch has been shown to short circuit water flow through Basin 1 (Bayley et al. 1995). Basin 1 and 2 are separated by a dyke, and water control structures are built on the inflows to Basins 2 and 3. Water from Basin 3 empties into the Little Bow River. Generally, there is little water release from Basin 2 to Basin 3, however, there was some release into Basin 3 in 1993 and again in 1996. Basin 4 is ephemeral, and fills to a shallow depth during spring runoff and slowly dries through summer. A small ridge called Gladys Ridge, spring runoff and artesian wells also contribute water to Frank Lake. Groundwater recharge or discharge into Frank Lake has not been quantified, but is thought to contribute fresh water into the basins.

Backflood Irrigation and Drawdowns

Backflooding is a technique used to flood an area during the spring, then allow the collected water to recede at a controlled rate throughout the summer. This procedure attracts several species of waterfowl and shorebirds by providing shallow water and exposed mudflat habitat. An additional 283 hectares (700 acres) is added to the existing basin every spring at Frank Lake with backflood irrigation (Haworth-Brockman and Smallwood 1989).

Backflooding can be alternated with another water management technique called drawdown. Drawdowns are the intentional lowering of the water level from an area thorough the use of a weir or water control structure. Gradual drawdowns are used in Frank Lake to expose mudflats and to maintain the full range of marsh vegetation and to create feeding habitat for waterbirds, marsh birds and shorebirds. Due to distinct differences in basin morphology and state of vegetative development, each basin of Frank Lake is managed differently.

Management of the four sub-basins of Frank Lake

Basin 1 (502 ha) receives all of the sewage and agricultural wastewater as a single point discharge. A zone of poor water quality has been identified in the immediate inflow plume (Bayley et al. 1995). Basin 1 has advanced vegetative development with extensive shallows and lush emergent vegetation, and provides the best marsh habitat at Frank Lake. Presently, it is managed at its Normal Operating Level (501.8 ha; 1 240 acres) at a depth of 1.0 m (3 feet), which is 0.6 m (2 feet) below Full Supply Level (FSL). The Normal Operating Level encourages continued growth and development of hemi-marsh conditions. If this basin becomes overgrown with emergent growth, the water level will be raised to FSL to drown out the excessive vegetation. At FSL, Basin 1 covers 601.1 ha (1 485 acres). During dry summers, the edges of the marsh dry and the flooded area is smaller.

At Normal Operating Level, Basin 2 covers 360.2 ha (890 acres) at a depth of about one metre (3 feet). Basin 2 has much less emergent vegetation than Basin 1 because Basin 2 was historically too deep for emergent macrophyte growth. Ducks Unlimited has changed the management of Basin 2 and will keep it shallow to encourage emergent vegetation growth. Future management of this basin is to develop hemi-marsh conditions (50% open water, 50% emergent vegetation) when vegetation returns.

Basin 3 lies south of the first 2 basins and has been fitted with a variable control structure to allow flooding of 138.8 ha (343 acres). This shallow seasonal marsh is valuable for staging waterfowl and breeding bird habitat. However, the basin is too shallow to maintain permanent marsh conditions for waterfowl. For this reason, the basin is managed to collect runoff in the spring then slowly drain (both naturally and with human intervention) through July. This exposes mud flats and shallow flooded areas, encourages shallow marsh vegetation and provides habitat for migrant shorebirds. Future management of Basin 3 includes seeding with whitetop grass *(Scolochloa festucacea)* to provide habitat for waterfowl and other birds. Ducks Unlimited recommends growing whitetop as forage for livestock and to provide cover for waterfowl in wetlands. Whitetop offers superior nutritive qualities and high productivity compared to other native grasses (Neill 1993). This basin is also used to backflood Basin 4 that lies northeast of Basin 3 at a similar elevation.

Basin 4 became available to Ducks Unlimited for management in the summer of 1995. It is a shallow ephemeral pool (12-16 ha; 30-40 acres) that forms each spring, and is augmented by backflooding of Basin 3. This basin is managed as a shallow seasonal wetland suitable for the establishment of whitetop grass.

Other wildlife management

Other wildlife management strategies employed at Frank Lake include the use of artificial structures to create habitats for breeding animals. Amphibian scrapes (dug by backhoe), nesting boxes for burrowing owls and mountain bluebirds, nesting structures such as flax bales and rock islands for Canada geese and platforms for hawks, rock piles for garter snakes, bat boxes and rock islands for nesting waterfowl have all been constructed (Sadler et al. 1995; Alberta NAWMP Centre 1992).

Sewage water treatment

Before pumping to Frank Lake, municipal wastewater is treated by the Town of High River through filtration with anthracite and sand, chlorination and lagoon treatment. Water is aerated, mixed and allowed to settle in a 67 day process that involves treatment through four cells. Cargill Foods treat their wastewater with modern primary and secondary treatment methods that include a final disinfection with sodium hypochlorite before pumping the water to Frank Lake.

Very little special consideration was given to optimize Frank Lake for sewage treatment. At the time, it was assumed that diluting Cargill wastewater with Highwood River water would ensure that the wastewater would not pose a threat to the integrity of the Frank Lake ecosystem. The only physical modification made to the marsh was the construction of a deep channel that runs from the inflow canal to the outflow of Basin 1. This ditch was dug to keep Basin 1 dry during construction. Unfortunately, this ditch was shown to short-circuit water flow through Basin 1 (Bayley et al. 1995).

Visitor management

Visitors are able to enjoy Frank Lake with controlled and planned access measures that separate visitors from wildlife activities spatially and temporally. The goal of visitor management is to promote use of the site with self-guided tours, and to provide enjoyment and education for visitors while maintaining the integrity and productivity of the area. Most of the marsh and upland areas are fenced, and an all-weather access road to the viewing blind is lined with boulders to keep vehicles off of the uplands area. Access to Basin 1 of Frank Lake is controlled by a locked gate which allows vehicle access from 9 a.m. to 5 p.m. Monday to Friday during the summer months. Access to the other basins is by foot only. Visitors are directed around Basin 1 on interpretive walking trails that include boardwalks, an observation mound, an observation blind and appropriate signage. Trail creation has been curbed in sensitive and productive areas. Access to the south of Basin 2 is controlled by fencing and gates, but no trail system has been developed to direct visitors away from sensitive areas in Basin 2.

Management and recreation activities such as hunting and bird-watching are minimized during critical periods to reduce impacts on wildlife. For example, DU restricts management such as hay cutting until July 15 each year to reduce effects on nesting waterfowl. Similar time constraints are placed on other management activities such as grazing and burning.

Restoration Benefits and Future Concerns

Environmental benefits

A system that can provide effective wastewater treatment and high quality wetland habitat is attractive. Frank Lake managers used strategies of adaptive management to ensure that the benefits of restoration outweighed any negative impacts. For Cargill Foods, the creation of an industry and a wetland that could improve water quality in nearby rivers and streams was both profitable and environmentally sound. For the Town of High River and the surrounding region, the creation of an agri-food industry with an environmentally friendly method of waste removal from effluent created opportunities for business expansion.

Habitat benefits

The Frank Lake conservation area provides high quality habitat for a variety of wildlife in a region where many native plants and animals have been significantly reduced or eliminated due to habitat loss or fragmentation. It restores a hemi-marsh in an arid region of southern Alberta and secured a constant water supply to effectively manage the marsh. Effective upland habitats have been created for nesting and foraging waterfowl. These degraded habitats are all restored while eliminating pollution of the Highwood River and the well known trout fishery. Industry, wildlife and the environment all benefit from this undertaking. Results from plant and animal inventories show that this co-operative venture has already been quite successful in restoring habitat and attracting plant and animal species (Wallis et al. 1996).

Species benefits

The Frank Lake conservation area currently hosts 194 species of vascular plants (147 are native), one reptile, two amphibian, 168 bird, 16 mammal and two fish species (Sadler *pers. comm.* 1996). Significant habitats at the site include patches of upland native mixed grassland, a productive shoreline complex, an extensive bulrush marsh and diverse wetland vegetation. Frank Lake is important to the maintenance of biodiversity in the prairie pothole region. The most significant plant and animal species at the marsh include: 9 prairie bird species considered high priority by the North American Waterfowl Management Plan; 7 vulnerable, 3 threatened and 2 endangered species (COSEWIC) and 8 species of concern in Alberta; 19 regionally or provincially rare bird species; and 1 provincially and 3 nationally rare plant species (Sadler *pers. comm.* 1996). A list of landforms, vegetation, vascular plants, amphibians, reptiles, birds and mammals can be found in Wallis et al. (1996).

Economic benefits

Cargill Foods is a significant economic force in the province of Alberta, especially in the Towns of High River and Okotoks, the Municipal District of Foothills and the city of Calgary (FMP/IDEK 1995). Currently, the Cargill plant provides 3 280 direct and indirect jobs and represents an impact of $262 million annually to the provincial economy (FMP/IDEK 1995). Cargill provides the local community with a secure tax base and generates revenues for associated and value-added industries. The establishment of this facility has added stability and viability to the local community.

Tourism is another money generating activity that occurs at the Frank Lake conservation area. Areas that attract wildlife such as birds have become important travel destinations for tour operators like Ornitholidays from the United Kingdom, who bring tourists to the Frank Lake Conservation Area. The value added industry from tourism includes hotel and restaurant business which is also beneficial to the region. Professional guides from Calgary can be hired to accompany visiting hunters on Frank Lake. Hunting also brings ancillary economic benefits with the sales of sporting equipment such as clothes and ammunition.

Social benefits

The social benefits provided by the sustainable development at the High River site include the creation of a conservation area where duck hunters, bird watchers and the surrounding community can share the pride from this joint venture in cooperative conservation. Ducks Unlimited Canada has been awarded the Province of Alberta's Emerald Award for Environmental Excellence for their efforts at Frank Lake. This is the highest honour the province can bestow on an organization for environmental excellence. Cargill Foods Ltd. is also seen as a good environmental citizen and sets an example for other big businesses.

Frank Lake provides an opportunity for public interpretation and education. In 1995, DU personnel augmented the public school wetlands curriculum with guided field trips to the marsh. About 350 students from the High River area took part in this outreach program. Other visitors to the marsh include the Calgary Field Naturalists' Society, who take regular interpretive trips to Frank Lake. Business leaders have traveled from New Zealand and Bangladesh to see this example of co-operative conservation (Anon, 1995).

Scientific benefits

As part of the adaptive management employed at Frank Lake, several studies on water quality have taken place over the last five years. The latest was a two phase study conducted by researchers from the University of Alberta where water, vegetation and sediments were studied (Bayley et. al. 1995). Further research has focused on the ability of a prairie marsh to treat wastewater in a cold climate. Other research at the marsh includes: Canadian Wildlife Service bird banding, Ducks Unlimited's breeding bird survey, habitat mapping and surveys of wildlife, vascular plants, amphibians, reptiles, mammals and birds (Sadler *pers comm.*). Results of inventory and monitoring programs and scientific studies are incorporated into future management decisions for Frank Lake. A permanent Breeding Bird Survey Route and three Breeding Bird Transects have been established for ongoing monitoring.

Future concerns

While the marsh seems to adequately treat inflowing water presently, there are concerns with the long term ability of the marsh to continue providing wastewater treatment. High nutrient loadings could lead to eutrophication of the system. Eutrophication could change the species composition of the marsh, such as an algal community change from greens to toxic blue greens. Constant high loadings of phosphorus could saturate the sediments and result in poor phosphorus treatment. Poor phosphorus treatment in the marsh means phosphorus export from the marsh, resulting in downstream leakage of nutrient rich water into the Little Bow River.

The danger of groundwater recharge of nutrient rich water (especially waters nearest the inflow canal) also exists. Groundwater pollution could affect the quality of drinking water taken from nearby groundwater wells. A danger exists to users of well water including the livestock that may also drink from these wells. Future management must deal with these issues if they arise.

Implementing Wetland Restoration Projects

As wetlands become increasingly degraded in North America, wetland restoration efforts become increasingly important and the demand for information on wetland restoration techniques to improve success rates of restoration have increased (Davis 1994). The success of the techniques used on the Frank Lake project and the speed at which the goals of the project were achieved are testimony to its ability to serve as a model for other successful wetland restoration projects.

The Success of the Frank Lake Project

Two important decisions must exist to ensure the success of a large scale environmental project. First, it must be ecologically feasible given local constraints and secondly, it must be socially desirable given local values (Wyant et al. 1995). The cooperation of dozens of individuals at several levels of organization (municipal, provincial, federal and private) was instrumental in making the Frank Lake project a successful venture. Their actions assured that implementation, permitting, and orchestration of the project went smoothly in a very small time frame. Generally, Ducks Unlimited wetland projects take at least three years to get underway with the larger ones taking more than 10 years. The Frank Lake project is Ducks Unlimited Canada's largest project, and was instituted in less than one year.

While the political will behind the Frank Lake project was a key factor in the implementation of the project, there were several other factors that helped to ensure success for the stakeholders. The short term and long term benefits for this project were shown to the landowners, stake-holders and the community in general, which resulted in their enthusiasm and support for the project. The negative issues that had to be addressed were successfully mitigated. The combined benefit of job creation and establishment of an environmentally sound product has produced one of the best examples of cooperative conservation and sustainable development in Alberta. For the Highwood River the benefits were twofold; the sewage wastewater from the Town of High River was removed from the watercourse and it was spared additional nutrient loadings.

An important factor that contributed to the success of the Frank Lake project was the leadership of a large non-governmental organization. Ducks Unlimited Canada played a key role in the quick development of this project with their background information, experience, and their state of readiness on the project. They agreed to minimize impacts on the Highwood River and were successful at satisfying the specific needs of some stakeholders. Finally, Ducks Unlimited's acceptance of future stewardship of the marsh left other stakeholders with no further obligations to the marsh after project completion. Stakeholders had no long term commitment to the project and were ensured a good return on their investment with management by a reputable environmental conservation organization.

Components of successful wetland projects

The Frank Lake project provides a decision-making framework that can be used to institute large scale wetland rehabilitation projects. Many large scale environmental projects can be sidelined due to poor planning and failure at some critical step in the development of the project scheme, or the omission of key stakeholder or landowner involvement. These pitfalls were avoided in the Frank Lake project by employing adaptive management strategies. Specifically, marsh managers advocated flexible policies to promote the development of shared understandings among the diverse range of stakeholders, an approach that McLain and Lee (1996) found to be essential for successful projects.

To succeed at implementing large scale wetland management projects, resource managers should concern themselves with:

1. Stakeholder identification. Resource managers must identify project stakeholders to understand their opinions and concerns (Haney and Power 1996). Stakeholders can then be educated from the onset of the project and will then have more enlightened opinions and attitudes towards the project. Stakeholders can include local residents, employees, consumptive and nonconsumptive recreational users, environmental groups, businesses and industries that depend on local natural resources. The support of these groups can be a critical variable to ensure project completion.

2. Clear, well defined goals. The project goals and objectives, benefits and possible negative impacts should be effectively communicated to stakeholders, area landowners and the general community. Goals and objectives should reflect information gathered during exchanges with stakeholders such as the environmental, socioeconomic and cultural considerations (Haney and Power 1996). Haney and Power (1996) stated that these goals and objectives must be communicated in written form so that stakeholders have a common understanding of the issues and underlying assumptions. Wyant (1995) stressed that the goals of restoration must have a meaning to society. Uncertainty and complexity can frustrate both science and management (Haney and Boyce 1996).

3. Anticipation. Understanding stakeholder concerns and the impact that the project may have on them will be essential to effectively minimize or eliminate any negative effects. Working as closely as possible with these groups is important to understanding their concerns. In most instances consensus building can lead to a compromise. Hilborn and Walters (1977) found that forcing both managers and stakeholders to quantify their objectives was useful in identifying conflicting objectives. An ongoing part of the adaptive management process is risk abatement, and the abatement of risk has been found to be an indicator of restoration success (Wyant et al. 1995).

4. Resourceful stakeholders. Participation of an organization that can purchase lands is an essential partner in a wetland restoration project. The ideal partner will have links to programs and funding agencies that will allow for the land purchase required for successful restoration.

5. Future management. The participation of an experienced organization to provide site management after project completion is essential. Restoration projects undertaken for environmental and economic reasons may require frequent adjustments in management to maintain a viable, healthy ecosystem (Wyant et al. 1995). The inherent complexity of wetland systems demands flexibility in the implementation phase (Wyant et al. 1995). It is essential for ongoing project success that future considerations are addressed by a reputable management partner.

Conclusions

Implementation of large scale wetland management projects generally involves the cooperation of several agencies. The ability of these cooperative ventures to successfully reach completion relies heavily on the communication skills of the agencies with the stakeholders, landowners and the local community. When the benefits of the project and the successful mitigation of negative impacts can be demonstrated, then the project development sequence is hastened. The establishment of the Frank Lake Conservation Area is a model of co-operative conservation of a project with dual mandates and provides an example of adaptive management in southern Alberta.

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Chapter 3: Impacts of municipal and agro-industrial wastewaters on the water chemistry of a northern prairie wetland at Frank Lake, Alberta.

Introduction

Wetlands are commonly used to treat municipal sewage, and several studies have demonstrated the ability of wetlands to improve sewage water quality (Nichols 1983, Dornbrush 1993). A database has been established to identify and evaluate treatment wetland systems in the United States (Knight et al. 1991, Moshiri 1993) and Canada (Pries 1995). Both natural and constructed wetlands receiving municipal and agricultural wastewater have been effective in removing nutrients from inflowing water (Kadlec 1978, Nichols 1983, Bayley et al. 1985, Richardson and Craft 1993, Davies and Cottingham 1993), even during the winter in northern climates (Kent 1987, Jenssen et al. 1993). Kadlec and Kadlec (1979) summarized existing data on wetlands receiving wastewater over long time periods and concluded that the long term assimilatory capacity of nitrogen (N) is high, but that of phosphorus (P) may be limited. However, there is little published data on the ability of northern prairie wetlands to provide wastewater renovation in a Canadian climate.

Several mechanisms allow wetlands to remove nutrients from surface waters over long time periods, including sedimentation (N and P) and degassing (N). Both of these pathways can function as almost unlimited sinks for added nutrients (Moustafa et al. 1996). The ability of wetlands to transform and store nitrogen is generally very high and provides satisfactory long term wastewater treatment via nitrification and denitrification. Nitrification is the aerobic conversion of ammonia to nitrate by nitrifying bacteria and occurs in the oxygenated zone of sediments, or in the overlying water. Nitrate diffuses down into the anoxic zone of sediments, where the anaerobic conversion of nitrate to ammonia gas (denitrification) by denitrifying bacteria occurs (Brodrick et al. 1988). Denitrification is an atmospheric pathway, and acts as an unlimited NO_3-N sink by export of N_2 (Johnston 1993). Ammonia-N is assimilated in wetlands by algal or macrophyte uptake, sediment adsorption or nitrification (Howard-Williams 1985). Nitrogen removal in wetlands depends on N loading rate, wetland area, sediment type, sedimentation rate and wetland capacity for denitrification. Most studies have shown that the high rates of nitrogen removal found by marshes in the literature is due to denitrification (Crumpton et al. 1993, Neely and Baker 1989) and sedimentation (Wolaver et al. 1983).

The ability of wetlands to transform and store phosphorus (P) is generally much lower than that of nitrogen (Kadlec and Alvord 1989) and long term P retention, especially under high P loadings, is generally poor (Nichols 1983). In wetlands, there is little direct uptake of phosphate from the water column by emergent vegetation (Sculthorpe 1967) and more than 95% of the P is stored in wetland sediments (Hammer 1989) due to the long turnover time of sediment nutrients (Johnston 1991). The ability of a wetland to store P is governed by the ability to scavenge P by the three reversible processes of sorption, precipitation (the formation of minerals or salts), and incorporation (biological immobilization) (Tofflemire and Chen 1977). Scavenging converts soluble forms of P (inorganic) into particulate forms (organic) that can be buried by sedimentation (Kitchens et al. 1975, Spangler et al. 1977, Boto and Patrick 1978, Watson et al. 1989). The ability of a wetland to scavenge P is related to the forms of P, because inorganic forms of P must be scavenged before they can be sedimented. Wastewater P is mostly in the inorganic form of P (soluble reactive P (SRP)), an estimate of ortho-P, which is incorporated by biota. When P scavenging exceeds mobilization in a wetland, the wetland functions as a P sink (Bostrom et al. 1982, Swindell and Jackson 1990).

The scavenging process is countered by the process of mobilization, the breakdown or decomposition of organic P. Both scavenging and mobilization are driven by the mass of nutrient loadings into the system. Nutrient additions from wastewater can alter the balance of these processes. When mobilization exceeds scavenging, the system may become a P-source and export the accumulated phosphorus (Kadlec and Hammer 1984). For example, net phosphorus export has been shown to continue in wetlands after wastewater loadings have ceased (Kadlec and Bevis 1990) because of P mobilization. In some cases, the capacity of a wetland to provide wastewater treatment can be predicted from the loading rates applied (Nichols 1983).

In some wetlands receiving wastewater, phosphorus removal is initially high, but declines as the marsh "ages" (Nichols 1983, Kadlec 1985, Richardson 1985, Mann 1990), due to saturation of finite adsorption sites (Howard-Williams 1985, Richardson 1985, Faulkner and Richardson 1989, Breen 1990, Kadlec 1997). When the marsh becomes saturated, removal efficiencies may suddenly decrease and the wetland may begin to export phosphorus (Kadlec and Hammer 1984). While some wetlands become saturated and export P, other wetlands maintain the ability to take up treated sewage for decades (Nessel and Bayley 1984, Cooke 1992).

The purpose of the present study was to quantify the treatment efficacy of a large northern prairie wetland to remove N and P from surface waters. The approach used was (1) to determine the spatial and temporal nutrient concentrations as water flows through Basin 1 of the marsh, (2) to quantify historic P loadings to the marsh since restoration in 1989 and (3) to compare outflow nutrient concentrations from our marsh to those of nearby reference wetlands. We expected to find a region of impact limited to a plume around the inflow pipe with surface water nutrient concentrations decreasing with distance away from the pipe. We also predicted that nutrient retention in Basin 1 would be higher in the summer than during the winter and hypothesized that treatment efficacy would be effective despite the high loadings applied.

Study area

Frank Lake, Alberta is a 1 246 ha (3 079 acre) bulrush marsh that was restored in 1989 with municipal and agro-industrial wastewater under the management of Ducks Unlimited Canada. The restored wetland complex is sixty kilometres south of Calgary, Alberta (50^0 33' N; 113^0 42' W) in the Foothills Fescue Prairie Ecoregion (Poston et al. 1990). This arid region of southern Alberta is characterized by short, hot summers, long cold winters and temperatures modified by Chinook winds. January temperatures range from -45 °C to 20 °C, but average -11 °C, and July temperatures range from 9 to 34 °C, but average 15 °C (Environment Canada 1982). Evapotranspiration exceeds precipitation by 34.7 mm year^{-1} (Environment Canada 1982). The Frank Lake region has a high water table with Thin Black Chernozemic soils (Ducks Unlimited 1993). Calcareous glacial till surrounds the area and the lake consists of lacustrine sediments of slightly alkaline pH.

The entire marsh is divided into three discrete basins with a total drainage area of 342 km^2 (Figure 3.1). Winter ice and snow-pack cover the marsh from November to mid-April. Mean water depth in Basin 1 is 0.67 m (Figure 3.1) and mean ice depth is 0.57 m. The wetland is managed as a hemi-marsh with half open water and half emergent vegetation (Sadler et al. 1995). Emergent vegetation is primarily hardstem bulrush (*Scirpus acutus* Muhl.), while submersed vegetation includes sago pondweed (*Potamogeton pectinatus* L.), northern water milfoil (*Myriophyllum exalbescens* Fern.) and Richardson's pondweed (*P. richardsonii* (Benn.) Rydb.). A comprehensive list of the flora and fauna of Frank Lake is available in Wallis et al. (1996).

Secondary treated wastewater from two sources, a beef slaughterhouse (Cargill Foods Ltd. 3 000 head day^{-1}) and the local municipality (pop. = 6 000) are combined and discharged into Frank Lake. Wastewater flows of more than 5 000 $m^3 day^{-1}$ (1.12 MGD) averaging 11.14 mg $litre^{-1}$ SRP are discharged at a point source into Basin 1 (Figure 3.1). An area of wastewater impact called Cargill Bay is approximately 33% of the total Basin 1 area (total Basin 1 area is 501.4 ha), while the rest of the area (66%) is the other Basin 1 sites. Water flows into Cargill Bay in the west lobe of Basin 1 through a 200 metre long ditch (Figure 3.1). Before water levels were stabilized in 1994, there was little surface outflow from Frank Lake as the basins were being refilled. Water now flows from the 501 hectare Basin 1 (1 240 acres) to Basin 2 (360.2 ha, 890 acres) and then into Basin 3 (138.8 ha, 343 acres), before surface discharge to the Little Bow River. Basins 2 and 3 are smaller, shallower, and have less vegetative development than Basin 1, probably because they have been dry longer than Basin 1. Water levels are controlled in each basin by outflow weirs. Additional sources of water into Frank Lake include Mazeppa Creek, Blackie Creek, six unnamed tributaries, non point source agricultural runoff and an artesian well. Frank Lake presently provides critical wildlife habitat for thousands of breeding colonial waterbirds, migratory birds, staging geese, staging ducks, and for several rare, threatened and endangered species (Poston et al. 1990, Wallis et al. 1996).

Reference wetlands

Four Reference wetlands were sampled: (1) 11 km south of High River on

Highway #2 on the east and (2) west sides of the road, (3) at 152nd St. East at 532 Ave 2 km east of High River and (4) the Ducks Unlimited wetland in the Town of High River cemetery (where Homestead Way meets the Little Bow Canal). Although much smaller than Frank Lake, these northern prairie wetlands receive agricultural runoff and have similar water levels and sediment compositions as Frank Lake (Table 1).

Methods

Field collection

Water samples were collected on eight occasions from July to October 1994 and February through June 1995. UTM coordinates were used to establish a grid of sampling stations spaced 200 m apart on Basins 1 and 2. These coordinates were input to a hand held GPS locator system to navigate while on the lake and to ensure repeatability of sampling. Shallow or densely vegetated areas that could not sampled by airboat were excluded. Figure 3.1 shows the 55 sites sampled in Basin 1 and the 21 sites sampled in Basin 2.

At each site water samples were collected and the temperature, dissolved oxygen (DO), abundance of submersed aquatics, water depth (summer) and ice depth (winter) were recorded. Water samples were analysed for nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_4-N), total phosphorus (TP), soluble reactive phosphorus (SRP), pH, conductivity, turbidity and chlorophyll a. Samples were collected from 0.25m below the surface in amber Nalgene acid washed 1L polyethylene and 250 ml polypropylene bottles and stored in coolers with block ice. DO concentrations and water temperature were taken with a YSI 54A DO meter. Winter samples were collected by drilling through the ice with a 1-inch cement drill bit and using tygon tubing and a peristaltic pump to retrieve water samples from below the ice. Winter samples were collected in 80 ml glass bottles and spiked with 5 mls of H_2SO_4 to preserve P until laboratory analysis. Ice was collected by chipping a subsurface block of ice with a hatchet and left frozen until analysis. Vegetation samples were brought back to the University of Alberta for identification.

Lab analysis

Water samples for ammonia (NH_4^+-N + NH_3-N) analysis were not filtered, while samples for nitrate (NO_3-N + NO_2-N) were filtered using a 0.45 μm HAWP millipore filter and both were analysed on a Technicon Auto Analyser II. Total dissolved nitrogen was analysed on the Technicon Auto Analyser II after digestion with 4N H_2SO_4 and H_2O_2 (Stainton et al. 1977). Soluble reactive phosphorus (SRP) was analysed according to methods of Menzel and Corwin (1965). Total phosphorus (TP) was analysed by the Bierhuizen and Prepas (1985) potassium persulfate method after digestion and measured spectrophoto-metrically *as per* APHA (1992). Conductivity was measured with a CDM 83 Bach-Simpson radiometer, pH was measured using a Fisher Accumet 925 pH meter, and turbidity was measured on a Hach Model 2100A Turbidimeter.

Loadings

Wastewater P loadings were calculated for 1990-1995, using individual flow volumes and nutrient concentrations from each source. This yielded loadings from the three sources individually, expressed in grams m^{-2} $year^{-1}$. Point source volumes were compared with NPS flows, using the drainage area of the wetland and mean annual rainfall into that area. We compared total flows to Frank Lake from wastewater with the maximum amount of water that the wetland could receive from agricultural runoff.

Statistical tests

Ward's minimum variance method of cluster analysis was used to describe the spatial distribution of all nutrient parameters measured. The cluster analysis grouped sites with relatively similar values together and separated sites with relatively dissimilar values. The clusters produced were used to show spatial patterns of nutrient concentrations during each sampling run. Because of the order of magnitude differences in water chemistry parameters from the inflow to the outflow, the data were log transformed to preserve the smaller values for more realistic clustering. The sample groupings established 3 distinct groups of sites in Basin 1 (Figure 3.1). The "Inflow" was the line of sites along the inflow canal. "Cargill Bay" is the south bay where wastewater enters Frank Lake from the inflow canal. The rest of Basin 1 sites were named "RB1". Basin 2 sites were grouped "Basin 2" and Reference wetlands were grouped "Reference wetlands". Sites were ranked from highest to lowest across all runs for each nutrient sampled. These rankings were then subject to probability analysis to determine the overall effect of added wastewater on Frank Lake (Conover 1971).

Results

Source loadings into Frank Lake

Nutrient inputs from both wastewater sources were constant throughout the 12 month monitoring period (Table 3.2). Nutrient concentrations in slaughterhouse effluent were on average an order of magnitude higher than domestic sewage from the town. Nitrate-N and TP concentrations were extremely high at the inflow, reaching concentrations as high as 100 and 21 mg litre^{-1}, respectively, and averaging 30 and 13 mg litre^{-1} respectively, over the study period. Most of the TP in effluent and in the marsh was in the form of bioavailable phosphorus (SRP).

Water from the municipality provided the largest (40%) volume of water to Frank Lake from 1990-1994 (Table 3.3). Cargill wastewater is low volume, high concentration wastewater, the Town of High River is high volume, low concentration wastewater and the Highwood River is high volume, dilute freshwater. Highwood River water was no longer required after the marsh was filled in 1993. By 1993, the three sources of Cargill, the Town and the river had supplied 27%, 40% and 32%, respectively to restore water levels in the marsh. By the end of 1995, a total of 141 760 kgs of P were pumped to Frank Lake from these water sources. Mean P loading to the marsh on an areal basis has been 4.7 g m^{-2} yr^{-1} since 1990, but the wastewater has not been evenly distributed.

Nutrient concentrations in Frank Lake

During the open water season, Basin 1 had two zones with significantly higher nitrogen concentrations, the Inflow (sites 801-805 and 901) and Cargill Bay (sites 902-905). The zone of enrichment extended past these regions during the winter only (Figure 3.1, Table 3.4). Mean annual ammonia and nitrate concentrations in the Inflow region (8.99 and 30.26 mg litre^{-1}) were significantly higher than those from Cargill Bay (3.13

and 21.34 mg litre^{-1}) based on their rankings ($P < 0.05$). Ammonia and nitrate concentrations in Cargill Bay were significantly higher than the rest of Basin 1 (RB1) sites (1.10 and 5.23 mg litre^{-1}), Basin 2 (B2) (0.29 and 0.51 mg litre^{-1}) and reference wetlands (0.56 and 0.02 mg litre^{-1}) ($P<0.05$). The rest of Basin 1 sites and Basin 2 sites did not significantly differ from each other or the reference wetlands. Under winter ice cover, RB1 nitrogen species concentrations were elevated to levels similar to those in the Inflow region, but this effect was not apparent in Basin 2 or reference wetlands.

A zone of significantly higher phosphorus concentration was identified in both the inflow and Cargill Bay regions, but this zone did not extend past the combined Inflow and Cargill Bay regions during the summer (Table 3.5). There was no difference between Cargill Bay and Inflow region phosphorus concentrations. Inflow and Cargill Bay region TP concentration (7.33 mg litre^{-1}) was significantly higher than RB1, B2 and Reference wetlands (2.88 mg litre^{-1}, 3.80 mg litre^{-1}, 3.02 mg litre^{-1}, respectively). The rankings also identified sites 601, 602 and 510 as having significantly high SRP concentrations in May and June samplings (i.e. comparable to inflow concentrations). Under winter ice cover, Frank Lake phosphorus concentrations were elevated under winter ice cover and there was no significant difference between any of the regions, including reference wetlands (Table 3.5).

Other parameters

Cargill Bay and Inflow region waters were more turbid than other sites in Basin 1. However, Basin 2 waters were much more turbid than Basin 1 waters. Sites nearest the outflow in Basin 1 were more basic (pH 9.00-11.00) than the rest of Basin 1 (pH 6.62-8.98), which was similar to reference wetlands (8.66 ± 0.18). Mean water temperatures in both Basins of Frank Lake increased from 2.5 °C during February to 7.8 °C in April to 13.3 °C in May. The detailed data are not shown.

Nutrient retention in Basin 1

Treatment efficacy varied seasonally for all nutrient species with greater reductions in nutrient concentrations in the summer than in the winter. From May to

September, nitrogen concentrations in the outflow decreased by 95% compared to the inflow. There was lower retention in April (61%) and October (87%). In February, nitrate was exported and only 46% of the ammonia was retained (Table 3.6).

Phosphorus concentrations in the outflow were 71% lower than inflow concentrations from May through October. However, winter and spring treatment was much less effective. During February and April only 26% and 19% of TP was retained (Table 3.7).

Basin 1 outflow water nutrient concentrations were similar or lower than reference wetland concentrations during the summer (Table 3.8). Winter treatment was poor for both N and P, with little reduction in concentration for all species (Table 3.9). Water leaving Basin 1 during February had much higher nutrient concentrations than those found in the reference wetlands.

Discussion

Loadings to Frank Lake

Slaughterhouse effluent had approximately ten times the NO_3, double the NH_3 and six times the phosphorus concentrations (both TP and SRP) than the municipal wastewater, based on our 1994-1995 sampling means. Slaughterhouse wastewater has annually contributed more than 80% of the TP loadings into Frank Lake since restoration. This figure was closer to 94% in 1993 and 1994. Municipal wastewater has only contributed 6% to 19% of the total phosphorus loadings annually to Frank Lake. The combined effluent flows resulted in TP and NH_3 inflows to Frank Lake that were similar to "strong" domestic wastewater, and nitrate and TDN concentrations that were much higher than "strong" domestic wastewater as defined by Metcalf and Eddy Inc. (1991, Table 3.10).

Highwood River water provided a large volume of the total water required to restore Frank Lake. This clean river water accounted for more than one-third of the volume of water discharged into the marsh up to the end of 1993, after which it was no longer needed. Since 1994, the Town of High River has pumped more than half of the point source wastewater into Frank Lake. It is not known if the loss of high volume, low nutrient Highwood River water will alter the marsh water chemistry, or change the ability of the marsh to provide wastewater treatment.

The majority of nutrients in Frank Lake are from wastewater point source loadings. Using a mean annual precipitation of 488 mm, we calculated that the maximum water contribution into the marsh from runoff (assuming no evapotranspiration) on the 342 km^2 drainage area of Basin 1 could be 167 032 m^3, which accounts for 6-8% of the total flows into Basin 1 of Frank Lake. Thus, based on this conservative calculation, point source volumes into Frank Lake should account for >90% of the total flows into the marsh. Nutrient loadings from non-point sources of water are assumed to be very small in comparison to the large point source water flows of nutrient rich water that Frank Lake is currently receiving.

Zone of impact

Nitrogen concentrations in Basin 1 of Frank Lake decreased rapidly with short distances away from the inflow pipe and the rapid decrease created two significantly different zones of high NO_3 and NH_3 concentrations. Several Inflow and Cargill Bay sites sampled had NH_3-N concentrations that exceeded the 2.2 mg $litre^{-1}$ limit for protection of aquatic life (CCME 1994). However, high nitrogen concentrations in this study were confined to the Inflow and Cargill Bay regions for all sampling periods, except under winter ice cover. All sites in Basin 1 and one site in Basin 2 had surface water NH_3-N concentrations that exceeded 2.2 mg $litre^{-1}$ during the winter. NO_3-N concentrations were also extremely high under ice cover across all sites, however there are no Canadian water quality guidelines for this nutrient. High winter NO_3-N concentrations may be due to reduced denitrification activity by facultative anaerobic bacteria in colder waters (Howard-Williams 1985). Several Basin 1 sites are shallow enough to freeze solid during the winter (Bayley et al. 1995) and denitrification is unlikely at these sites where the surface water was completely frozen to the sediment. Water with high concentrations of NO_3-N spilling into Basin 2 is cause for concern and the amount of flow will determine the severity of impact on Basin 2 and downstream waters.

The zone of elevated phosphorus concentrations (TP and SRP) identified in Basin 1 was limited to the Inflow and Cargill Bay areas. The elevated SRP zone was limited to these sites for all runs, except under winter ice cover. Three additional sites of high SRP surface water concentrations were identified in Basin 1 (sites 601, 602 and 510) in May and June. It is possible that these sites had elevated SRP concentrations from Blackie Creek inflows or from waterfowl guano. Studies on wetland nutrient dynamics have found that animals can significantly influence nutrient cycling processes (Andersson et al. 1988, Parmenter and Lamarra 1991). McColl and Burger (1976) found that colonies of Franklin's gulls, in numbers similar to those occurring on Frank Lake, can mobilize large quantities of nitrogen and phosphorus into the water column.

Nitrogen treatment

The high nitrogen removals and net retention of nitrogen seen in Frank Lake has been shown in several wetlands receiving nitrogen loadings as high as those applied to Frank Lake (Johnston 1993). However, Frank Lake had seasonal export of nitrate from Basin 1 during the winter. Moustafa (1996) had widely fluctuating TN retention estimates in a Florida marsh which also seasonally released nitrogen. Seasonal export of both NO_3-N and NH_4-N from a tidal wetland was found by Simpson et al. (1983) due to decreases in vegetative uptake and N leaching from tissues following plant senescence. In the ice free months in Basin 1, large decreases in surface water nitrogen concentrations were detected between sampling stations. Ammonia and nitrate concentrations decreased by as much as 99% only 600 m away from the inflow. This decrease in concentration may be due to dilution, volatilization, denitrification and biological uptake. Most authors assume that the high rates of nitrogen removal found by marshes is due to denitrification (Howard-Williams 1985, Neely and Baker 1989, Crumpton et al. 1993), especially when the influent N is mostly in the nitrate form (Brodrick et al. 1988). van Oostrom and Russell (1994) found denitrification rates in a New Zealand wetland receiving meat processing effluent was between 219 - 1 095 g NO_3 m^{-2} yr^{-1}, however, denitrification can be inhibited by high ammonia loading rates (van Oostrom and Cooper 1990). Volatilization is another mechanism of NO_3-N elimination in Frank Lake, as NO_3-N accumulated in large quantities under winter ice cover. Nitrogen can be released to the atmosphere as ammonia, nitrous oxide and dinitrogen produced by denitrification (Kadlec 1995).

Ammonia losses were less variable than nitrate losses, but were also lowered during winter ice cover. Nitrification is commonly curtailed in summer during anoxic conditions (ie. high plant oxygen demand) and during winter under ice cover. During the winter, ammonia may have been converted into inorganic compounds, released from the bottom sediments and discharged from Basin 1 without nitrification (Hosomi et al. 1994). Low water temperatures in Frank Lake may have suppressed nitrification, findings that concur with Hosomi et al. (1995). However, Wood (1990) found that temperature had little effect on water quality in the range from 0 to 25 °C due to the insulating effect on the rhizosphere from plant litter cover and the heat produced from microbial activity. While NH_4 concentrations were elevated under winter ice cover in Frank Lake to levels toxic to aquatic life, NH_4 was never exported from Basin 1.

Nichols (1983) estimated that 70-90% of the N loading in effluent can be removed in natural wetlands on a sustained basis if N loadings do not exceed 20 g N $m^{-2} yr^{-1}$. Boney Marsh in Florida was able to annually assimilate 17 g TN m^{-2} yr^{-1} in a study by Moustafa (1996). At Frank Lake, inorganic N inputs are 54 g NO_3 m^{-2} yr^{-1} and 27 g NH_4 m^{-2} yr^{-1}. Clearly, this inorganic N value (81 g m^{-2} yr^{-1}) exceeds the optimum for sustained removal. The amount of additional N from organic inputs to the loading rate is not known. Future studies of the marsh should include TKN in the suite of water chemistry parameters to better estimate TN loadings.

Phosphorus treatment

A mean annual TP removal in Frank Lake of 64% was comparable to nutrient removal efficiency in other wetland treatment systems (Gersberg et al. 1984, Godfrey et al. 1985, Cooper and Findlater 1990, Pride et al. 1990). La Rock et al. (1990) found high summer removal at Lake Jackson in Florida, but P export in the winter. Seasonality of export was documented by Lee et al. (1975), Spangler et al. (1977), Klopatek (1978), Gehrels and Mulamootil (1989) and Moustafa et al. (1996), all of whom found greater nutrient releases in the fall due to anaerobic conditions leading to P release from the sediments (Patrick and Khalid 1974) and leaching of P from senescent vegetation (Klopatek 1978). Seasonality of export was not shown in Frank Lake, and the marsh provided net P retention, even during February.

Some amount of P removal is expected during the winter because sedimentation processes are unaffected by lowered temperature or decreased microbial activity (Johnston 1993). Finlayson and Chick (1983) found that much of the nutrient reduction in a constructed wetland was due to the filtering of particulate forms of P, rather than nutrient transformations or recycling. The large concentrations of P detected in water collected under winter ice cover may be a direct result of P resuspension from sediment under anoxic conditions as the barrier between sediment and overlying water is removed. When the water becomes anoxic, the sediments reduce Fe^{+3} to Fe^{+2}, dissolving soil oxides and hydroxides releasing bound P (Kadlec 1979, Wentzel et al. 1985, Sinke et al. 1993). When the ice melts in the spring allowing oxygen exchange with the water, wetland sediments will re-oxidize and show an increased P sorption capacity (Stumm and Morgan 1981). The elevated phosphorus concentrations during February could also be due to P release from plant breakdown, or freezing out of the forming ice (Kadlec 1979, Li 1985). It is possible that higher SRP concentrations detected in Basin 2 during the spring melt period were due to inputs of water containing high phosphorus concentrations from Basin 1 during the winter (8-12 mg litre). Other mechanisms such as agricultural runoff may also contribute phosphorus into Basin 2. Again, flows into Basin 2 were not measured, thus the nutrient loadings to Basin 2 could not be calculated and this may underestimate our treatment efficacy as much as 50% for P and 100% for N (Moustafa et al. 1996). As well, we reported treatment as a decrease in surface water concentration, and these concentrations are subject to evapotranspiration, dilution (from snow-melt, runoff, rainwater and groundwater), mineralization, uptake by phytoplankton and decomposition by macrophytic litter (van der Valk and Jolly 1992).

Phosphorus removal in wetlands is due to a variety of mechanisms including sedimentation, precipitation, adsorption, and plant and microbial uptake (Watson et al. 1989). The primary long term sink for P is the sediment, because P taken up by biological processes generally returns to the water column when the organisms die (Richardson 1985). Wetland sediments have a finite capacity to retain P depending on the organic, clay, iron, aluminum and calcium content of the soil. Some authors suggest that P removal in wetlands is enhanced by slowly decomposing litter, due to P burial in the litter over the winter (Meyers 1985) or due to the microbial uptake of P associated with the litter.

Phosphorus removal from recently created wetlands is initially high, but declines when a marsh "ages" (Kadlec 1985), due to the saturation of adsorption sites on detrital material, wetland soil or both (Fox and Kamprath 1971, Howard-Williams 1985, Meyers 1985, Faulkner and Richardson 1989, Breen 1990, Johnston 1993). Sediments in Cargill Bay in Basin 1 of Frank Lake may be becoming saturated with respect to phosphorus, resulting in the poor water quality zone detected at those sites. Nichols (1983) suggests that natural wetlands can have long term phosphorus retention capacities of 60-95% if P loadings do not exceed 4 g $m^{-2}y^{-1}$. Loading rates to Basin 1 were about 5 g P $m^{-2}y^{-1}$, assuming an even distribution across the basin. However, it is likely that loadings to the Cargill Bay and Inflow regions were much higher due to short circuiting of water flow as waters followed a preferential path. As well, there are P inputs from tributaries to consider when calculating total loadings to Basin 1.

Some studies have shown no relationship between loading rates and long term retention in wetland systems (Kadlec 1983, Knight et al. 1987). While some studies of marshes from warmer climates show higher capacities of freshwater marshes to store P, other studies disagree. Richardson and Craft (1993) suggested that permanent storage of P in natural prairie marshes was below 1.0 g m^{-2} yr^{-1} and averaged 0.5 g m^{-2} $year^{-1}$. Eagle Lake Marsh, a prairie marsh that received agricultural runoff, was able to store 0.62 g P m^{-2} yr^{-1} (Davis and van der Valk 1978). Frank Lake may have a greater ability to retain P due to P precipitation associated with the calcareous lacustrine sediments, as well as the biologically mediated processes of P retention.

Frank Lake treatment effectiveness

Nutrient uptake in Basin 1 of the marsh is high in the spring and summer but decreases in the fall and winter. This is likely due to the decreased biological activity associated with lower water temperatures (Mitsch and Gosselink 1993). Water levels and wind action may resuspend nutrients in the water column in shallower sites across Basin 1 and Basin 2, and this would be more pronounced in the fall when water levels are lower. Elevated concentrations of nutrients in surface waters decrease the retention estimates.

Nutrient retention in Frank Lake can be attributed to shallow marsh depths and long residence times which allow more contact time with the soil and biota. Moustafa et al. (1996) found that shallow water levels improved treatment in Boney Marsh while Mulholland et al. (1991) showed that increased residence times enhanced nutrient uptake by biota and reduced water column nutrient concentrations.

The large decreases of nutrient levels from surface waters away from the inflow may be due to the scavenging ability of the abundant submergent aquatic vegetation at these sites (Bayley et al. 1995). In contrast, the poor nutrient removal from Cargill Bay waters may be from the lack of vegetation and turbid conditions found there. It is possible that the murky, shallow waters of Cargill Bay may be hindering treatment by shading out submergent aquatic macrophytes. Further, the lack of vegetation and shallower depths may result in higher turbidities in Cargill Bay caused by wind induced resuspension of sediments. This is supported by our winter findings of low turbidity under ice cover. Sediment resuspension may be partially responsible for the elevated nutrient concentrations in the water column.

Generally, sites with higher pH and lower turbidity in the marsh had more diverse plant communities and provided the best treatment. Higher pH values may be due to CO_2 utilization by photosynthetic organisms such as phytoplankton. Intensive photosynthesis can raise the pH to above pH 10 during the day (Wetzel 1983). The elevation of pH brought about by actively photosynthesizing macrophytes such as *Myriophyllum* may have contributed to P reductions from the water column through apatite formation and the coprecipitation of phosphate with carbonates (Otsuki and Wetzel 1972). Lower pH values near the inflow are likely due to the bleach added into Cargill wastewater. Water temperature was positively correlated with phosphorus treatment as an increase in temperature from 7.8 °C to 13.3 °C from April to May led to a near doubling of phosphorus removal from 40% to 70%. Water temperature in the marsh did not affect nitrogen treatment, but ice cover may have impaired N cycling processes. Finally, long-term exposure to high nutrient loadings have been found to significantly reduce the ability of wetlands to retain nutrients (Mattson et al. 1975, Whigham and Simpson 1978), so Cargill Bay in Basin 1 of Frank Lake may have a reduced ability to retain nutrients which is reflected in the high surface water nutrient concentrations detected.

Comparison of Basin 1 outflow to Reference wetlands

Nitrogen concentrations (NO_3 and NH_3) in Basin 1 were similar to those in Basin 2 and reference wetlands for most of our study, with pronounced differences under winter ice cover. Phosphorus concentrations in RB1 were less than those found in Basin 2 and reference wetlands for all P species measured, with elevated Basin 1 concentrations under winter ice cover. Concentrations of nutrients in the natural prairie marshes were high and probably influenced by the proximity of agriculture and non point source runoff. Our reference wetland estimates of P were most similar to the highest estimates reported in northern prairie wetlands and lakes (Rutherford 1970, Barica 1975, La Baugh et al. 1987).

While the Frank Lake marsh has the ability to treat agro-industrial and municipal wastewaters nutrient concentrations to concentrations as low as those found in nearby natural marshes, there are concerns about the long term ability to continue providing treatment. Nitrogen removal from surface waters was highly variable but on average, was greater than P removal from surface waters. The disparity between N and P retention spatially and temporally may be attributed to the complexity of wetland nutrient cycling mechanisms. High loading rates of N and P could lead to eutrophication of the wetland and have serious negative wildlife effects. Eutrophication could alter the algal and macrophyte species composition of the marsh. Constant high P inputs may saturate the sediments and result in little P removal from water. This in turn may result in downstream leakage of nutrient rich water into the Little Bow River by surface flow and groundwater recharge. Groundwater pollution could affect drinking water quality and cause problems for local cattle farmers.

Conclusions

Despite high nutrient loadings being received by Frank Lake, the marsh provided net nutrient retention during our study from July 1994 through 1995. Surface water quality was greatly improved as the marsh removed 87% of influent ammonia, 80% of nitrate, and 64% TP annually. Marsh retention was much higher during the warmer months, with 99% nitrogen removal and 87% phosphorus removal. Phosphorus removal was less variable than nitrogen removal as N removal was very high in the summer and much lower in the winter. Water discharged from Basin 1 of Frank Lake had similar quality as nearby Reference wetlands during the ice free months, but released nutrient rich water into Basin 2 during February. In the spring, nitrogen removal quickly reached optimal treatment while phosphorus treatment took an additional month to reach peak efficiency. Short circuiting of water flow through the marsh and cold seasonal conditions caused spatial and temporal variation in marsh treatment. While the marsh provided excellent summer treatment during our study, the literature suggests that continued high loadings to the marsh could result phosphorus export from the marsh into the Little Bow River. This could have negative impacts on the proposed Little Bow River diversion project currently under development. Future studies should address the role of the sediments to scavenge and sediment inflowing nutrients and quantify the ability of the marsh to retain nutrients.

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Chapter 4: The role of sediment in phosphorus storage of a northern prairie wetland receiving municipal and agro-industrial wastewater

Introduction

The use of constructed and natural wetlands is a cost-effective alternative for tertiary wastewater treatment and is an established practice in many temperate and subtropical climates (Kaynor et al. 1985, Reddy and Smith 1987, Hammer 1989, Knight et al. 1993). The capacity of wetlands to transform and store nitrogen is usually very high and provides satisfactory long term wastewater treatment (Hammer and Knight 1994). However, the ability of wetlands to transform and store phosphorus over a long term is generally much lower (Kadlec and Alvord 1989) due to differences between the two element cycles (Johnston 1989). Phosphorus has no significant atmospheric fluxes and has a much longer biogeochemical cycle than nitrogen (Froelich 1988). Despite these shortcomings, effective P storage has been shown in natural and constructed wetlands (Boyt et al. 1977, Kadlec 1978, Tilton and Kadlec 1979, Nichols 1983, Bayley et al. 1985, Richardson and Craft 1993, Davies and Cottingham 1993, Hammer and Knight 1994), even during the winter in northern climates (Reed et al. 1988, Gover 1993, Jenssen et al. 1993, Reed 1993).

Phosphorus retention in wetland systems depends on a balance of P-scavenging and P-mobilization. Phosphorus is scavenged by three reversible processes: sorption, precipitation (the formation of minerals or salts), and incorporation (biological immobilization) (Tofflemire and Chen 1977). These processes convert soluble forms of P into particulate forms that can be buried by sedimentation (Kitchens et al. 1975, Spangler et al. 1977, Boto and Patrick 1978, Watson et al. 1989). The ability of a wetland to scavenge P is related to the forms of P. The majority of wastewater P is the inorganic form of SRP, which is a biologically available form of P that is incorporated by biota. When P scavenging exceeds mobilization in a wetland, the wetland functions as a P sink (Bostrom et al. 1982, Swindell and Jackson 1990).

The scavenging process is countered by the process of mobilization, the breakdown or decomposition of organic P. Both scavenging and mobilization are driven by the mass of nutrient loadings into the system. Nutrient addition from wastewater can alter the balance of these processes. When mobilization exceeds scavenging, the system may become a P-source and export the accumulated phosphorus (Kadlec and Hammer 1982). For example, net phosphorus export has been shown to continue in wetlands after wastewater loadings have ceased (Kadlec and Bevis 1990) because of P mobilization. In some cases, the capacity of a wetland to provide wastewater treatment can be predicted from the loading rates applied (Nichols 1985).

In wetlands, there is little direct uptake of phosphate from the water column by emergent vegetation (Sculthorpe 1967) and more than 95% of the P is stored in wetland sediments (Hammer 1989) due to the long turnover time of sediment nutrients (Johnston 1991). Phosphorus removal or storage in wetland ecosystems over a long term is ultimately limited by sedimentation (Dolan et al. 1981, Kadlec and Hammer 1982, Nichols 1983, Richardson 1985). A low water flow velocity through a wetland is essential for net accumulation of particulate phosphorus to allow settling to occur (van der Valk et al. 1978). Even if other P-storage pools become saturated, sediment burial can effectively function to remove P at a rate similar to the sedimentation rate (Howard-Williams, 1985).

In recently created wetlands, phosphorus removal is initially high, but declines as the marsh "ages" (Dolan et al. 1981, Nichols 1983, Kadlec 1985, Richardson 1985, Mann 1990), due to saturation of finite adsorption sites (Howard-Williams 1985, Richardson 1985, Faulkner and Richardson 1989, Breen 1990, Kadlec 1997). For example, chronic high nutrient loadings can reduce the capacity of a wetland to store P (Simpson et al. 1983) and when sediments in the wastewater inflow region become saturated with P, a zone of sediment saturation may spread out across the marsh (Hammer and Kadlec 1983, Richardson 1985, Kent 1987, Hiley 1995).

The present study is an analysis of sediments from a hypereutrophic northern prairie wetland (Frank Lake, Alberta) to determine the spatial distribution of P and to estimate the P sorption ability of sediments. The Frank Lake wetland is unique because it is the largest Canadian example of a marsh to be restored by nutrient rich wastewater and the marsh is managed for the dual objectives of water quality improvement and provision of wildlife habitat. Our approach to analyzing the ability of a northern prairie wetland to retain P was:

(1) to determine the spatial distribution of P sedimentation in the two main basins of Frank Lake and (2) to compare the spatial distribution of sorption ability of Frank Lake sediments with nearby wetland sediments to identify sites of saturated P-sorption and (3) comment on the capacity of the marsh sediments to provide continued P retention. A previous study of the water chemistry of Frank Lake from July 1994 to June 1995 concluded that the marsh was providing seasonal treatment of N and P, by decreasing concentrations as water flowed through the marsh (White and Bayley unpubl.). However, a poor water quality zone was identified, characterized by persistent high SRP concentrations at the wastewater inflow region in Basin 1. This study tests the hypothesis that sediments in the inflow region of Basin 1 may be near saturation, resulting in the high SRP concentrations in the overlying water. We further hypothesized that inflow site sediments would have higher P deposition and lower ability for sorbing added P than other sites in the marsh and reference wetlands. This research will give an indication of the historic sediment and P deposition in the marsh and yield an estimate of the long term P storage ability of the wetland to provide continued wastewater treatment.

Study area

Frank Lake, Alberta is a 1 246 ha (3 079 acre) bulrush marsh that was restored in 1989 with municipal and agro-industrial wastewater under the management of Ducks Unlimited Canada. The restored wetland complex is sixty kilometres south of Calgary, Alberta (50^0 33' N; 113^0 42' W) in the Foothills Fescue Prairie Ecoregion (Poston et al. 1990). This arid region of southern Alberta is characterized by short, hot summers, long cold winters and temperatures modified by Chinook winds. January temperatures range from -45 °C to 20 °C, but average -11 °C, and July temperatures range from 9 to 34 °C, but average 15 °C (Environment Canada 1982). Evapotranspiration exceeds precipitation by 34.7 mm year^{-1} (Environment Canada 1982). The Frank Lake region has a high water table with Thin Black Chernozemic soils (Ducks Unlimited 1993). Calcareous glacial till surrounds the area and the lake consists of lacustrine sediments of slightly alkaline pH. The entire marsh is divided into three discrete basins with a total drainage area of 342 km^2. Winter ice and snow-pack cover the marsh from November to mid-April. Mean water depth in Basin 1 is 0.67 m (Figure 3.1) and mean ice depth is 0.57 m. The wetland is managed as a hemi-marsh with half open water and half emergent vegetation (Sadler et al. 1995). Emergent vegetation is primarily hardstem bulrush (*Scirpus acutus* Muhl.), while submersed vegetation includes sago pondweed (*Potamogeton pectinatus* L.), northern water milfoil (*Myriophyllum exalbescens* Fern.) and Richardson's pondweed (*P. richardsonii* (Benn.) Rydb.). A comprehensive list of the flora and fauna of Frank Lake is available in Wallis et al. (1995).

Secondary treated wastewater from both a Cargill Foods Ltd. (3 000 head day^{-1}) beef slaughterhouse and a local municipality (pop. = 6 000) are combined and discharged into Frank Lake. Wastewater flows of more than 5 000 m^{3} day^{-1} (1.12 MGD) averaging 11.14 mg litre^{-1} SRP (White and Bayley unpubl.) are discharged at a point source into Basin 1 (Figure 4.1). An area of impact previously described by White and Bayley (unpubl.) called Cargill Bay is approximately 33% of the total Basin 1 area (total Basin 1 area is 501.4 ha), while the rest of the area (66%) is the other Basin 1 sites. Water flows into the west lobe of Basin 1 through a 200 metre long ditch (Figure 4.1). Prior to restoration in 1994, there was little surface outflow from Frank Lake as the basins were being refilled. Water now flows from the 501 hectare Basin 1 (1 240 acres) to Basin 2 (360.2 ha, 890 acres) then Basin 3 (138.8 ha, 343 acres), before discharge over land to the Little Bow River. Basins 2 and 3 are smaller, shallower, and have less vegetative development than Basin 1. Water levels are controlled in each basin by outflow weirs. Organic matter began to accumulate significantly in the Basins after marsh restoration in 1990. Additional sources of water into Frank Lake comes from non point source agricultural runoff and two small creeks. Frank Lake presently provides critical wildlife habitat for thousands of breeding colonial waterbirds, migratory birds, staging geese, staging ducks, and for several rare, threatened and endangered species (Poston et al. 1990, Wallis et al. 1996).

Reference wetlands were sampled (1) 11 km south of High River on Highway #2 on the east and (2) west sides of the road, (3) 152nd St. East at 532 Ave., 2 km east of High River and (4) the Town of High River cemetery wetland. Water chemistry parameters of Basin 1, Basin 2 and reference wetlands are given in Table 3.1.

Methods

Field collection

Sediment cores were collected in a stratified random method from representative areas in Frank Lake and reference wetlands June 15-19, 1995 by hand with an acrylic core tube (diameter = 5 cm). Nineteen sites in Frank Lake were sampled and one site from each of three reference wetlands were sampled. At each site, a full sediment core down to the mineral soil and a second 0.5 cm thick sample of the surface sediment was collected. The sampling procedure created minimal disturbance at the sediment-water interface. Collected samples were quickly extruded from the corer, emptied into pre-labeled ziploc bags, double-bagged and frozen in coolers containing dry ice. The coring tubes were rinsed in lake water before resampling. At each site, a water sample was collected in a 1L amber acid washed Nalgene polyethylene bottle. Samples were brought back to the University of Alberta and water was kept at +4°C, while sediments were kept frozen at -4 °C until analysis.

Sediment P analysis

Within a month of collection, full cores were thawed overnight and the gross wet mass determined to 0.1 mg (approximately ± 10% of wet weight) on a Mettler AT 261 DeltaRange scale. Samples were then homogenized in a plastic container with a hand held blender on low speed for 20 seconds, and a 10 ml subsample of sediment taken with a modified syringe. Five ml were put into a flamed, tared crucible and the gross wet mass recorded. The other 5 ml went into a new 10 ml glass scintillation vial and capped. Both samples were frozen for 48 hours, covered with a folded kim-wipe tied with an elastic band. Samples were freeze dried at -30°C for 24 hours and +4°C for 72 hours in a Labconco FreeZone 12L freeze drier. After freeze drying, sediment in vials were analyzed for TP by the nitric acid and HCl digestion method of Mayer and Williams (1981). Accumulation of P in Frank Lake was extrapolated for the surrounding area using Equation 1.

Equation 1:

$$\frac{1\ \text{gram}}{10^{6}\ \mu\text{g gram}^{-1}} \ \text{X}\ \frac{[\text{P}]\ \text{in sediment}}{(\mu\text{g gram}^{-1})} \ \text{X}\ \frac{\text{core mass (g)}}{\text{core area (m}^{2})} \ \text{X Area (m}^{2})$$

The samples in crucibles were reweighed to within 0.1 mg to determine % moisture loss (APHA 1992). Organic matter content of sediments was determined by mass loss of dried samples after 1 hour at 550°C in an NEY 2-525 Series II muffle furnace. Samples were stored in a dessicator overnight before determination of sedimentary $CaCO_3$ by heating samples at 950°C for 3 hr in the muffle furnace (Wetzel 1970).

Surface sediment adsorption experiments

The methods of Sundby et al. (1992) were used to determine the residual P uptake capacity of Frank Lake and reference surface sediments. Within three months of collection, each 0.5 cm surface sediment sample was thawed and centrifuged for 20 min at 3 000 rpm an IEC Centra MP4R Centrifuge at room temperature. The supernatant pore water was withdrawn from the pellet by syringe and filtered through a 0.45 µm Millipore filter for SRP analysis *as per* Menzel and Corwin (1965). The nine subsamples of the sediment pellet (~10 mg wet mass each) were individually placed into plastic 50 ml centrifuge tubes. The nine pieces of sediment were suspended in 10 ml of filtered site-specific surface water water that was collected at each site at the time of coring. This water had been amended with $NaH_2PO_4^{3-}$ to SRP concentrations of 25, 50, 75, 100, 200, 300, 400, or 500 µg P litre^{-1} *as per* Nyffeler et al. (1984). Another nine tubes containing only spiked Frank Lake water were paired and used as mudless controls to approximate adsorption of P to filters and glassware. The tubes were equilibrated for 2 hours by shaking on a Burell Model 75 wrist action shaker at room temperature. After shaking, the tubes were centrifuged for 20 min at 3 000 rpm and the supernatant drawn off with a syringe and filtered through a 0.45 µm filter. No attempt was made to keep the sediments under anoxic conditions. The supernatant was put in a scintillation vial, refrigerated at 3°C and SRP analyses were done within 24 hours. Adsorption of P to filters and glassware was calculated by subtraction from the paired treatment tube. Phosphorus adsorbed onto the sediment particles was found by the difference of the P added to the sediment and P remaining in the water after shaking. The sediment was freeze dried and weighed by the methods above so that sorption could be expressed per unit dry mass.

The samples were analyzed for Ca, K, Mg and Na by digesting with a 1:1 concentrated hydrochloric acid:HNO_3 solution for 16 hours at 20°C and 2 hours at 90°C. The extract was filtered through a Whatman No. 44 filter, diluted with double distilled water and analyzed for Ca, K, Mg and Na on the atomic absorption spectrophotometer.

Statistical tests

Sampled sites were pooled on the basis of previous water quality studies (White and Bayley unpubl.). These groupings were: (1) sites near the inflow (Cargill Bay), (2) the rest of Basin 1 (RB1) and (3) Basin 2 and reference sites (reference sites, Figure 4.1). Sediment thickness, Ca, $CaCO_3^{2-}$, K, Mg, Na, organic C and TP concentrations of the full cores were analyzed by 1-way ANOVA across the 3 groupings. SRP concentrations of sediment pore water between the 3 groupings were analyzed by 1-way ANOVA. Fisher's post-hoc LSD tests were applied to significant ANOVA tests.

Results

Sediment spatial distribution

Cargill Bay (CB) sites had significantly higher sediment thickness (15.4 cm) and therefore, sedimentation, than the Rest of Basin 1 sites (RB1, 10.1 cm) (1 way ANOVA; $P < 0.05$). Similarly, all Basin 1 sites had significantly higher sediment thickness than those in Basin 2 (2.0 cm) (1 way ANOVA; $P < 0.05$; Figure 4.2). Sediment mean TP concentration in CB was 2.57 mg P gram sediment^{-1}, which was significantly higher than the mean TP concentration at RB1 sites (1.04 mg P gram sediment^{-1}) and the mean TP concentration at reference wetlands (0.99 mg P gram sediment^{-1}) (1 way ANOVA, $P = 0.04$; Figure 4.2). Spatial accumulation of P since restoration in 1990 was: 31 923 kg of P buried in Cargill Bay sediments, 39 861 kg of P buried in RB1 and 7 878 kg buried in Basin 2 (Figure 4.3). These estimates were found by averaging the P concentrations across all sites within a region and multiplying by the size of that region (Equation 1).

P uptake experiments

The P uptake capacity of CB sediments was lower than RB1 and reference sediments. When exposed to 500 µg PO_4^{3-} litre^{-1}, CB sediments had a maximal uptake ability of approximately 1 000 µg PO_4^{3-} g sediment^{-1}, while the reference sediments sorbed more than 2 500 µg P g sediment^{-1}, and RB1 sites sorbed greater than 1 500 µg PO_4^{3-} g sediment^{-1} (Figure 4.4). All sediments except sediments from the CB region showed a smooth trend of increasing P uptake with amount of P added. Cargill Bay sediments had little P uptake until very high concentrations were added, but then became saturated after 400 µg PO_4^{3-} litre^{-1} were added. Pore water mean SRP concentration from CB sediments was 8 098 µg litre^{-1}, which was not significantly higher than either RB1 or reference sites SRP concentrations of 5128 µg litre^{-1} and 5 044 µg litre^{-1}, respectively (1-way ANOVA; $P = 0.055$).

Sediment composition

There were no significant differences in sediment concentrations of Ca, K, organic C, or CO_3^{2-} among Basin 1, Basin 2 or reference wetland sites. Reference wetlands had significantly higher Mg and Na concentrations than Cargill Bay and RB1 sites ($P < 0.000$; $P < 0.000$), post-hoc tests revealed that Cargill Bay and RB1 sites did not significantly differ for Mg or Na (Table 3.2). Cargill Bay had significantly higher TP than RB1 or references ($P < 0.05$).

Discussion

P deposition

The poor water quality zone identified as Cargill Bay in Basin 1 of Frank Lake by White and Bayley (unpubl.) characterized by low water quality and high surface water SRP concentrations closely overlaps the Cargill Bay region of sites identified in this study. The Cargill Bay region is this study was characterized by high sediment accumulation, high pore water SRP concentrations, high TP burial, high sediment P load and a diminished capacity for additional P-uptake.

As predicted, sediment burial has been the major mechanism of P storage in Frank

Lake since marsh restoration in 1990. As much as 79 662 kgs have accumulated in Frank Lake sediments from the total 1990-1995 input load of 141 760 kg (White and Bayley unpubl.). Basin 1 is responsible for retaining 51% and Basin 2 is responsible for retaining 6%) of the total point source P load that has been added to Frank Lake. Approximately 38.5 g P m^{-2} $year^{-1}$ (105.4 mg P m^{-2} day^{-1}) have been deposited in the Cargill Bay area, while 24 g P m^{-2} $year^{-1}$ (65.7 mg P m^{-2} day^{-1}) have accumulated at the other Basin 1 sites and 0.43 g P m^{-2} yr^{-1} have accumulated in Basin 2 since 1990. Phosphorus retention rates as high as 8.03 g P m^{-2} yr^{-1} have been reported in the literature (Buchanan 1982). Modelling simulations predict that rates closer to 1.05 g P m^{-2} yr^{-1} are permanently retained in wetland sediments (Mitsch and Reeder 1991). The mean P load retained by Basin 1 sediments (67%) is very close to the mean annual surface water P concentration reductions as waters pass through Basin 1 (64%, White and Bayley unpubl.). Our results support the literature review findings of Johnston (1991), who concluded that sediment deposition in freshwater wetlands can result in large fluxes of P from surface waters to wetland sediments. Since the plant P pool in wetland systems is typically very small (<5%, Hammer (1989)), the majority of the unaccounted P loading since 1990 (62 098 kg) has likely flowed out of the marsh into the Little Bow River.

Our Cargill Bay region phosphorus accumulation estimates are slightly higher than the 22 mg P m^{-2} day^{-1} value reported by Mitsch and Reeder (1991) for a Great Lakes coastal wetland, but much smaller than the 30 000 mg P m^{-2} day^{-1} sedimented by a New Zealand wetland that had received sewage effluent for over 10 years (Cooke 1992). Richardson and Craft (1993) suggest that permanent storage of P in natural wetlands is less than 1.0 g P m^{-2} $year^{-1}$, and averages 0.5 g P m^{-2} $year^{-1}$. Frank Lake may have an ability to permanently store higher amounts of P than suggested by Richardson and Craft (1993) due to the high sediment accumulation in Frank Lake. Accelerated sedimentation is at least partially responsible for P storage in Basin 1. Cargill Bay has accumulated 3 cm of sediment $year^{-1}$ since restoration and RB1 sites have accumulated 2 cm $year^{-1}$, while Basin 2 has accumulated less than 0.5 cm $year^{-1}$. Basin 1 sedimentation rates are similar to the sedimentation rate of 2.9 cm $year^{-1}$ found for eutrophic Lake Apopka in Florida

(Lowe et al. 1992) which receives P loading from floodplain farms. Enhanced sedimentation occurring in Basin 1 of Frank Lake is likely due to accelerated biological processes, resulting in detrital and sediment accumulation. Mass increases of the detrital components over time following nutrient addition was initially predicted in models by Dixon and Kadlec (1975), and is supported by our findings. Long hydraulic residence times in the marsh may have helped increase sedimentation rates because no waters were released from the marsh from 1990-1994 when it was being filled. It is also conceivable that significant sediment loading may have come from Highwood River water that was pumped into the marsh from 1990-1993.

Sediment uptake ability

The P-uptake data supported our hypothesis that Cargill Bay sediments have an impaired ability to scavenge P. The identified Cargill Bay area is approximately 33% of the Basin 1 area. We expected to find a smooth uptake response of greater P adsorbed with increasing P added. The Cargill Bay sites were only able to take up additional P at very high loadings before saturating, suggesting that the CB sediments have fewer available sorption sites. In contrast, RB1 and reference sites both showed increasing uptake with increasing levels of P added. Thus, sediments from sites in RB1 and reference regions have double the phosphate uptake ability than sediments from Cargill Bay. However, Cargill Bay sediments have 6 times the sedimentation rates of RB1 sites, so overall, Cargill Bay sediments have 3 times the ability to sequester P.

Although our handling of the sediments may have altered the P-adsorption capacity, it seems unlikely that the relative sorption capacity among samples would differ because all samples were treated similarly. Sediments in contact with the air during the spiking experiments may have an altered equilibrium than normally *in situ*. However, we compared the three sites relative to each other and we do not infer that our sorption values will be the maximal sorption capacities of sediments from these regions. In fact, the amount of P adsorbed by sediments after 2 hours may represent only 60% of the maximal capacity of sediments (Kadlec and Hammer 1982), because longer term processes bind sediment with greater amounts of P over time. This process is consistent with the continuous slow removal of P in sediments into a less exchangeable form over time (Barrow and Shaw 1975, Van Riemsdijk et al. 1977).

Differences in amounts of P taken up are assumed to be due to the availability of adsorption sites. However, reference sites had significantly higher sediment Mn concentrations, and this can increase the amounts of P-sorbed in aerobic sediment systems (Patrick and Khalid 1974, Cembella et al. 1984). Since Cargill Bay and RB1 had similar Mn sediment concentrations, the difference in P-sorbing ability must be due to availability of other sites. We can infer that the sediments from the reference wetlands have the greatest amount of residual P-adsorption sites, followed by RB1 sites. Cargill Bay sediments may have fewer available sites of P adsorption and could be saturated due to the high P loadings being applied to Basin 1.

Diminished sorption capacity of inflow site sediments suggest that a P-saturation plume could be moving away from the inflow canal out into the marsh. The progression of a saturation front in sewage-treating wetlands is consistent with the concept of equilibrium P adsorption (Kadlec and Hammer 1982) and higher loading rates for P than available P-sinks. When sediments reach equilibrium with the overlying water, they are no longer able to remove P. At present, the zone of saturated sediments in Basin 1 of Frank Lake extends approximately 800 m into the marsh. Our data from one sampling period is insufficient to determine if this zone is advancing towards the outflow weir. If this front does extend to the outflow weir, lowered P removal by sediments may result in degradation of marsh surface water quality. Relocation of the sewage input site into the marsh may delay the advancement of a saturation zone. Unfortunately, when the Frank Lake system was constructed, the input canal was located within 1 000m of the outflow weir, rather than at the head of the marsh (Figure 4.1) and this creates short-circuiting of water flow.

Our findings support those of Kadlec (1994) who found that surface water P concentrations are indicative of chemical and biological activity and directly proportional to the P deposition at a site (Kadlec 1994). Because the sediment affects overlying water P concentrations through sediment sorption-desorption processes (Meyer 1979, Mayer and

Gloss 1980, Hill 1982), we hypothesized that sediments in the inflow region of Frank Lake may be at or near saturation. Saturated sediments would necessarily have higher pore water P concentrations due to the lack of sorption sites. Significantly higher sediment pore water concentrations found in Cargill Bay sediments further support this hypothesis. Pore water P concentrations have been shown to regulate P exchange between the water column and sediment (Meyer 1979, Mayer and Gloss 1980, Hill 1982).

Long term P storage

Our data suggests that 66% of Basin 1 and all of Basin 2 of Frank Lake still has some sorption and burial capacity for further wastewater P loadings. However, we do not know what the ultimate capacity of the marsh will be, nor do we know what affect continued high wastewater loadings will have on the wildlife habitat. Data from other P-loaded wetlands suggests that the high P removal presently demonstrated by Frank Lake will not likely be sustainable. We have shown P removal in Frank Lake by scavenging and sedimentation, processes that have benefitted by the long retention times of the marsh to improve P storage in the past (Spangler et al. 1977, van der Valk et al. 1978). Since the restoration of water levels in 1994, the hydraulic residence times and subsequent P treatment are likely to decrease.

In other wetland wastewater systems, phosphorus removal declines after 4-5 years of continuous loadings (Richardson 1985, Kadlec 1985). If Frank Lake follows this trend, the efficacy of P retention may begin to decline. Removal efficiency has been shown to be strongly dependent on the loading rate applied, with highest removal efficiencies of less than 5 g P m^{-2} $year^{-1}$ for long term removal (Richardson 1985). Since restoration, Frank Lake has received a mean loading of 4.7 g P m^{-2} $year^{-1}$ from point sources. While studies of marshes from warmer climates show higher capacities of freshwater marshes to store P, other studies disagree. Due to the short Canadian summers, we cannot recommend exceeding this loading rate in northern prairie wetlands. Exceeding 10-15 g P m^{-2} $year^{-1}$ results in P retentions of 30-40% or less (Hammer 1989). Even low level cumulative nutrient loadings have led to declines of P retention over time (Richardson and Nichols 1985). We believe that some of the sediments in the inflow region of Frank Lake are near saturation and that the saturation plume could spread and cause water quality problems in the marsh and downstream. To avoid potential eutrophication in Frank Lake and downstream water quality problems in the Little Bow River, P loadings and water quality in the marsh should be closely monitored. The treatment ability of the marsh may be extended by reducing the concentrations and loadings of P from wastewater sources, and by moving the inflow pipe to the head of the marsh.

Conclusions

The Frank Lake wetland is the largest project of its kind in Canada and allows an insight into the treatment ability of northern prairie marshes. The major mechanism of P storage in Frank Lake has been through sedimentation. Fifty-seven percent of the total point source load of P added to Frank Lake from 1990-1995 has been buried in the sediments. Inflow sediments have an impaired ability to take up added P, and have high sediment pore water SRP concentrations. This may be related to the high overlying water SRP concentrations also seen in the inflow region. However, 66% of Frank Lake is not yet saturated with P and displays some capacity for continued P uptake. Based on relationships between loading rates and water quality in other wetlands, Frank Lake may not provide continued high P removal from wastewater at the high loadings being applied, and eutrophication of the system and downstream water quality problems could result.

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Chapter 5: Major impacts of municipal and agro-industrial wastewater on the water and sediment chemistry of Frank Lake.

Conclusions

Frank Lake, Alberta is a large (1 246 hectare) northern prairie wetland in southern Alberta, Canada, that was restored using secondary treated municipal and agro-industrial wastewater. The development process of the Frank Lake project outlined restoration goals to ensure that the marsh would treat wastewater as well as provide wildlife habitat. Implementation of the Frank Lake wetland project involved the cooperation of several agencies. The ability of this cooperative venture to successfully reach completion relied heavily on the communication skills of the agencies with the stakeholders, landowners and the local community. Because the project benefits and the mitigation of negative impacts were demonstrated, the project development sequence was hastened. The establishment of the Frank Lake Conservation Area is a model of co-operative conservation of a project with dual mandates and provides a Canadian example of adaptive management.

The Frank Lake wetland is the largest project of its kind in Canada and provides scientific data on the capacity of northern prairie marshes to treat wastewater. Five years after restoration began, a one year study from July of 1994 to June of 1995 determined (1) spatial distribution of nutrients in marsh surface waters (2) surface water nutrient treatment efficacy and (3) the uptake ability of sediments to retain added phosphorus. Mean annual wastewater inflow surface water concentrations of the nutrients were 17 mg litre^{-1} NH_3-N, 30 mg litre^{-1} NO_3-N and 11 mg litre^{-1} SRP. Mean flows greater than 5 000 m^3 day^{-1} loaded the marsh with 23 626 kgs of P annually.

Despite high nutrient loadings being received by Frank Lake, the marsh provided net nutrient retention during our study from July 1994 through 1995. During the ice free seasons, NH_3-N, NO_3-N and total phosphorus (TP) surface water concentrations were decreased by 76%, 87% and 64% respectively, as waters flowed through the first basin of the marsh. February treatment was less successful, with surface water NH_3-N, NO_3-N and

TP concentration reductions of 46%, -26% (export) and 26%, respectively, through Basin 1. Annual retention in the marsh was 87% of influent ammonia, 80% of nitrate, and 64% TP. Phosphorus removal was less variable than nitrogen removal as N removal was very high in the summer but much lower in the winter.

Water discharged from Basin 1 of Frank Lake had similar quality as nearby Reference wetlands during the ice free months, but nutrient rich water was released into Basin 2 during February. In the spring, nitrogen removal quickly reached optimal treatment while phosphorus treatment took an additional month to reach peak efficiency. Short circuiting of water flow through the marsh and cold seasonal conditions caused spatial and temporal variation in marsh treatment. While the marsh provided excellent summer treatment during our study, the capacity for long term storage of high nutrient wastewater is unknown. Continued high loadings to the marsh may ultimately result in sediment saturation, eutrophication or phosphorus export from the marsh into the Little Bow River. This could have negative impacts on the proposed Little Bow River diversion project currently under development.

The major mechanism of P storage in Frank Lake has been through sedimentation. Approximately 60% of P inputs into the marsh since restoration began in 1990 have been stored in the sediments. Sorption isotherms showed that sediments near the inflow had a limited ability for additional P-sorption. When exposed to 500 μg litre^{-1} of P, inflow sites sorbed a maximum of 1 000 μg P g sediment^{-1}. In contrast, the rest of the sites in the marsh sorbed up to 1 700 μg P g sediment^{-1}, while nearby reference wetland sites sorbed more than 2 500 μg P g sediment^{-1}. However, sites near the sewage inflow had greater sedimentation and P burial rates than all other sites, presumably due to rapid growth and subsequent death of algae and macrophytes.

Based on the P retention in sediments at the inflow sites, we concluded that the inflow sites have a lowered ability for P uptake due to the high P loadings applied to the marsh, but a greater capacity for P burial. While the Frank Lake is presently providing effective P retention, it seems likely that this treatment efficacy may decrease as the remaining sediments become saturated. Based on relationships between loading rates and water quality in other wetlands, Frank Lake may not provide continued high P removal from wastewater at the high loadings being applied, and eutrophication of the system and downstream water quality problems could result.

Table 2.1: Schedule for the Frank Lake wetlands project developed by the Project Implementation Committee in June, 1988.

Project Components	Parties Involved	Key Components	Implementation Schedule
Establish the Frank Lake Implementation Committee	Cargill Foods, Ducks Unlimited Canada, Town of High River, M.D. of Foothills, Alberta Environment, Transportation and Utilities, Fish & Wildlife	Oversee project	June 1988
Evaluate Tertiary Treatment Options	Cargill, Town of High River, Alberta Environment, Transportation and Utilities	Joint vs. Separate system Sizing Cost sharing Ownership/Operation Government Approvals	Evaluations (June) Predesign/Design (July) Government Approvals (August/September) Construction (Fall 1988)
Frank Lake Wetland Development Options and Associated Water Needs	Ducks Unlimited, Fish and Wildlife, Environment	Existing vs. future flows Flooding of deeded land	Surveying (June), Options (July) Water Needs (July), Final Option (August) Design (August/September) Government Approval (October), Construction (1989)
Define Acceptable Highwood River Withdrawal Period	Environment, Fish and Wildlife, Ducks Unlimited	Evaluate period fishery requirements withdrawal needs Withdrawal approvals	Define withdrawal window (June) Finalize withdrawal period and water needs (July/August)
Evaluation of locations for withdrawal of water from Highwood	Environment, Fish & Wildlife, Ducks Unlimited, M.D. of Foothills	Fishery requirements Water resource approvals	Preliminary evaluations (June) Site selection (August) Government approvals (October)
Evaluate pump station, pipeline and discharge options	Entire Implementation Committee	Pipeline sizing, head Rights of way/Access Turnouts along pipeline Discharge location/Design Cost sharing Ownership/operating agreement Government approvals	Select pipeline size (July/Aug) Route (July/Aug) Pump station location (August) Predesign/Design (Aug/Sept) Government approval (October) Construction (1988-1989)

Table 2.2: Detailed project goals and long term management goals of the Frank Lake project.

Project Goals

1. Provide a sink for secondarily treated sewage from Cargill
2. Create more marsh area and a permanent marsh by providing a reliable source of water to the area
3. Provide a sink for secondarily treated wastewater from the Town High River
4. Reduce pollution in the Highwood River by removing wastewater inputs from the nearby Town of High River
5. Maintain the trout fishery in the Highwood River

Management Goals

1. Maintain the existing vegetation and wildlife in the marsh
2. Stimulate the growth of new vegetation for habitat
3. Provide additional habitat (ie. nesting sites) for waterfowl and other birds
4. Provide additional habitat (ie. nesting sites) for other wildlife
5. Restore the biodiversity of upland vegetation and wildlife
6. Treat the nutrients from the wastewater
7. Maintain the marsh as a hemi-marsh over a long time period
8. Create a wildlife conservation area for the public to enjoy
9. Augment the local school wetland curriculum with outreach programs to the marsh

Table 3.1 Description of the reference wetlands sampled from July 1994 to June 1995.

Location	Size (ha)	Runoff inputs	Vegetation
11 km south of High River on east side of Highway # 2	2.0	agriculture	2 m fringe of emergents, abundant submergents
11 km south of High River on west side of Highway # 2	1.0	agriculture	1 m fringe of emergents, abundant submergents
2 km east of High River at 152nd St. East and 532 Ave	0.5	agriculture	0.5 m fringe of emergents, few submergents
Town of High River	2.0	urban	hemi-marsh conditions with abundant submergents

Table 3.2: Cargill Foods and Town of High River wastewater nitrogen and phosphorus concentrations measured at their respective sources from July 1994 to June 1995[1].

	Concentration (mg litre^{-1})							
Source[2] Form[3]	Jul 94	Aug 94	Sep 94	Feb 95	Apr 95	May 95	Jun 95	Mean ± S.E.
Cargill NO_3-N	NS	NS	251	NS	115	34.5	97	124.3±8.9
High River NO_3-N	NS	NS	1.6	0.3	1.0	0.7	0.8	0.9 ±0.1
Inflow[4] NO_3-N	67.5	81.1	100	NS	4.9	43.7	42.3	30.2+4.3
Cargill NH_3-N	54	NS	56	42	27	9.3	16	34.0±8.0
High River NH_3-N	NS	NS	9.7	23	19	17	16	16.9±2.1
Inflow NH_3-N	28	13	22	NS	16	17	12	8.99± 1.3
Cargill TP	18.1	NS	33.8	31.7	35.9	32.9	33.1	30.91±2.6
High River TP	NS	NS	2.1	4.8	4.5	4.4	13.4	5.89±1.7
Inflow TP	3.2	13.5	19.5	21.2	4.76	15.3	13.6	13.00±1.06
Cargill SRP	23.5	NS	27.4	28.8	33.9	32.9	32.7	27.6 ± 2.9
High River SRP	NS	NS	2.6	4.3	4.2	4.0	3.5	3.8 ± 0.36
Inflow SRP	4.3	13.5	17.8	16.4	3.45	14.6	6.7	11.00±2.45

NS = No sample collected.

[1] Data from White and Bayley 1997b.

[2] Cargill = Final effluent from the Cargill beef processing plant; High River = Final effluent from the Town of High River municipal lagoons; Inflow = Combined sources (Town + Cargill) into Frank Lake.

[3] NO_3-N = NO_3+ NO_2 nitrogen; NH_3-N = ammonia-ammonium nitrogen; TP = Total phosphorus; SRP = soluble reactive phosphorus

[4] Samples occasionally greater at the source reflect the temporal variation in collection.

Table 3.3: Phosphorus loadings to Frank Lake by source[a].

Year	Source	Volume[b] (m^3)	Mean TP (mg $litre^{-1}$)	kg P	kg P yr^{-1}	g P $m^{-2} yr^{-1}$ [c]
90	Cargill	601 391	30.92	18 595		
90	Town	1 019 992	2.33	2 383	20 979	4.18
90	River	7 164	.06	1		
91	Cargill	556 831	30.92	17 217		
91	Town	1 028 151	2.88	2 961	20 240	4.03
91	River	998 037	.06	62		
92	Cargill	676 491	30.92	20 917		
92	Town	1 075 076	3.32	3 569	24 553	4.89
92	River	1 068 770	.06	67		
93	Cargill	850 124	30.92	26 285		
93	Town	719 612	2.20	1 583	27 935	5.57
93	River	1 076 216	.06	67		
94	Cargill	851 563	30.92	26 330		
94	Town	1 216 102	4.27	5 192	27 980	5.58
94	River	0	.06	0		
95	Cargill	532 137	30.92	16 453		
95	Town	1 316 463	2.75	3 620	20 073	4.00
95	River	0	0	0		
Mean					23 626	4.70
Total					141 760	

[a] Water sources: Cargill = Cargill Foods beef processing plant, Town = municipal wastewater from the Town of High River, River = clean water from the Highwood River.

[b] Water volume data are from the Town of High River annual effluent reports (20 samples 1990 to 1995, analysed by Chemex laboratories). Mean TP concentrations for Cargill Foods from Bayley et al. (1995) and extrapolated for 1990-1993. Mean annual TP concentrations for the Town of High River from Alberta Environment quarterly effluent reports for the Town of High River. Mean Highwood River TP concentrations from Bayley et al. (1995), and extrapolated for 1990-1993.

[c] An area of 501.8 hectares was used for Basin 1, which is Normal Operating Level.

Table 3.4: Nitrogen in Basin 1 and Basin 2 of Frank Lake and Reference wetlands from July 1994 to June 1995[1] .

	Concentration (mg litre^{-1})								
	1994				1995				Mean Annual
Region[1]/Form[2]	Jul	Aug	Sep	Oct	Feb	Apr	May	Jun	±S.E.
Inflow NO_3-N	29.2*	44.3*	86.0*	47.0*	28.2	26.5*	13.0*	22.5*	30.26±4.33
Cargill Bay NO_3-N	11.3**	22.1**	35.0**	50.4**	30.0	17.3**	2.4**	6.7**	21.34±2.90
RB1 NO_3-N	0.06	1.05	0.8	2.21	33.1	7.22	0.22	0.54	5.23±3.72
B2 NO_3-N	NS	0.01	<0.01	0.06	0.73	0.59	0.54	0.77	0.51±0.12
References NO_3-N	0.01	<0.01	<0.01	0.06	0.07	0.03	0.01	0.02	0.02±.00
Inflow NH_3-N	10.6*	11.0*	11.0*	10.0*	17.0	7.1*	6.5*	3.8*	8.99±1.34
Cargill Bay NH_3-N	0.45**	1.5**	3.8**	4.5**	10.4	1.9**	0.8	2.6**	3.13±0.73
RB1 NH_3-N	0.16	0.2	0.3	0.4	9.4	0.9	1.4	1.2	1.10±0.27
B2 NH_3-N	<0.01	0.1	0.1	0.2	0.56	0.24	0.83	0.2	0.29±0.06
References NH_3-N	0.15	0.4	0.3	0.5	0.55	0.04	0.05	1.6	0.56±0.26

NS = No sample collected.

* and ** indicate significance at $P < 0.05$.

[1] Inflow = combined High River + Cargill Foods effluent; Cargill Bay = Bay that receives the inflow; RB1= the rest of Basin 1 (i.e. Basin 1 not including Cargill Bay); B2 = Basin 2; References = the mean of 4 nearby Reference wetlands.

[2] NO_3-N = NO_3+NO_2 nitrogen; NH_3-N = ammonia-ammonium nitrogen.

Table 3.5: Phosphorus concentrations in Basin 1 and Basin 2 of Frank Lake and Reference wetlands from July 1994 to June 1995[1].

	Concentration (mg litre^{-1})								
	1994				1995				Mean Annual
Region[2]/Form[3]	Jul	Aug	Sep	Oct	Feb	Apr	May	Jun	±S.E.
Inflow/CB SRP	2.8*	5.4*	5.4*	7.2*	10.3	2.4	3.8*	7.7*	5.50±0.49
RB1 SRP	1.1	1.7	1.6	1.7	10.0	1.6	1.6	3.4	2.30±0.22
B2 SRP	0.9	1.2	1.0	1.1	6.8	2.3	2.5	3.5	3.30±0.28
References SRP	2.1	4.4	3.5	2.8	3.0	2.5	2.2	3.8	3.00±0.26
Inflow/CB TP	3.5*	6.1*	6.4*	8.1*	11.8	4.3*	3.8*	8.7*	6.07±0.47
RB1 TP	1.4	2.0	1.96	1.9	12.7	2.8	2.2	3.9	2.42±0.13
B2 TP	NS	1.1	1.7	1.3	7.0	3.0	3.0	3.8	3.41±0.28
References TP	2.1	4.4	3.7	2.8	3.0	2.5	2.2	4.6	2.27±0.33

NS = No sample collected.

*Indicates significance at $P < 0.05$.

[1] Inflow = combined High River + Cargill Foods effluent; Cargill Bay = Bay that receives the inflow; RB1 = the rest of Basin 1 (i.e. Basin 1 not including Cargill Bay); B2 = Basin 2; References = the mean of 4 nearby Reference wetlands.

[2] SRP = soluble reactive phosphorus; TP = total phosphorus.

Table 3.6: Nitrogen retention in Basin 1 of Frank Lake calculated from concentrations in inflow and outflow sites.

Nutrient Species	**Month**	**Mean Inflow (mg litre^{-1}, n=7)**	**Mean Outflow* (mg litre^{-1}; n=17)**	**% Decrease**
NO_3	July	29.2	0.12	99
	August	44.3	3.1	93
	September	86	2.1	97
	October	47	5.89	87
	February	28.2	37.4	-26
	April	26.5	10.2	61
	May	13	0.41	96
	June	22.5	0.55	97
(Mean)		30.02	2.88	(80)
NH_3	July	10.6	0.1	99
	August	11.0	0.2	98
	September	11.0	0.3	97
	October	10.0	0.3	97
	February	17.0	9.1	46
	April	7.1	0.9	87
	May	6.5	1.3	80
	June	3.8	0.2	95
(Mean)		8.98	1.16	(87)

* Inflow and outflow sites refer the group of sites closest to the inflow pipe and the outflow weir.

Table 3.7: Phosphorus retention in Basin 1 of Frank Lake calculated from concentrations in inflow and outflow sites.

Nutrient Species	**Month**	**Mean Inflow (mg litre^{-1}, n=7)**	**Mean Outflow* (mg litre^{-1}; n=17)**	**% Decrease**
SRP	July	2.86	0.75	74
	August	5.42	0.89	84
	September	5.46	0.80	56
	October	7.22	1.38	81
	February	10.37	10.31	1
	April	2.41	1.71	29
	May	3.80	1.62	57
	June	7.73	1.96	75
(Mean)		(4.90)	(2.41)	(57)
TP	July	5.17	0.99	81
	August	7.59	1.00	87
	September	7.97	1.04	87
	October	7.43	1.70	77
	February	18.21	13.49	26
	April	4.00	3.23	19
	May	5.76	2.29	60
	June	8.42	2.11	75
Mean		(8.20)	(2.52)	(64)

* Inflow and outflow sites refer the group of sites closest to the inflow pipe and the outflow weir.

Table 3.8: August treatment at Frank Lake, Alberta expressed as the difference between the inflow point (1 site) and the outflow point (1 site). Nutrient concentrations are reduced as waters flow through Basin 1. Mean reference wetland concentrations are provided for comparison to Basin 1 outflow concentrations.

	Concentration (mg litre^{-1})		
	Inflow site	Outflow site	Reference wetlands n = 4
Nitrogen species			
NH_3-N	13	0.1	0.3
NO_3-N	81	0.5	0.01
Phosphorus species			
SRP	13	1	4
TP	13	1	4

Table 3.9: February treatment at Frank Lake, Alberta expressed as the difference between the inflow point (1 site) and the outflow point (1 site). Nutrient concentrations are reduced as waters flow through Basin 1. Mean reference wetland concentrations are provided for comparison to Basin 1 outflow concentrations.

	Concentration (mg litre^{-1})		
	Inflow site	Outflow site	Reference wetlands n = 3
Nitrogen species			
NH_3-N	20	17	0.3
NO_3-N	37	45	0.07
Phosphorus species			
SRP	16	10	1
TP	24	11	2

Table 3.10: Domestic* wastewater dissolved oxygen and nutrient concentrations compared to treated wastewater from the Cargill Foods beef processing plant (July 1994-June 1995).

Variable	Strong domestic wastewater (mg litre^{-1})	Combined inflows to Frank Lake (mg litre^{-1})
Dissolved oxygen	0	0
Total dissolved nitrogen	35	71.1
Free ammonia	50	18.5
Nitrate	0	52.6
Total phosphorus	15	12.2

*Domestic wastewater concentrations adapted from Metcalf and Eddy, Inc., 1991.

Table 4.1: Water quality parameters sampled at the time of sediment collection (mean ± 1 SD).

Parameters	Cargill Bay	Rest of Basin 1	reference
n	4	6	8
Conductivity	1.8 (0.7)	1.6 (0.3)	3.3 (3.2)
NO_3^--N (mg litre^{-1})	7.7 (6.2)*	0.9 (0.8)	0.6 (0.3)
Ca (mg litre^{-1})	73.4 (4.7)	80.1 (11.5)	76.0 (2.7)
K (mg litre^{-1})	46.2 (9.5)	53.9 (8.7)	75.7 (6.7)*
Mg (mg litre^{-1})	45.1 (4.3)	51.3 (8.9)	100.4 (12.7)*
Na (mg litre^{-1})	288.6 (68.2)	324.9 (64.1)	408.4 (148.4)*

* denotes sites significantly post-hoc test (Fisher's LSD)

Table 4.2: Mean sediment composition of study regions. Data from full core samples. CB = Cargill Bay sites, RB1 = Rest of Basin 1 sites, Ref = reference sites. (mg g^{-1} ± 1 SD)

	mg g^{-1}						
	P	Ca	Mg	Na	K	org C	CO_3^{2-}-C
CB	2.58 (0.92)*	38.8(8.9)	8.9 (0.8)	0.78 (0.1)	6.8 (1.7)	53.1 (10.4)	57.6 (33.0)
RB1	1.04 (0.17)	29.8 (5.8)	8.1 (0.7)	0.72 (0.1)	5.8 (0.9)	43.3 (6.7)	42.8 (8.2)
Ref	1.04 (0.08)	34.8 (7.3)	11.5 (1.3)*	2.46 (1.7)*	7.6 (2.1)	52.7 (13.3)	49.0 (15.7)

* denotes sites significantly post-hoc test (Fisher's LSD)

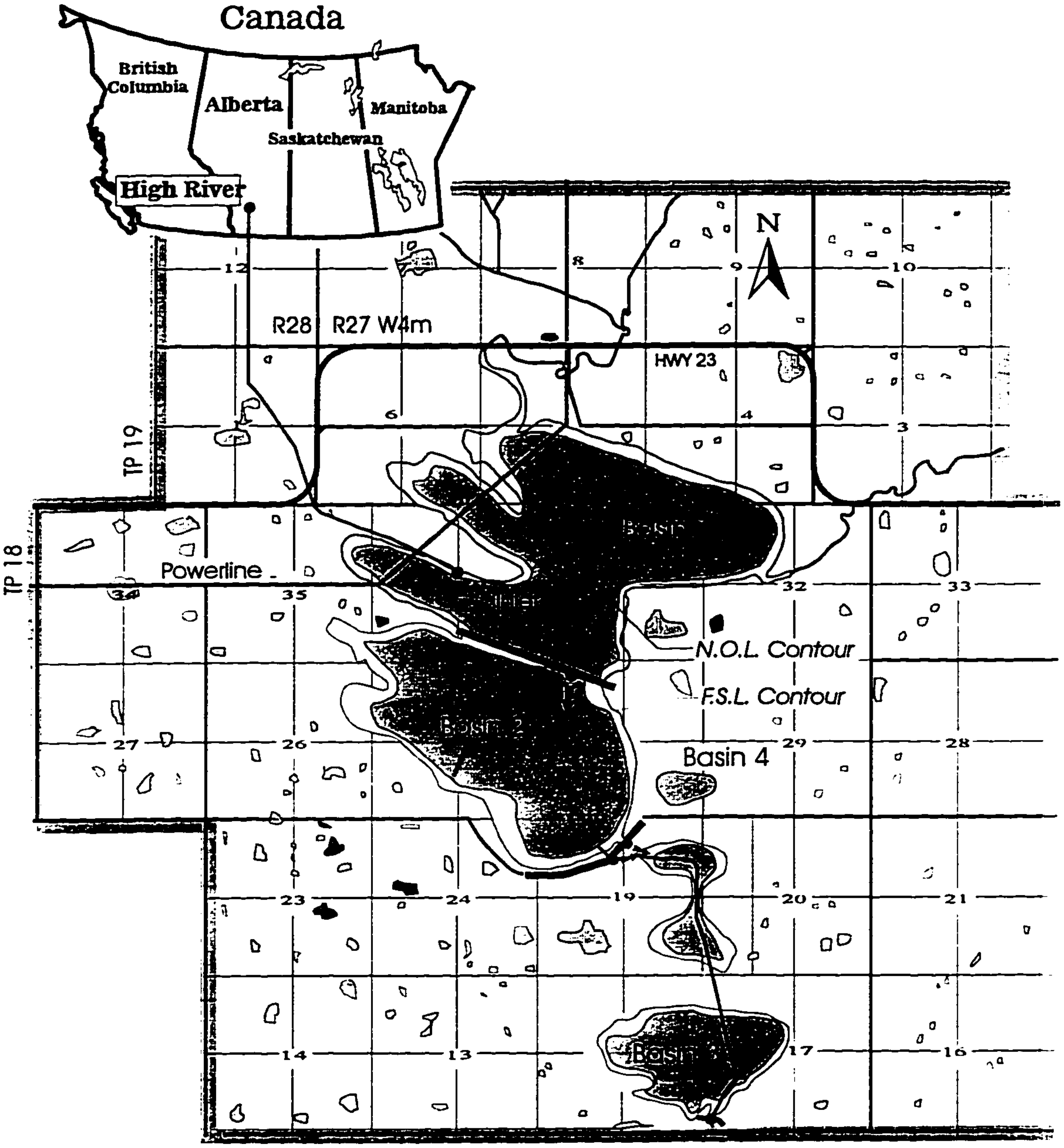

Figure 2.1: The 9 325 hectare (23 040 acre) Frank Lake Intensive Management Unit in southern Alberta, Canada. Wastewater flows underground from the town of High River and is discharged at a single point source into Basin 1. N.O.L. = Normal Operating Level, F.S.L. = Full Supply Level.

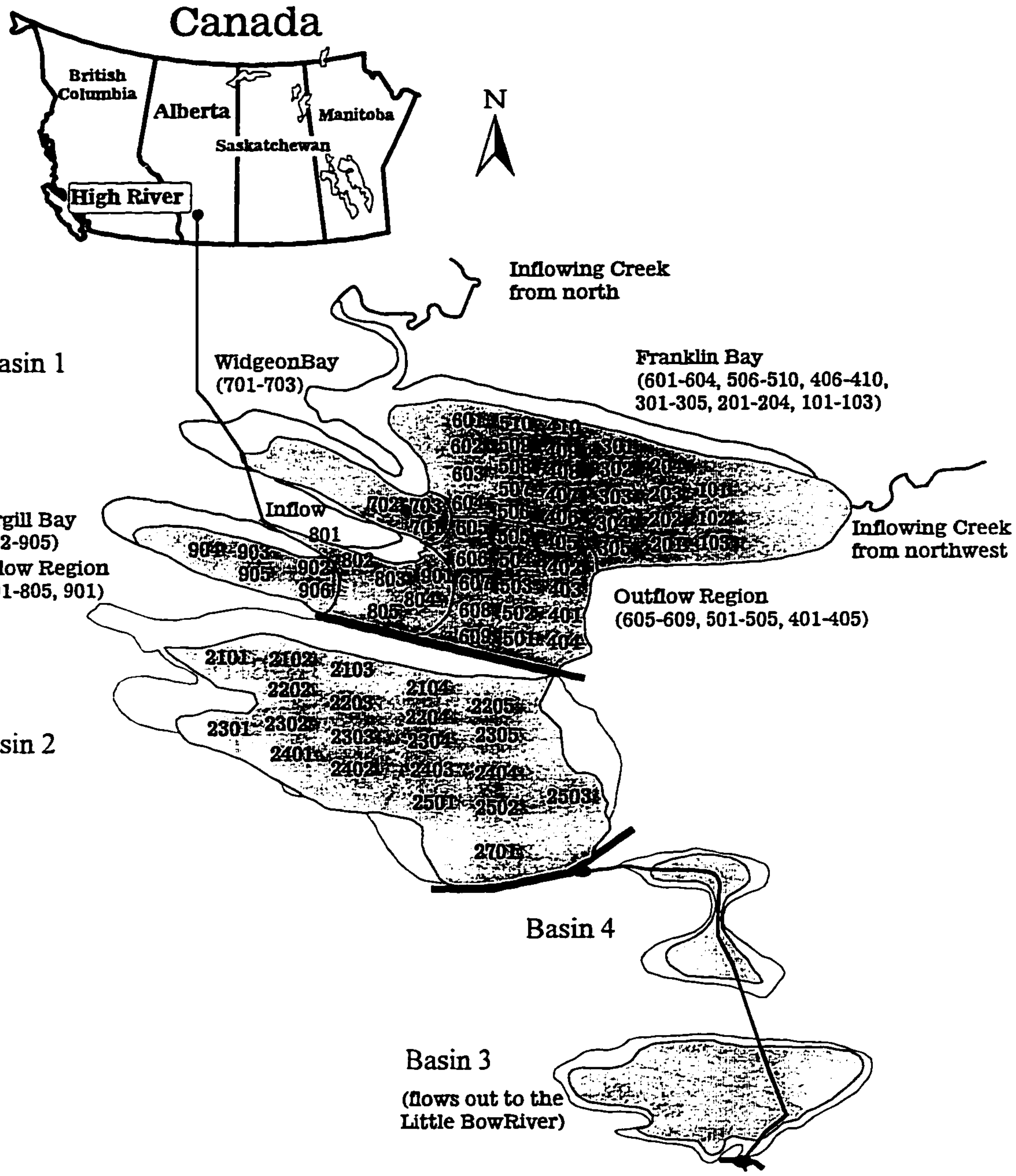

Figure 1: The 1 246 hectare wetland complex at Frank Lake, Alberta. Wastewater flows underground from the Municipal lagoons at High River and is discharged into the west lobe of Basin 1. Sampling sites and regions are identified on Basin 1 and Basin 2.

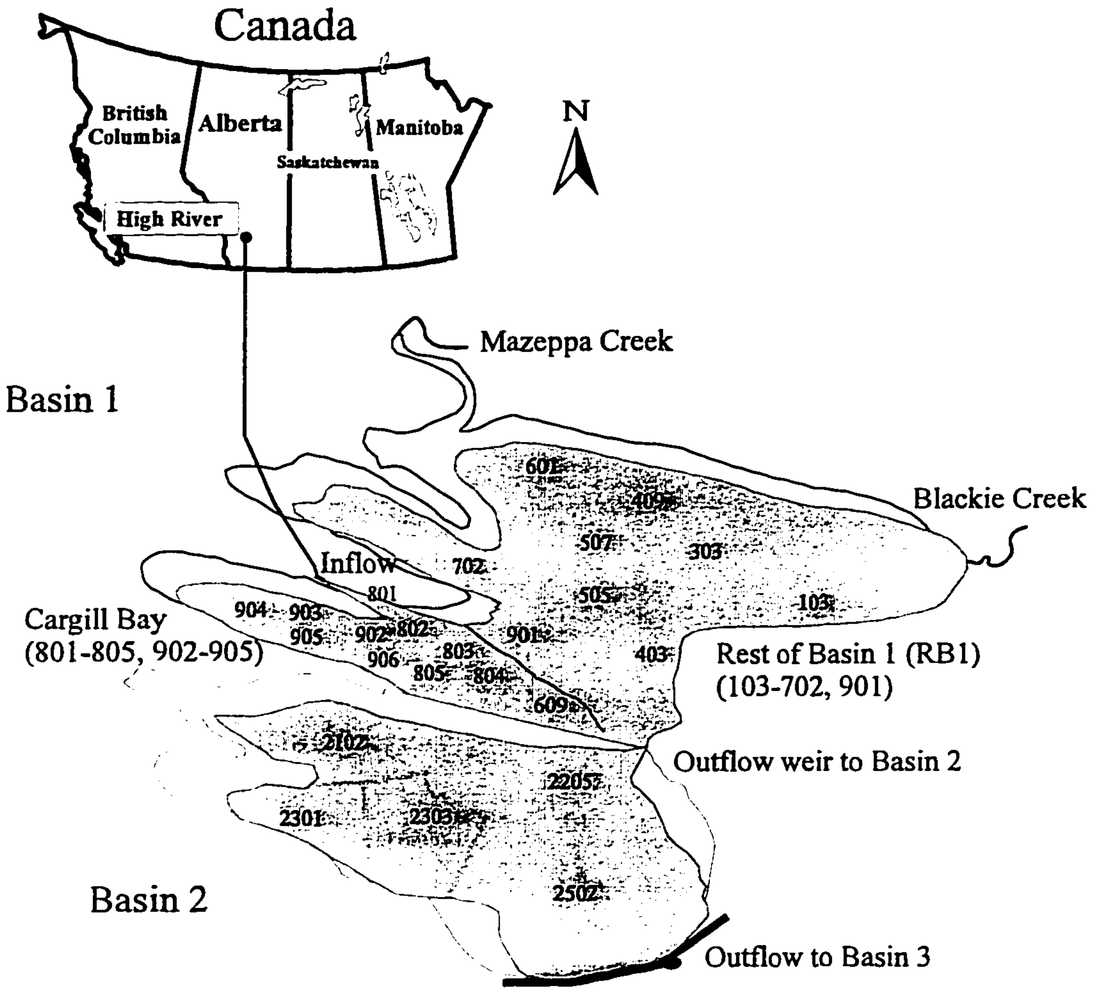

Figure 4.1 The 1 246 hectare wetland complex at Frank Lake, Alberta, with sediment collection sites indicated. Basin 1 division identifies zone of impact based on sediment thickness and TP concentrations.

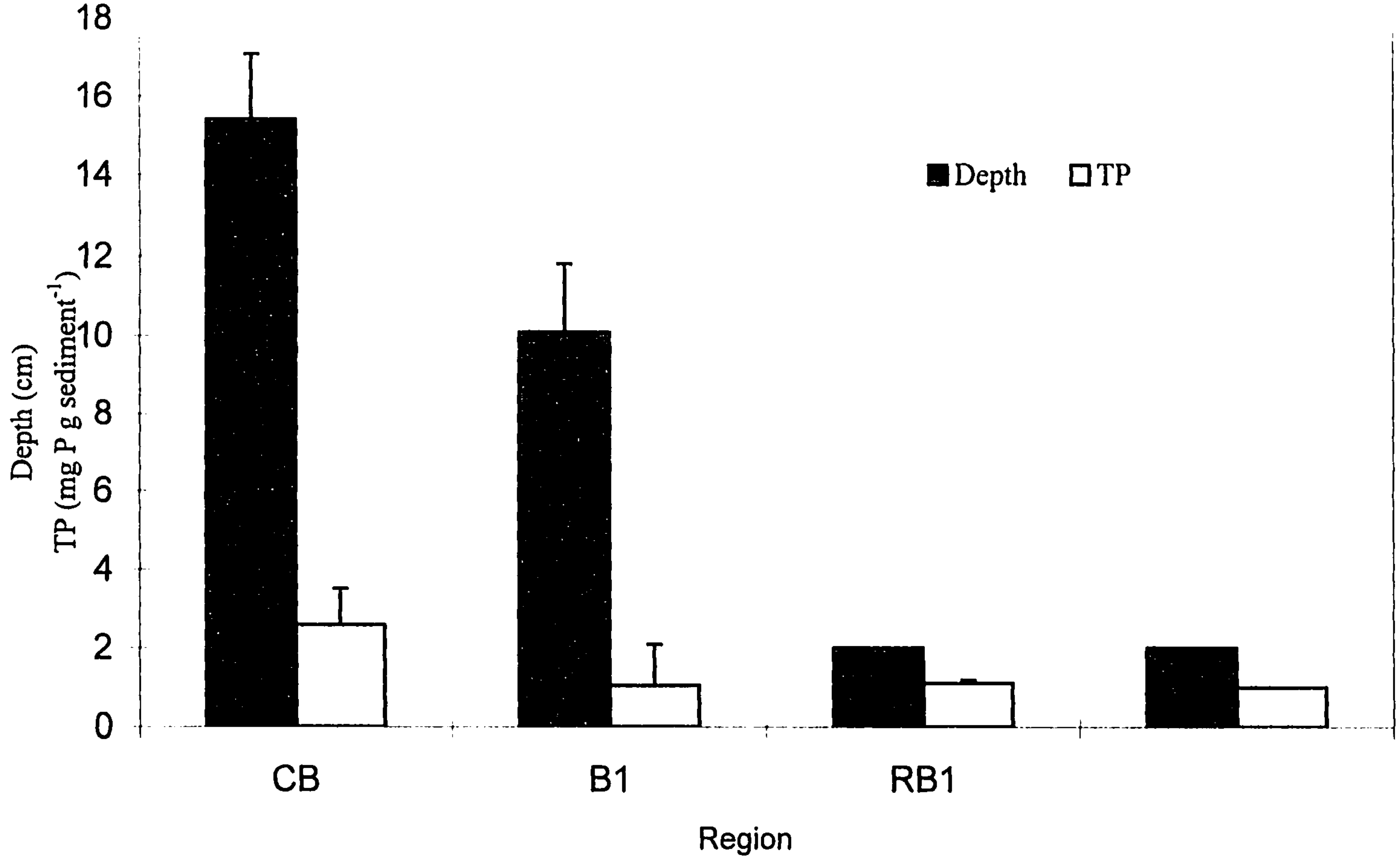

Figure 4.2: Sediment Depth and TP Across Frank Lake and Reference Wetlands. CB = Cargill Bay, RB1 = Rest of Basin 1, Ref = References.

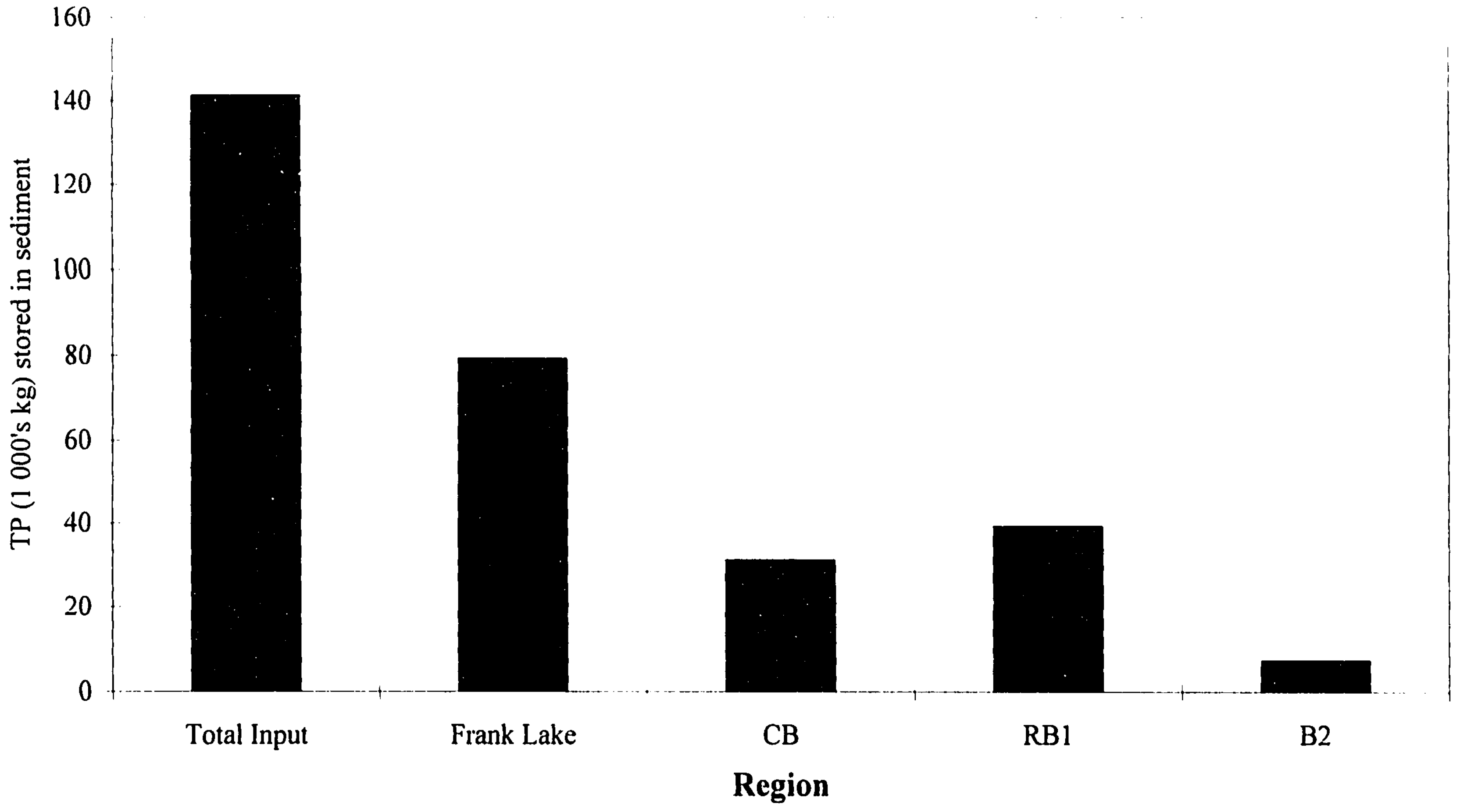

Figure 4.3: TP accumulation in Frank Lake sediment by region since restoration in 1989. Frank Lake = TP stored by all of Frank Lake (sum of CB + RB1 + B2), CB = Cargill Bay, RB1= Rest of Basin 1, B2 = Basin 2.

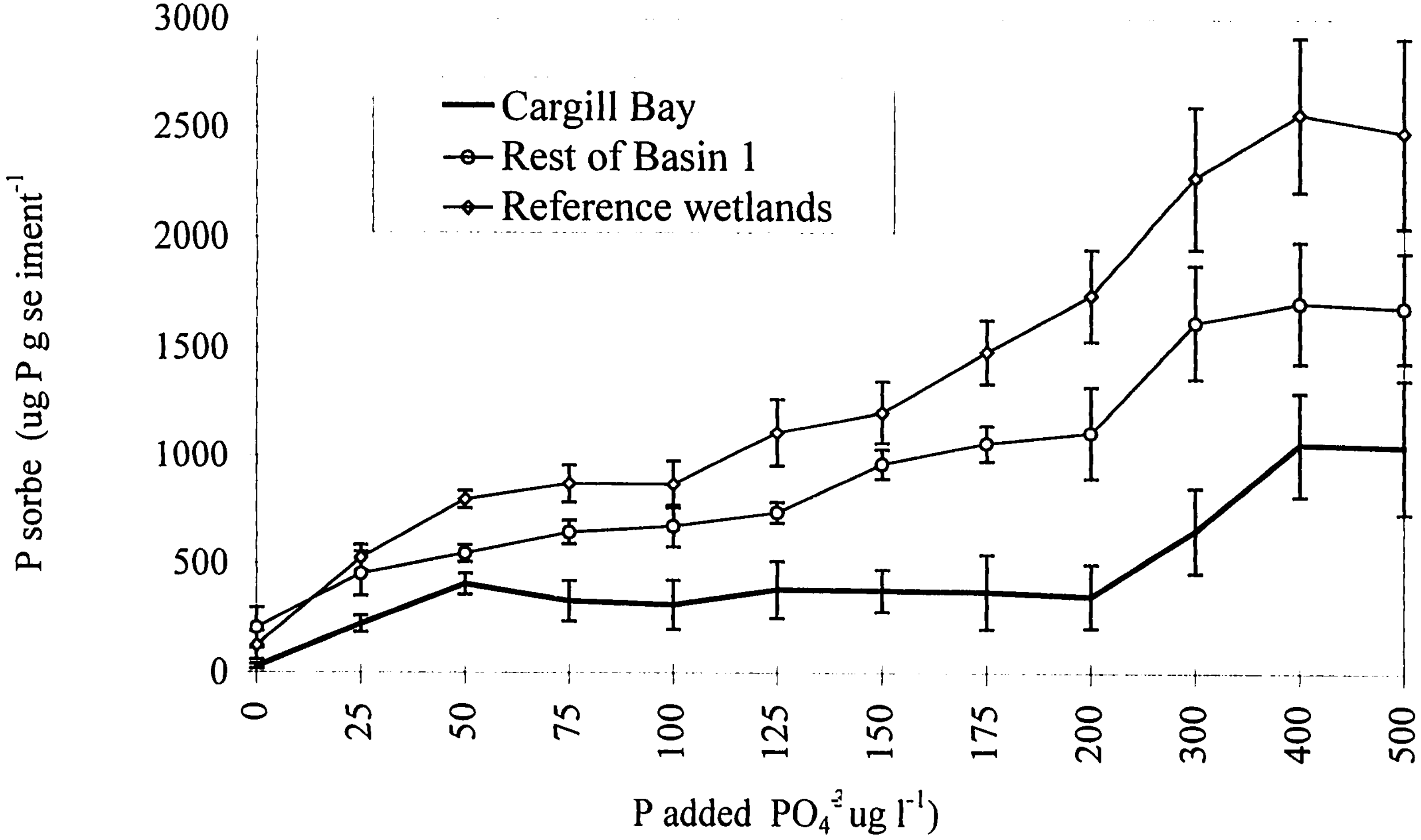

Figure 4.4: Phosphate sorption isotherms for sediments collected June 18 1995. P added as NaH_2PO_4 to 10 mg (wet weight) sediment, standardized as dry weight. Mean (SE) uptake.