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A COST-BENEFIT ANALYSIS FOR THE DENITRIFICATION
OF WASTEWATER UTILIZING WETLANDS VERSUS
WASTEWATER TREATMENT FACILITIES

A Project
Presented to the
Faculty of
California State University,
San Bernardino

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Environmental Sciences

by
Jennifer Michelle Bell, MPA
June 2008

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June 2008

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ABSTRACT

A cost-benefit analysis for the denitrification of wastewater utilizing wetlands versus wastewater treatment facilities was conducted for the purposes of determining which, if any treatment system is more appropriate for meeting advanced treatment needs. Utilizing energy consumption of methane emissions and national figures pertaining to tourism, recreation, and the commercial fishing and shellfish industries, a monetary valuation was assigned to wetlands.

Although extremely beneficial to society, wetlands were determined to only be a practical solution for meeting advanced treatment needs when certain conditions exist. These conditions are: 1) topography favoring gravity flow; 2) soils that are able to withstand saturated conditions; 3) adequate supply of quality water; 4) economical land that is proximate to the supply source waters; and 5) ability of the wetlands to treat pollutants of concern (POCs). If these conditions do not exist, then wetlands are not a practical or cost-effective approach for the advanced treatment of wastewater.

Where these conditions do not exist, wastewater treatment facilities are the best choice for treatment.

However, due to the large quantity of wastewater that can be treated by wastewater treatment facilities, if the option is available, green technology designed to minimize environmental impacts should be utilized.

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2. Dr. Kimberley Renee Cousins, Committee Member
3. Dr. Jeffrey Wynn Beehler, Committee Member and Internship Mentor.

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TABLE OF CONTENTS

ABSTRACT	iii	
ACKNOWLEDGEMENTS	v	
LIST OF TABLES	xi	
LIST OF FIGURES	xiii	
LIST OF ABBREVIATIONS AND ACYRONYMS	xiv	
CHAPTER ONE: ORGANIZATION OF THE PROJECT		
Introduction to the Project	1	
Purpose	1	
Scope	1	
Significance of the Project	3	
Limitations to the Project	3	
Definition of Terms	5	
Review of Related Literature	5	
CHAPTER TWO: WATERSHEDS AND THEIR REGULATORY FRAMEWORK		
Introduction to Watersheds	6	
The Regulatory Framework Guiding Wetlands	10	
Santa Ana River (SAR) Watershed	22	
Prado Wetlands	24	
CHAPTER THREE: CHEMISTRY OF NATURAL WATERS		31
Important Atmospheric Gases Common to Surface Waters	36	
Molecular Oxygen	40	

Biochemical Oxygen Demand	41
Oxidation-Reduction Potential	46
Carbon Dioxide	47
Nitrogenous Compounds	54
Negative Effects Associated with Inorganic Nitrogenous Compounds	58
Microbial Processes	59
Geochemistry	62
Internal and External Loading	64
Influent/Effluent	67
 CHAPTER FOUR: MUNICIPAL WASTEWATER TREATMENT	
History of Wastewater Disposal Methodologies	71
Wastewater Regulatory Permits	77
Wastewater Treatment - Primary Treatment	79
Wastewater Treatment - Secondary Treatment	80
Trickling Filters	81
Rotating Biological Contactors	83
Wastewater Treatment - Disinfection	84
Wastewater Treatment - Denitrification	89
Wastewater Treatment - Tertiary Treatment	91
 CHAPTER FIVE: ALTERNATIVE TREATMENT SYSTEMS	
Background	93
Wetland Design - Feasibility	96

Wetland Design - Wastewater Characteristics	101
Field Testing	101
Suspended Solids	102
Organic Matter	103
Nutrients	104
Trace Elements and Organic Compounds	110
Major Ion Concentrations	110
Treatment Mechanisms in Wetlands	110
Public Health Issues	110
Wetland Design - Prado Wetlands	111
CHAPTER SIX: COST-BENEFIT ANALYSIS	
Decision Making Process	114
Calculating Costs of Tertiary Treatment: Wastewater Treatment Facilities	118
Examples of Construction Costs: Wastewater Treatment Facilities	119
Examples of Construction Costs - Green Technology: Wastewater Treatment Facilities	122
Calculating Costs of Tertiary Treatment: Wetlands	129
Examples of Construction Costs: Constructed Treatment Wetlands	132
Calculating Costs of Tertiary Treatment: Intangibles	135
Intangible Costs: The Costs Associated with Methane Emissions	137

Intangible Costs: The Costs Associated with Methane Emissions - Wastewater Treatment Facilities	139
Intangible Costs: The Costs Associated with Methane Emissions - Constructed Wetlands	149
Intangible Costs: The Costs Associated with National Pollutant Discharge Elimination System Permits - Wastewater Treatment Facilities	155
Intangible Costs: The Costs Associated with Impervious Surfaces - Wastewater Treatment Facilities	157
Intangible Costs: The Costs Associated with Vector Control - Constructed Wetlands	158
Calculating the Benefits of Tertiary Treatment: Wetlands	158
Intangible Benefits: Valuating Wildlife and Aesthetics - Constructed Wetlands	159
Intangible Benefits: Valuating Wildlife and Aesthetics - Florida Everglades	161
Intangible Benefits: Valuating Wildlife and Aesthetics - Prado Wetlands	161
Intangible Benefits: Valuating Wildlife and Aesthetics - The Commercial Fishing Industry	162
Intangible Benefits: Flood Attenuation	163
Intangible Benefits: Valuating Public Health - Wastewater Treatment Facilities	167
CHAPTER SEVEN: SUMMARY/CONCLUSION/RECOMMENDATIONS	168
REFERENCES	174

LIST OF TABLES

Table 1.	Causes of Waterborne Outbreaks. Published by the Center for Disease Control	33
Table 2.	Air/Water Interface	38
Table 3.	Nitrogen and its Oxidative States	57
Table 4.	Comparison of Nitrogen Concentrations for Average Phase 1, 2, and 3	108
Table 5.	Monetary Costs Associated with Nitrification	121
Table 6.	Monetary Costs Associated with Denitrification	121
Table 7.	Comparison of Blue Plains Wastewater Treatment Facility and Coyle Biological Denitrification Plant	127
Table 8.	Design and Construction Costs for the Hemet San Jacinto Multi-Purpose Constructed Wetlands and Wetland Research Facility	132
Table 9.	Comparative Costs of Constructed Wetlands within Arizona and California	135
Table 10.	Comparison of Combined Heat and Power Systems	146
Table 11.	Costs of Operating an Anaerobic Digester	148
Table 12.	Costs of Operating A Wetlands	152
Table 13.	Costs of Operating an Anaerobic Digester	154
Table 14.	Costs Associated with National Pollutant Discharge Elimination System Permits	156
Table 15.	Economical Benefits Associated with Wetlands	165

Table 16:	Costs Incurred Due to the Declination of the Nation's Wetlands	166
Table 17.	National Benefits and Costs Provided by Wetlands Resources	172
Table 18.	Summarization of Known Costs Associated with Wastewater Treatment Facilities and Wetlands	173

LIST OF FIGURES

Figure 1.	Drainage Basin	6
Figure 2.	Santa Ana River Watershed	23
Figure 3.	Prado Wetlands Vicinity Map	26
Figure 4.	Prado Treatment Wetlands	27
Figure 5.	Environmental Sphere of Influence	35
Figure 6.	Global Carbon Cycle	49
Figure 7.	The Hydrologic Budget	69
Figure 8.	Minoan Sanitation System	72
Figure 9.	Preliminary Treatment Process	79
Figure 10.	Trickling Filters	82
Figure 11.	Vicintiy Map of Prado Wetlands Detailing Basins.....	113
Figure 12a.	Blue Plains Wastewater Treatment Facility.....	124
Figure 12b.	Blue Plains Wastewater Treatment Facility.....	125
Figure 13.	Coyle, Oklahoma, Water Treatment System	128
Figure 14.	Free Water Surface Flow Wetlands	131
Figure 15.	Combined Heat and Power System	140

LIST OF ABBREVIATIONS AND ACYRONYMS

AGR	Agricultural Supply
ASFPM	Association of State Floodplain Managers
Basin Plan	Water Quality Control Plan for the Santa Ana River Basin
BAT	Best Available Technology
BGD	billion gallons per day
BIOL	Preservation of Biological Habitat of Special Significance
BMPs	Best Management Practices
BOD	Biochemical Oxygen Demand
BPWTF	Blue Plains Wastewater Treatment Facility
Btu	British Thermal Units
Cal EPA	California Environmental Protection Agency
CAP	Corrective Action Plan
CBA	Cost Benefit Analysis
CDPH	California Department of Public Health
CDWA	California Safe Drinking Water Act
CHP	Combined Heat and Power
COLD	Cold Freshwater Habitat
COMM	Commercial and Sportfishing
CWA	Clean Water Act
DO	Dissolved Oxygen

EMWD	Eastern Municipal Water District
EST	Estuarine Habitat
EVT	Evapotranspiration
FWS	Free Water Surface System
GWP	Global Warming Potential
GWR	Groundwater Recharge
IND	Industrial Service Supply
IPCC	International Panel on Climate Change
LWARM	Limited Warm Freshwater Habitat
MAR	Marine Habitat
MGD	million gallons per day
MS4	Municipal Separate Storm Sewer System
MUN	Municipal and Domestic Supply
NAV	Navigation
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
OCWD	Orange County Water District
POCs	Pollutant of Concern
POTWs	Publicly Owned Treatment Works
POW	Hydropower Generation
PROC	Industrial Process Supply
PRP	Palmdale Reclamation Plant

RARE	Rare, Threatened, or Endangered Species
REC1	Water Contact Recreation
REC2	Non-Contact Water Recreation
RWQCB	Regional Water Quality Control Board
SAR	Santa Ana River Watershed
SAWPA	Santa Ana Watershed Project Authority
SDWA	Federal Safe Drinking Water Act
SFS	Subsurface Flow System
SHEL	Shellfish Harvesting
SPWN	Spawning, Reproduction, and Development
SWRCB	State Water Resources Control Board
TDS	Total Dissolved Solids
TMDLs	Total Maximum Daily Loads
TSS	Total Suspended Solids
USACOE	United States Army Corp of Engineers
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Society
VOCS	Volatile Organic Carbon
WARM	Warm Freshwater Habitat
WDR	Waste Discharge Requirements
WILD	Wildlife Habitat

CHAPTER ONE

ORGANIZATION OF THE PROJECT

Introduction to the Project

As cities grow, more demand and regulatory stipulations are placed on a watershed for its water resources, city managers and water leaders are challenged with how to meet ever-growing needs of increasing demand for potable water. Often, budgetary crises occur along side of capital improvement needs and infrastructure decisions ultimately become based on current economic conditions.

Purpose

The purpose of this project was to not only identify current regulatory issues, as they pertain to water and denitrification, but also could be used to assist policy makers with identifying other factors to be considered when choosing the appropriate advanced treatment systems for their facilities.

Scope

This project has been divided into seven chapters. Chapter Two focuses on California's regulatory issues and ultimately narrows its scope to the Santa Ana Watershed and its specific regulatory framework.

Chapter Three provides an overview of natural water chemistry and the interactions that the hydrosphere has with other environmental spheres. The objective of Chapter Two is to understand the chemistry involved within a natural water system and the role that environmental conditions have on the overall health of a watershed.

Chapter Four discusses the history of wastewater treatment and the processes involved in wastewater treatment.

Chapter Five provides a case study of treatment wetlands within the Santa Ana Watershed, Prado Wetlands, to demonstrate the effectiveness of wetlands in meeting advanced treatment needs.

Chapter Six presents an overview of the economic components to wastewater treatment, while at the same time, placing a financial valuation on aesthetics and recreation. Although "hard" numbers can be determined for wastewater treatment facilities (WWTFS), only "soft" figures can be placed on societal values, which make the results somewhat subjective.

Finally, Chapter Seven summarizes the findings and qualifies the conclusions significant to the project in

terms of the monetary valuations assigned to both wetlands and wastewater treatment facilities.

The overall goal of the project is to make the reader aware of all the costs and benefits involved in treatment options.

Significance of the Project

Many attempts have been made to provide dollar figures for migratory birds and beauty, but when it comes to the final outcome, it is very difficult. The studies always conclude that it is difficult to determine these values. This project is significant in that a dollar figure is placed on methane emissions from wetlands in terms of the energy cost that would have been incurred had the capture and reuse of methane occurred, as well as, estimating as to the worth of wetlands in the United States in terms of tourism and the commercial fishing and shellfish industries.

Limitation to the Project

The project has inherent limitations. The cost of land acquisition can not be adequately determined because it is extremely variable. It is entirely dependent on the geographical region in which it is to be purchased and current market values. The value of public lands can not be determined, as they tend to be heavily subsidized when used

for public infrastructure needs. The inability to calculate land costs creates significant difficulties in determining an overall wetland development cost.

The cost of impervious surfaces can not be calculated. There are estimates that can be used to determine surface runoff based on the percentage of pervious versus impervious surfaces, but water is also heavily subsidized. If an exact percentage of runoff could be calculated, the true value of water is unknown, and therefore, the value of runoff, in term of monies lost due to the lost of water resources, can not be determined.

Significant strides were made to determine the costs of recreation and aesthetics, but actual values assigned by an individual ultimately reflects the individual's personal feelings toward recreation and wildlife.

The ability to get concrete figures and budgets was ultimately dependent on local cities and their willingness to share information. Additionally, to share information supervisors and directors had to take time out of their own busy schedules.

Definition of Terms

Please refer to the List of Abbreviations and Acronyms, beginning on page vii. Definitions to specific terms are provided in each chapter.

Review of Related Literature

Each chapter presents a review of pertinent literature. Please refer to individual chapters for the corresponding literature review.

CHAPTER TWO

WATERSHEDS AND THEIR REGULATORY FRAMEWORK

Introduction to Watersheds

Commonly referred to as a drainage basin, as shown in Figure 1¹, a watershed is a region from which the local

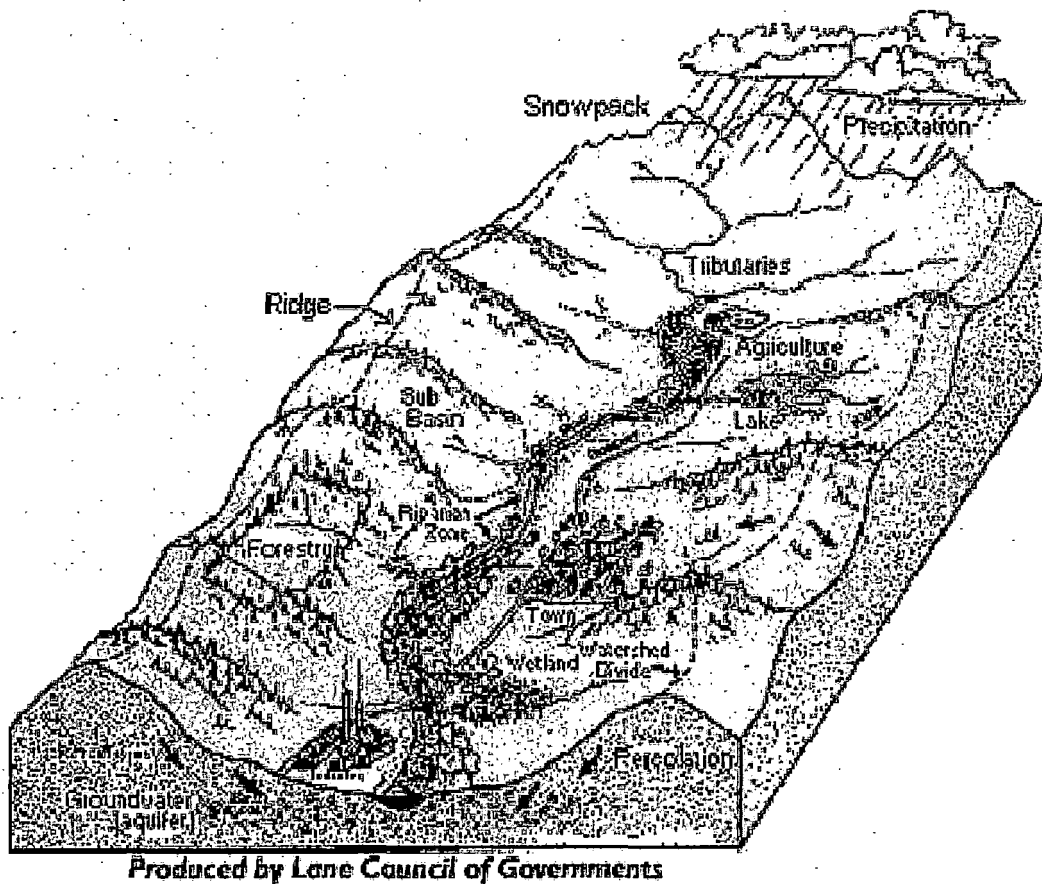


Figure 1. Drainage Basin.

¹Source: Reprinted from U.S. Environmental Protection Agency Home Page.
[http:// www.epa.gov/OWOW.wetlands/what/defintions.html](http://www.epa.gov/OWOW.wetlands/what/defintions.html) (accessed July 3, 2007)

waterbody (i.e., river) receives its principle water supply (1). Runoff waters collected from the surrounding area are topographically separated from neighboring watersheds by ridges, mountains, or other natural or anthropogenically induced water "divides." Separated into its individual basin, water will gravity flow via various conveyance channels (i.e., rivers, streams, riparian corridors, etc.) providing the water source to the overall larger system (i.e., ocean, estuary, wetlands, etc.).

Of particular importance to a watershed are its wetlands, those areas that naturally provide a home to an array of wildlife and function within the watershed to protect water quality (2). Wetlands can be described and classified in many ways. For the purposes of this project the formal definition of wetlands will be that which is defined for regulatory purposes under the Clean Water Act by the United States Environmental Protection Agency (USEPA) and the United States Army Corp of Engineers (USACOE):

. . . those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (2).

Under this definition, for a waterbody to be titled wetlands, it must be capable of holding water long enough to provide some inherent benefit to the environment and would include swamps, marshes, bogs, and so forth. The USEPA and USACOE generally agree that for a waterbody to be classified as wetlands it must have three characteristics:

- 1) hydrophytic vegetation - plants that are adapted for growing in water, soil, or other substrate that may go through periods of oxygen deprivation due to extensive saturation (3);
- 2) hydric soil - soils that are depleted of oxygen due to long periods of saturation during the growing season (3); and
- 3) wetland hydrology - defined under the Water Quality Control Plan (Basin Plan) as the "presence of water at or above the soil surface for sufficient periods of the year to significantly influence the plant and soil types that occur in the area (3)."

Given the latitude of the definition, wetlands may vary widely from region to region based on soil, topography, climate, hydrology, water chemistry, vegetation, human disturbance, and wildlife; and are found on almost every continent from the tundra to the tropics (4). Since they

vary so significantly, regional differences have been a large factor in the declination and destruction of wetlands, due to seasonal wetness; they were not always recognized as wetlands.

A vast majority of wetlands were destroyed due to their unpleasant odors and production of vector-borne diseases. Lack of public support, the rise of development, and the increased need for additional agricultural lands encouraged the intentional draining of these sub-watersheds. It is estimated that over one-half of America's original wetlands have been destroyed (4).

It wasn't until the ecological benefits of wetlands were understood that laws were enacted to preserve and restore local wetlands. Stakeholders now recognize that wetlands serve to:

. . . regulate water levels within the watershed; improve water quality; reduce flood and storm damages; provide important fish and wildlife habitat and support hunting, fishing, and other recreational activities (4).

Given the importance wetlands serve in the reduction of flooding, and their ability to improve water quality, regulatory guidelines pertaining to the protection of

wetlands are discussed within the four major laws that regulate water quality protection in California.

The Regulatory Framework Guiding Wetlands

The Porter-Cologne Water Quality Control Act, adopted in 1969, defines water quality law for California; it establishes the regulatory program to protect water quality and beneficial uses of the State's water supply. Through the enactment of Porter-Cologne, the authority of the State Water Resources Control Board (SWRCB) "to preserve and enhance the quality of California's water resources and to ensure proper allocation and efficient use of water for present and future generations" was recognized (5).

The SWRCB divides its functions into nine smaller regulatory agencies known as the Regional Water Quality Control Boards (RWQCB) while the SWRCB maintains the integrity of regulatory issues and oversees the planning activities of each RWQCB. Each RWQCB is responsible for developing a Basin Plan for its region, issuing waste discharge permits (WDR), seeking enforcement actions against violators, and monitoring water quality under the guidance of the SWRCB, California Environmental Protection Agency (CalEPA), and the USEPA (5).

The Basin Plan is the water quality control plan for the region as such; its development and implementation are the primary functions of the Regional Board. The Basin Plan reflects the unique hydrological and geological attributes of the watershed, differences in water quality, the beneficial uses of the region's surface and groundwater, and implementation methods necessary to meet water quality objectives (3).

Water quality objectives are established to ensure the reasonable protection of beneficial uses (3). Given that water quality objectives and implementation measures are dependent on beneficial use designations, a definition and discussion of each basic category are necessary to fully understand the regulatory structure of local watersheds.

The term "beneficial use" describes how a body of water, surface or ground water(s), benefits those (people or wildlife) who are dependent upon it (e.g., drinking, swimming, etc.). The Guidance Document, known as the Basin Plan, identifies 18 categories for which water may be classified as "beneficial" within a given region.

According the Basin Plan:

Municipal and Domestic Supply (MUN) waters are used for community, military, municipal or individual water supply systems. These uses may include, but are not limited to, drinking water supply.

Agricultural Supply (AGR) waters are used for farming, horticulture or ranching. These uses may include, but are not limited to, irrigation, stock watering, and support of vegetation for range grazing.

Industrial Service Supply (IND) waters are used for industrial activities that do not depend primarily on water quality. These uses may include, but are not limited to, mining, cooling water supply, hydraulic conveyance, gravel washing, fire protection, and oil well re-pressurization.

Industrial Process Supply (PROC) waters are used for industrial activities that depend primarily on water quality. These uses may include, but are not limited to, process water supply and all uses of water related to product manufacture or food preparation.

Groundwater Recharge (GWR) waters are used for natural or artificial recharge of groundwater for purposes that may include, but are not limited to, future extraction, maintaining water quality or halting saltwater intrusion into freshwater aquifers.

Navigation (NAV) waters are used for shipping, travel or other transportation by private, commercial or military vessels.

Hydropower Generation (POW) waters are used for hydroelectric power generation.

Water Contact Recreation (REC1) waters are used for recreational activities involving body contact with water where ingestion of water is reasonably possible. These uses may

include, but are not limited to, swimming, wading, water-skiing, skin and scuba diving, surfing, whitewater activities, fishing, and use of natural hot springs.

Non-contact Water Recreation (REC2) waters are used for recreational activities involving proximity to water, but not normally involving body contact with water where ingestion of water would be reasonably possible. These uses may include, but are not limited to, picnicking, sunbathing, hiking, beachcombing, camping, boating, tidepool and marine life study, hunting, sightseeing, and aesthetic enjoyment in conjunction with the above activities.

Commercial and Sportfishing (COMM) waters are used for commercial or recreational collection of fish or other organisms, including those collected for bait. These uses may include, but are not limited to, uses involving organisms intended for human consumption.

Warm Freshwater Habitat (WARM) water supports warm water ecosystems that may include, but are not limited to, preservation and enhancement of aquatic habitats, vegetation, fish, and wildlife, including invertebrates.

Limited Warm Freshwater Habitat (LWARM) waters support warmwater ecosystems which are severely limited in diversity and abundance as the result of concrete-lined watercourses and low, shallow dry weather flows which result in extreme temperature, pH, and/or dissolved oxygen conditions. Naturally reproducing finfish populations are not expected to occur in LWRM waters.

Cold Freshwater Habitat (COLD) waters support coldwater ecosystems that may include, but are not limited to, preservation and

enhancement of aquatic habitats, vegetation, fish and wildlife, including invertebrates.

Preservation of Biological Habitats of Special Significance (BIOL) waters support designated areas or habitats, including, but not limited to, established refuges, parks, sanctuaries, ecological reserves or preserves, and Areas of Special Biological Significance (ASBS), where the preservation and enhancement of natural resources requires special protection.

Wildlife Habitat (WILD) waters support wildlife habitats that may include, but are not limited to, the preservation and enhancement of vegetation and prey species used by waterfowl and other wildlife.

Rare, Threatened or Endangered Species (RARE) waters support habitats necessary for the survival and successful maintenance of plant or animal species designated under state or federal law as rare, threatened, or endangered.

Spawning, Reproduction, and Development (SPWN) waters support high quality aquatic habitats necessary for reproduction and early development of fish and wildlife.

Marine Habitat (MAR) waters support marine ecosystems that include, but are not limited to preservation and enhancement of marine habitats, vegetation (e.g., kelp), fish and shellfish, and wildlife (e.g., marine mammals and shorebirds).

Shellfish Harvesting (SHEL) waters support habitats necessary for shellfish (e.g., clams, oysters, limpets, abalone, shrimp, crab, lobster, sea urchins, and mussels) collected for human consumption, commercial or sports purposes.

Estuarine Habitat (EST) water support estuarine ecosystems, which may include, but are not limited to, preservation and enhancement of estuarine habitats, vegetation, fish and shellfish, and wildlife, such as waterfowl, shorebirds, and marine mammals.

~ Basin Plan (3)

It should be noted that more than one beneficial use may be assigned to a given waterbody. The degree of stringency is dictated by the beneficial use with the most stringent water quality objective, thus ensuring that it meets the standards of the beneficial use that is considered to be the most stringent.

When evaluating the effectiveness of wetlands and constructed treatment wetlands within a watershed, a thorough understanding of beneficial use designations are imperative for determining the effectiveness of the wetlands in meeting the watershed's water quality objectives.

The Basin Plan gives the RWQCB the jurisdictional power to incorporate and enforce other laws pertaining to clean water: the federal Clean Water Act (CWA), the federal Safe Drinking Water Act (SDWA), and the California Safe Drinking Water Act (CDWA) (3, 5).

The Federal Water Pollution Control Act (Clean Water Act), enacted by the Senate and House of Representatives in

1948 and re-enacted in 1972, to "restore, and maintain the chemical, physical, and biological integrity of the Nation's waters" making waters of the United States "fishable and swimmable (6)." At the time of its original enactment,

. . . due regard was to be given to improvements necessary to conserve waters for public water supplies, propagation of fish and aquatic life, recreational purposes, and agricultural and industrial uses (7).

The enactment of the Clean Water Act (CWA) set the framework for the current regulatory structure of the Basin Plan and its beneficial uses.

Upon its initial implementation, authority of the CWA was the responsibility of the Department of Public Health Services (CDPH). They were commissioned to develop programs and guidelines for reducing and eliminating discharge to interstate waters with the goal of improving sanitary conditions of surface and groundwater. Since 1948 regulations have extended to include:

. . . federal effluent limitations, state water quality standards, permits for the discharge of pollutants into navigable waters, enforcement mechanisms, funding for wastewater treatment works, and funding to states and tribes for their water quality programs (7).

As a result of increased regulations, implementation and enforcement authority resides with the USEPA. The USEPA delegates this authority to the SWRCB, who in turns authorizes the RWQCB as the overseeing authority.

The enactment of the CWA to restore the nation's waters includes the restoration and protection of wetlands. Recognized as a vital component to the CWA, wetlands protect water quality by absorbing floodwaters, assisting in the control of erosion along shorelines, serving as an area of recharge, and they also function to remove and/or reduce pollutants that would otherwise accumulate and concentrate in local water bodies as they travel downstream. In addition to their ability of protecting water quality, wetlands are fundamental to the health of the ecosystem, such as, providing suitable habitat and breeding grounds for a wide array of indigenous species, including a lay-over/resting point for migratory birds, which provides an important connectivity points in wildlife corridors (2); and facilitating societal intrinsic values of aesthetics, recreation, scientific, and educational pursuits.

To provide for a regulatory basis for wetlands management programs, and to protect its wetland resources, the USEPA is requiring states to employ beneficial use

designations and water quality objectives to wetlands (7). In having done so, the RWQCB are given the jurisdictional power of approving, conditioning, or denying federal permits and licenses pertaining to its water quality certification process (3, 7). Once a designation has been assigned to the resource (i.e., wetlands), the CWA prohibits the discharge of pollutants into waters of the US (3, 7). Exceptions to this rule are enforced through the National Pollutant Discharge Elimination System (NPDES). Industries, developers, and publicly owned treatment works (POTWs) may apply for a permit to discharge pollutants to the Nation's waters. Permits are issued on the basis that discharges do not

"interfere with the attainment or maintenance of water quality necessary to assure protection of public health, public water supplies, agricultural and industrial uses, and the protection and propagation of a balanced population of shellfish, fish and wildlife, and allow recreational activities in and on the water (7).

If the receiving waterbody is listed by the State as being impaired, or is under consideration for an impaired listing, more stringent regulations may dictate additional restrictions placed on the permit. The USEPA's 303(d) list identifies waters failing to meet water quality objectives

as designated per their Region's Basin Plan. These waters are labeled as "impaired" due to the alteration of the physical, chemical, or biological integrity of the waterbody. These restrictions may apply to limitations based on established total maximum daily loads (TMDLs) (3, 7). TMDLs pertain to the daily load (discharge) capacity for each 303(d) listed constituent (e.g., nutrients, pathogens, metals, etc.) per permittee per discharging site. Once listed under Section 303(d) of the CWA, permittees, in conjunction with the RWQCB, are obligated to devise and adopt a corrective action plan (CAP) that is aimed at the goal of removing the impaired waterbody over a specific time frame from the 303(d) list (3).

Per the CAP, permittees are mandated to keep records of best management practices (BMPs) employed, report failures or upsets of properly or improperly placed BMPs to the Regional Board, establish a monitoring plan, and submit to site inspections upon request to ensure compliance with the CWA. BMPs are sediment and erosion control techniques used to ensure that water leaving a site during a dewatering activity or rain event (run-off) is treated for pollutants prior to entering storm drains or receiving waters (8). These defense systems are generally a combination of soil

stabilizing techniques (grassed outlets, chemical stabilizers, buffer strips, etc.) and overflow interruption mechanisms (creation of wetlands, construction of infiltration and/or retention basins) with the purpose of controlling pollutants at their source (8). Failure to comply with the CWA can result in revocation of discharge permits, monetary fines, and/or imprisonment (8).

The Federal Safe Drinking Water Act (SDWA) was enacted by Congress in 1974 to "protect public health by regulating the nation's public drinking water supply" (9). At the time of its enactment, the primary method of ensuring safe drinking water was focused on treatment. In 1986 and 1996 the SDWA was amended to include source control protections for waters designated as drinking water (9). The introduction of source control protections was to ensure the safety of drinking water from "source to tap" by employing barriers (i.e., source water protection, treatment, distribution system integrity, and public information) to protect against the inadvertent introduction of pollutants to local water supplies (7, 9). The most effective way of guaranteeing that tap water is safe to drink, is to utilize all available pollution control barriers upstream to ensure that pollutants do not have the opportunity to get in the

water in the first place. As a result of SDWA, States and water suppliers must conduct regular assessments of its sources to determine where it is most likely vulnerable to contaminants (9).

The California Safe Drinking Water Act (CDWA), seeks to improve upon the minimum requirements set forth by the enactment of the SDWA. Its goals are to:

. . . establish a program that is more protective of public health, to establish a drinking water regulatory program to provide for the orderly and efficient delivery of safe drinking water within the state, and to give the establishment of drinking water standards and public health goals greater emphasis and visibility within the state department (10)."

The purpose of providing a regulatory framework within this chapter was to demonstrate the laws that govern issues pertaining to water quality, while establishing precedence for the role that beneficial use designations play on wetlands resources. The remainder of this chapter will focus on the Santa Ana River Watershed (SAR) and the major legislative document presiding over issues pertaining to the Santa Ana River. The Water Quality Control Plan, Santa Ana River Basin is the Basin Plan for Region 8, Santa Ana River, and is the basis for much of the Region's regulatory framework.

Santa Ana River (SAR) Watershed

Flowing over 100 miles and draining a 2,847-square-mile area, the SAR, shown in Figure 2, originates high in the San Bernardino and San Gabriel Mountains and empties into the Pacific Ocean at the city boundaries of Newport and Huntington Beach (11). Part of the largest stream system in Southern California (12), SAR is the smallest of the nine regions within California (11). The SAR watershed serves a population of 4.8 million, requiring 1.4 million acre-feet of water (467 billion gallons) to meet its current demands (11). Being one of the fastest growing regions, projections indicate that the current "demand will increase 47% over the next 50 years, so that, in 2050, the watershed will require 2.1 million acre-feet (687 billion gallons) of water to meet demand" (11).

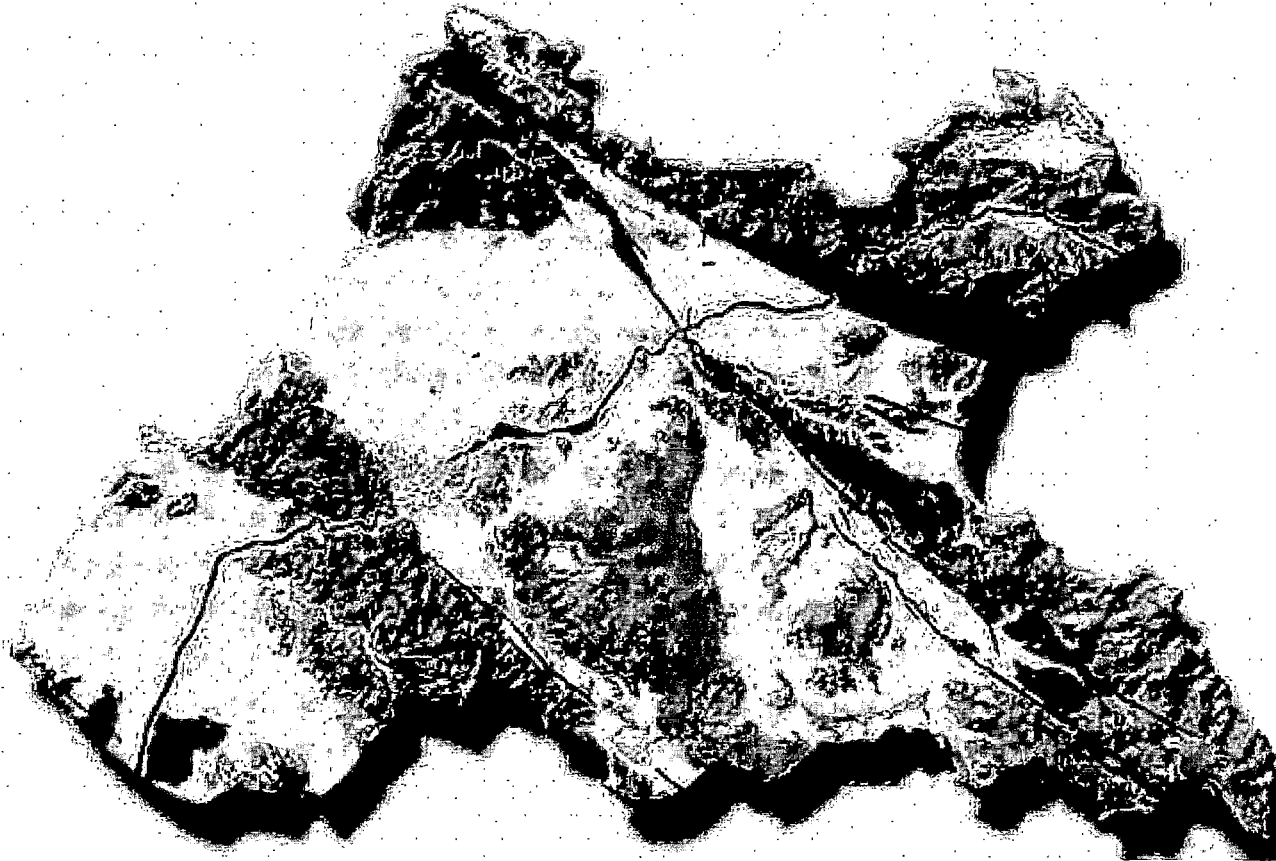


Figure 2. Santa Ana River Watershed².

² Source: Reprinted from U.S. Environmental Protection Agency Home Page.
<http://www.epa.gov/OWOW/wetlands/vital/wetlands.html> (accessed July 3, 2007)

In addition to population demands, the SAR watershed is the home to an array of wildlife and habitats. Southern California is considered a top biodiversity hot spot (12). A hot spot is an area that is rich with endemic species but is recognized as needing protection/conservation due to the declination of significant habitat (12). The loss of habitat is considered important as it would result in the loss of the ecological function of the SAR watershed as a whole. Having lost over 95 percent of its historic wetlands since the 1880's, the SAR watershed is considered to be a hotspot in need of protection and conservation (12). Wetlands of particular importance within the SAR are the constructed wetlands at Prado Dam (Prado Wetlands).

Prado Wetlands

Serving as a treatment system for the removal of nitrates from river water, and a recreational resource for the Inland Empire, flows from the Santa Ana River are diverted behind Prado Dam to feed 465-acres of constructed wetlands known as the Prado Wetlands (13). A vicinity map providing the location of the Prado wetlands in relation to the rest of the watershed is detailed in figure 3.

Treatment wetlands differ from natural wetlands in that they are specifically designed and constructed for meeting

water quality objectives documented in the Basin Plan. In general, constructed wetlands are engineered basins designed to utilize the benefits gained from natural systems.

Natural wetlands take advantage of microbial processes by breaking down nitrogenous compounds, as well as, reducing many constituents typically found in surface run-off. To mimic natural systems, constructed wetlands have four main components: soil and drainage materials, water, plants, and micro-organisms. Utilizing these four basic components, constructed wetlands are capable of achieving the same, or better, treatment results as that of natural systems.

In the United States, more than 150 wetlands treat both municipal and industrial wastewaters by removing suspending solids, lowering biochemical oxygen demand, and reducing nutrients (phosphorus and nitrogen), metals, and volatile organic compounds (VOCs), and treating other pollutants of concern (POC) (15). Prado wetlands shown in figures 3 and 4 are one of the systems in this network.



Figure 3. Prado Wetlands Vicinity Map³

³ Source: Reprinted with permission from Orange County Water District (OCWD). Vicinity Map was provided by OCWD, 18700 Ward Street, Fountain Valley, CA 92728



Figure 4. Prado Treatment Wetlands⁴.

⁴Source: Reprinted from Orange County Water District.
<http://www.ocwd.org/html/prado.htm> (accessed January 25, 2008)

Serving as a source of recharge for the Orange County groundwater basin, the constructed wetlands behind Prado Dam have become a key factor in enhancing water quality for downstream users (16). Historically, discharged waters, and surface runoff, were of low quality due to high inorganic nitrogen levels, the build-up of total dissolved solids (TDS) from extreme recycling, reduced summer flows, and high evaporation rates.

As recycling and reuse become more prominent in the watershed, the higher loads of TDS are becoming more significant to water purveyors and districts. Every time water is recycled or reused the TDS rises by 200-300 mg/L (3, 17). Although wetlands have high removal rates for some of the constituents that contribute to the overall TDS, biological systems are generally not very effective at reducing TDS. This is largely due the numerous compounds (organic and inorganic) that contribute to the total sum of the dissolved solids, including those that are not considered contaminants (17).

The Basin Plan designates the beneficial use for the Orange County groundwater basin as "municipal and domestic supply (3)." According to the 1986 and 1996 SDWA amendment, water designated for domestic use (i.e., drinking water)

must apply source control protections to maintain the integrity of the supply. Further, the CWA requires the assignment of a beneficial use to protect wetland resources. The assignment of a "beneficial use" dictates which regulations (CWA and SDWA) govern the resource. Since the Prado Wetlands has a multitude of beneficial uses, both CWA and SDWA have legal precedence of the waters. The act with the most stringent beneficial use, generally, this is the CWA, will take precedence for ensuring beneficial use designations are upheld. Thus, Orange County is assured that waters attained from upstream users meet water quality objectives.

Recharge waters are imperative to downstream users due to the Santa Ana River being located within a region that is arid and dry. "Wet" seasons are not consistent within the region and do not always result in an abundant supply of fresh water, making the capture and conservation of water a high priority within the watershed and to the entities responsible for its continued delivery. It is for this reason that the Santa Ana River is generally referred to as an effluent dominated stream (18). This means that its principal supply is derived from reclaimed water discharged from local POTWs and untreated nuisance flows accumulated

via storm drains and direct runoff from local residential tracts, dairies, and development. Untreated flows from multi-use properties have resulted in the inorganic nitrogen levels approaching or exceeding the established water quality objectives (18). Exceeding water quality objectives has elicited increased awareness regarding the discharge of waste streams containing nitrogenous compounds and the negative impact nitrogen loading can have on a watershed.

CHAPTER THREE

CHEMISTRY OF NATURAL WATERS

In Chapter Two, much attention was focused on the regulatory framework of waterbodies, as well as the need to establish beneficial uses for all waterbodies. With 97.4% of the global water sources in the ocean undrinkable due to salinity, and 2.59% of the fresh water bound in ice caps, glaciers, and ground water, only 0.014% of the remaining fresh water is readily available for consumptive uses. This becomes particularly problematic during nationwide/global water shortfalls, due largely to the strain of drought, overuse, and the elimination of supplies due to pollution.

Water pollution, particularly in terms of sources deemed "undrinkable", is of increasing concern due to the health implications that arise from improperly managed drinking supplies. Throughout history, water-borne diseases have been attributed to a significant number of deaths. The World Health Organization (WHO) estimates that 1.1 billion people lack access to clean water and five million people annually die from water related disease (90% of these deaths are of children under the age of 5) (19). Thus, polluted water ranks as the third leading cause of world wide deaths,

after heart disease, malnutrition, and starvation (19). The WHO recognizes water-borne illnesses, predominately from bacteria/viruses, as a world-wide crisis amongst the poorest populations. Table 1 provides a breakdown of the number of deaths attributed to bacteria and viruses from 1991-2000. It should be noted, that these numbers are only attributed to microorganisms, and do not account for deaths from other water quality related issues.

Due to the limited supply of readily accessible fresh drinking water, the number of deaths associated with poor quality water, and the necessity of water to sustain human life, it is imperative to global health to maintain adequate supplies of potable water.

As noted in Chapter Two, waterbodies have standards based on their designated use. Drinking water, regulated by the CDPH under the guidance of the SDWA, is commonly tested for nitrogenous compounds, pH, dissolved oxygen, bacteria/viruses, turbidity, temperature, heavy metals, organic compounds, etc.

Table 1. Causes of Waterborne Outbreaks. Published by the Center for Disease Control.

Etiological Agent	Community Water Systems ¹		Noncommunity Water Systems ²		Individual Water Systems ⁴		All Systems	
	Outbreaks	Cases	Outbreaks	Cases	Outbreaks	Cases	Outbreaks	Cases
<i>Giardia</i>	11	2,073	5	167	6	16	22	2,256
<i>Cryptosporidium</i> ³	7	407,642	2	578	2	39	11	408,259
<i>Campylobacter</i>	1	172	3	66	1	102	5	340
<i>Salmonellas</i> , nontyphoid	2	749	0	0	1	84	3	833
<i>E. coli</i>	3	208	3	39	3	12	9	259
<i>E. coli</i> O157:H7/Cjsuni	0	0	1	781	0	0	1	781
<i>Shigella</i>	1	83	5	484	2	38	8	605
<i>Plasimonas shigelloides</i>	0	0	1	60	0	0	1	60
Non-O1 <i>V. cholerae</i>	1	11	0	0	0	0	1	11
Hepatitis A virus	0	0	1	46	1	10	2	56
Norwalk-like viruses	1	594	4	1806	0	0	3	2400
Small, round-structured virus	1	148	1	70	0	0	2	218
Chemical	18	522	0	0	7	9	25	531
Undetermined	11	10,162	38	4,837	11	238	60	15,237
Total	57	422,364	64	8,934	34	548	155	431,846

⁵ Source: Reprinted from Water Quality and Health Organization.

http://www.waterandhealth.org/newsletter/new/spring_2003/waterborned.html (accessed January 25, 2008)

Data in Table 1⁵ are compiled from CDC Morbidity and Mortality Weekly Report Surveillance Summaries for 1991-1992, 1993-1994, 1995-1996, 1997-1998 and 1999-2000. Figures include adjustments to numbers of outbreaks and illness cases originally reported, based on more recent CDC data.³ Community water systems are those that serve communities of an average of at least 25 year-round residents and have at least 15 service connections. Non-community water systems are those that serve an average of at least 25 residents and have at least 15 service connections and are used at least 60 days per year. Individual water systems are those serving less than 25 residents and have less than 15 service connections. There were 403,000 cases of illness reported in Milwaukee in 1993.

General discussions pertaining to the chemistry of waterbodies are difficult, as each body of water is unique, varying significantly from one watershed/subwatershed to another, although they may only be separated by a few meters. A prime example of the variation that occur within a watershed is Reach 3 and Reach 4 of the Santa Ana River. These reaches differ from the remainder of the River in that they are 303(d) listed for impairments due to pathogens, while the other reaches (1, 2, 5, and 6) remain within the EPA's allowable limits for pathogen.

In order to fully appreciate the differences, while acknowledging the delicate balance existing within natural waters, it is necessary to assess the role of competing factors and how they assist in determining the chemistry of a waterbody. Although key factors will be discussed in individual sections, it is important to understand how environmental sphere effect the overall environment. To visualize this, a diagram (20), shown in Figure 5, has been prepared to introduce the dependence of each sphere (atmosphere, hydrosphere, anthrosphere, geosphere, and biosphere) on the others. Demonstrating its sphere of influence, this visual cue displays the overlapping nature

and inter-reliance of environmental science in its full circle form. Co-dependent factors influencing inter-reliance include, but are not limited to the following: atmospheric gas exchange, microbial processes, geochemistry of the watershed, internal and external nutrient loading, and the rate of influent (including precipitation) and effluent (including evaporation).

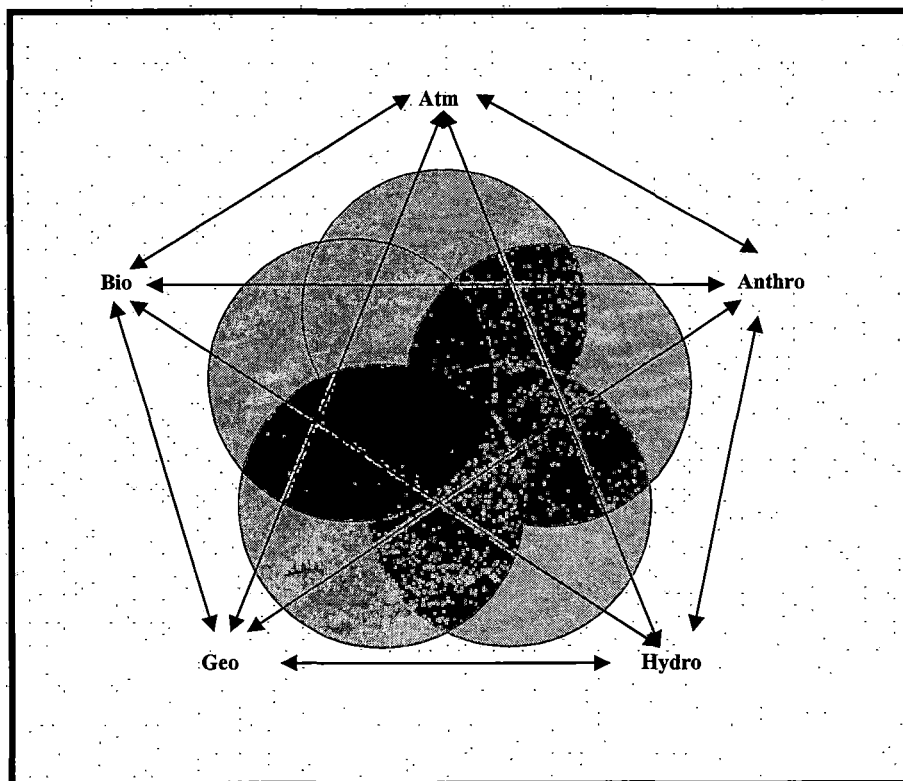
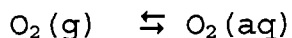


Figure 5. Environmental Sphere of Influence⁶.

⁶ Source: Adapted from Manahan, Stanley. Environmental chemistry and Chemical Cycles. *Environmental Chemistry*, Edition 6; CRC Press: Florida, 1994 p. 37.

Important Atmospheric Gases Common to Surface Waters

Surface waters continually interact with atmospheric gases. That is, they capture gaseous molecules dissolving them into their aqueous molecular species, as shown in the following reaction:



Interactions between atmospheric gases and surface waters are fundamental in determining the chemistry of natural waters. As such, a discussion pertaining to the likelihood of gaseous constituents to dissolve in water is pertinent.

The dissolution of a gas into its aqueous species is depended on the individual properties of each gas (e.g., partial pressure, solubility, temperature, and the relative reactivity of the gaseous constituent with the varying components of the hydrosphere) and requires an understanding of how LaChatelier's Principle applies to Henry's Law.

The driving theory behind LaChatelier's Principle is the need of a given system to move to a system that is in equilibrium. In terms of the air/water interface, when the pressure above the water surface is increased, gases will move more rapidly across this interface, via absorption, until sufficient quantities of the gas have been dissolved

to reach equilibrium at the surface interface (21).

LaChatelier's Principle is applicable to Henry's law as it defines equilibrium.

Henry's law states that the solubility of a given gas is proportional to the pressure at which the gas is exerted (22). The higher the gas pressure, the more apt the gas is to dissolve in the water. This is best demonstrated by a gas bubble that gets trapped under water. As the bubble descends below the surface, the increasing pressure exerted on the bubble by the water makes the bubble appear as though it is getting smaller. This decrease in size is actually due to the gas leaving the bubble and entering the water. As the bubble travels deeper, the water temperature is becomes cooler, deeper depths and cooler water increases the pressure exerted on the bubble by the water and the pressure inside the bubble, increasing the solubility of the gas, resulting in a smaller gas bubble (22). Eventually all the gas will have been forced into solution and the bubble will cease to exist (22).

Using Henry's law and the K values depicted in Table 2, the saturation level of O_2 in water can be determined by calculating the interactions occurring at the air/water interface. The following example demonstrates solubility as

O₂ gas is dissolved in 1kg (1L) of water at a temperature of 25°C and a partial pressure of 154.2 Torr. For the purposes of this calculation, n is equivalent to moles of gas evaluated, K is Henry's constant, p is the gas partial pressure, and X is mole fraction in solution.

Applying Henry's law ($P_{O_2} = KX_{O_2}$), when the temperature is constant (25°C), the amount of gas that will dissolve in a given type of liquid (water) and volume of that liquid (1L) will be proportional to the partial pressure of that gas ($P_{O_2} = 154.2$ torr) at equilibrium with the given liquid (21).

Table 2. Air/Water Interface⁷.

	K/TORR	SATURATION
CO ₂	1.25 x 10 ⁶	0.5035 ppm
H ₂	5.34 x 10 ⁷	
N ₂	6.51 x 10 ⁷	13.72 ppm
O ₂	3.30 x 10 ⁷	8.29 ppm

⁷ Source: Adapted from Manahan Stanley. Environmental Chemistry and Chemical Cycles. *Environmental Chemistry*, Edition 6; CRC Press Florida, 1994; p. 37

$$\begin{aligned}
P_{O_2} &= KX_{O_2} \\
P_{O_2} &= 154.2 \text{ torr} \\
K &= 3.30 \times 10^7 \text{ torr} \\
X &= \frac{P_{O_2}}{K} = \frac{n_{O_2}}{n_{H_2O}} \tag{1}
\end{aligned}$$

$$\begin{aligned}
X &= \frac{154.2 \text{ torr}}{3.30 \times 10^7 \text{ torr}} \\
X &= 4.67 \times 10^{-6} = \frac{n_{O_2}}{n_{H_2O}}
\end{aligned}$$

Equation 1 determined the interactions at the air/water interface by solving for the mole fraction (X). Now that X has been determined the saturation level for O₂ at 25°C can be solved algebraically by substituting in the moles of water as shown in Equation 2.

$$\begin{aligned}
1 \text{ Kg} \left(\frac{1000 \text{ g}}{1 \text{ Kg}} \right) \left(\frac{1 \text{ mole } H_2O}{18.00 \text{ g } H_2O} \right) &= 55.5 \text{ mol } H_2O \\
[H_2O] &= 55.5 \text{ M @ } 25^\circ \text{C} \\
[O_2] &= (X) ([H_2O]) \tag{2} \\
[O_2] &= (4.67 \times 10^{-6}) (55.5 \text{ M}) \\
[O_2] &= 2.59 \times 10^{-4} \text{ M}
\end{aligned}$$

Using dimensional analysis, the molarity can readily be converted to ppm via dimensional analysis.

$$\left(2.59 \times 10^{-4} \frac{\text{mol}}{\text{L}} \right) \left(\frac{32.0 \text{ g } O_2}{1 \text{ mol } O_2} \right) \left(\frac{1000 \text{ mg}}{1 \text{ g}} \right) = 8.29 \text{ ppm } O_2$$

Using the preceding equation (Henry's law), the saturation level of oxygen is calculated to be 8.3 ppm at 25°C. Saturation refers to the point of which the reverse reaction proceeds at the same rate as the forward reaction. In other words, the air/water interface has reached a dynamic equilibrium and the amount of oxygen dissolving in the water is equal to the amount that is being released back to the atmosphere. Saturation levels are important because the ability for a chemical to move through the different phases (e.g., gaseous, liquid, and solid) ultimately explains how readily constituents will be taken up through the food chain or contribute to atmospheric and/or hydrospheric problem(s). This phase transfer can also be referred to as a transport process. The remainder of this chapter will be used to discuss the transport processes of diatomic oxygen, diatomic nitrogen, and carbon dioxide.

Molecular Oxygen

As briefly mentioned in the preceding chapter, diatomic oxygen or molecular oxygen is the most important oxidizing agent found in natural waters. The availability of molecular oxygen for uptake in a watershed is vital for

life. For a waterbody to be considered healthy or well-oxygenated, its molecular oxygen concentration would be at the saturation level for the temperature at which it is being measured. Waters meeting this oxygenated criterion are typically associated with "clean" surface waters, fast moving rivers and/or streams, or slow moving waters with abundant aquatic life undergoing photosynthesis. To achieve and/or maintain a dissolved oxygen (DO) concentrations at or above the atmospheric saturation level can be very difficult for most bodies of water, due to the dynamic nature of aquatic systems.

Seasonal fluctuations can also greatly affect the rate at which DO is being produced due to amount of biota that may be present. Seasonal fluctuations are especially prevalent in wetlands, due to their stagnant nature, shallow depth, and more pronounced seasonal life cycles of biota (to be discussed in more detail in the biota section).

Biochemical Oxygen Demand

The biochemical oxygen demand (BOD) is a numerical representation indicating the amount of oxygen required to completely break down the organic matter present in the waterbody. Analytically, it is defined as the "amount of

oxygen that a wastewater sample will consume in 5 days (BOD₅)" (24). In simplest terms, it is the demand that microorganisms place on a body of water for enough free oxygen to break down all food sources. As such, BOD and DO can be positively and negatively influenced by the presence of organic matter. In ideal situations, the DO and BOD are at equilibrium with one another and are not pushed to either extreme.

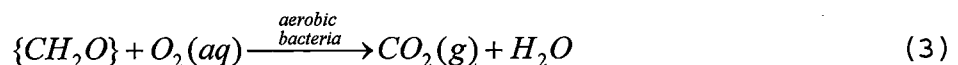
When sufficient quantities of O₂ are present, biological processes have enough DO to breakdown food sources. In this type of an environment, the system is likely to undergo aerobic processes as a means of decomposing organic matter. Aerobic decay requires oxygen to complete the decomposition process. As biota begins to die and decay, more food sources are available for microorganisms to break them down. When more food sources are available, the demand for DO (or the BOD) from aerobic bacteria also increases.

During seasonal life cycles, a high BOD may occur as a result of excessive O₂ consumption resulting from the breakdown of a surplus supply of organic matter (food) from the die-off of an overly productive growth season. In this situation, the high BOD is directly related to the oxygen demand required of aerobic bacteria to break down food and

the presence of thriving biota and other forms of aquatic life.

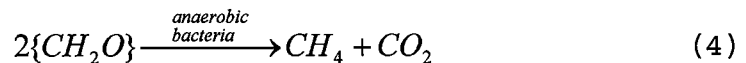
As living matter continues to compete for oxygen, the system (waterbody) begins to lose its ability to keep up at the air/water interface. If not maintained, the waterbody may continue to decline, eventually reaching a state where the consumption of oxygen from biological species and aerobic decomposition processes exceeds the rate at which O_2 can be absorbed into the water. If this continues unabated, the waterbody eventually succumbs to the effects of eutrophication.

Eutrophication is the inability of a waterbody to maintain a state of equilibrium between the BOD and DO. It is for this reason that it is important to understand the role of bacteria (aerobic and anaerobic) in the decomposition of organic matter. The reaction in Equation 3 represents aerobic decomposition, where CH_2O represents organic matter, primarily carbohydrates. In this reaction, aerobic bacteria utilize the O_2 in the electron transfer:



As depicted in Equation 3, a healthy aquatic system will have enough DO in the waterbody to fully oxidize decaying

organic matter to carbon dioxide and water. In the presence of oxidizing conditions, other species such as NH_3 and H_2S would oxidize to nitrate and sulfate. These are considered healthy by-products in the natural water cycle. Waterbodies lacking sufficient oxygen to complete the decomposition process will undergo anaerobic decay reducing organic matter to more undesirable by-products, as shown in the following reaction:



In Equation 4, anaerobic bacteria are consuming the organic matter to produce the unwanted by-product of methane. Other species present during oxygen-depleted processes would also undergo reducing conditions producing by-products of hydrogen sulfide (H_2S), and ammonia (NH_3) (25). The productions of these species are considered to be more toxic, emitting the "rotten egg" smell typically associated with wetlands (25). The biological decomposition of other species will be discussed later in this chapter as there respective chemical species are introduced.

Regardless of whether a waterbody responds to the BOD via anaerobic or aerobic process, the availability of DO is an important factor in water chemistry as it ultimately

determines the survival of that body of water. For fish to survive the [DO] must be at least 5 ppm (25). A DO of 8.5 ppm allows for the continued survival of other aquatic species (e.g., fish) while ensuring that a residual concentration of O₂ remains in the water to break down organic matter under aerated conditions. It is for this reason that waterbodies are often classified based on the amount of organic matter present and their ability to break down the organic matter.

There are three types of classifications that a waterbody can be assigned: 1) Oligotrophic - typically assigned to lakes that are deep and nutrient poor; 2) mesotrophic - assigned to waterbodies whose nutrient production tends to fall somewhere in the moderate zone between the oligotrophic and eutrophic classifications; and 3) eutrophic - waterbodies that are typically shallow, nutrient rich, and due to their high production of phytoplankton tend to have a high BOD (26).

These classifications are not permanent, they do have the ability to change over time; a waterbody can worsen to eutrophic classifications or progress to less severe classifications depending on the maintenance that it receives. If well-managed, conditions improve and the

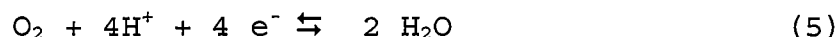
classification can be upgraded. If not properly managed, waters worsen as organic matter increases resulting in the declination of the status of the waterbody (i.e., mesotrophic or eutrophic). As a result, management of water resources often involves certain predictions pertaining to how apt it is to undergo oxidizing or reducing conditions.

Oxidation-Reduction Potential

As previously detailed, the most important oxidizing agent in natural waters is dissolved molecular oxygen (27). However, the ability of molecular oxygen to be taken up by plants and microorganisms and be used for aerobic decomposition is based on the organic matter present in the body of water. As such, pE/pH diagrams are often used to determine the likelihood for water to favor reducing conditions. The term, pE, indicates how apt a species is to gain or lose electrons, and is defined as the negative log of the electron activity, analogous to pH (the negative log of the hydronium ion concentration), electron activity shares commonalities with acid-base reactions.

In an aquatic system, a low pE/pH environment is indicative of reducing conditions, while a high pE/pH environment favors oxidizing conditions due to the dissolved

species being oxidized. While in the presence of low and high pH environments, respectively, the oxidizing nature of molecular oxygen are provided by the following half-reactions



In Equations 5 and 6, each oxygen atom in the diatomic molecule is reduced from the zero state into its -2 state as it gains electrons to form H_2O and OH^- . In addition to the oxidizing properties of molecular oxygen, reduction and oxidation (redox) reactions are catalyzed by bacteria, which will be discussed in a separate section due to the importance of microorganisms in the chemistry of natural waters.

Carbon Dioxide

Carbon dioxide (CO_2) is the most essential weak acid in natural waters due to its ability to aid in the neutralization of alkaline species, its role in the production of biomass with photosynthetic algae, and the importance the cycling of carbon has on the various environmental spheres. It is for this reason that the

global carbon cycle shown in Figure 6, has been included as a reference for demonstrating the exchange of carbon through the various spheres.

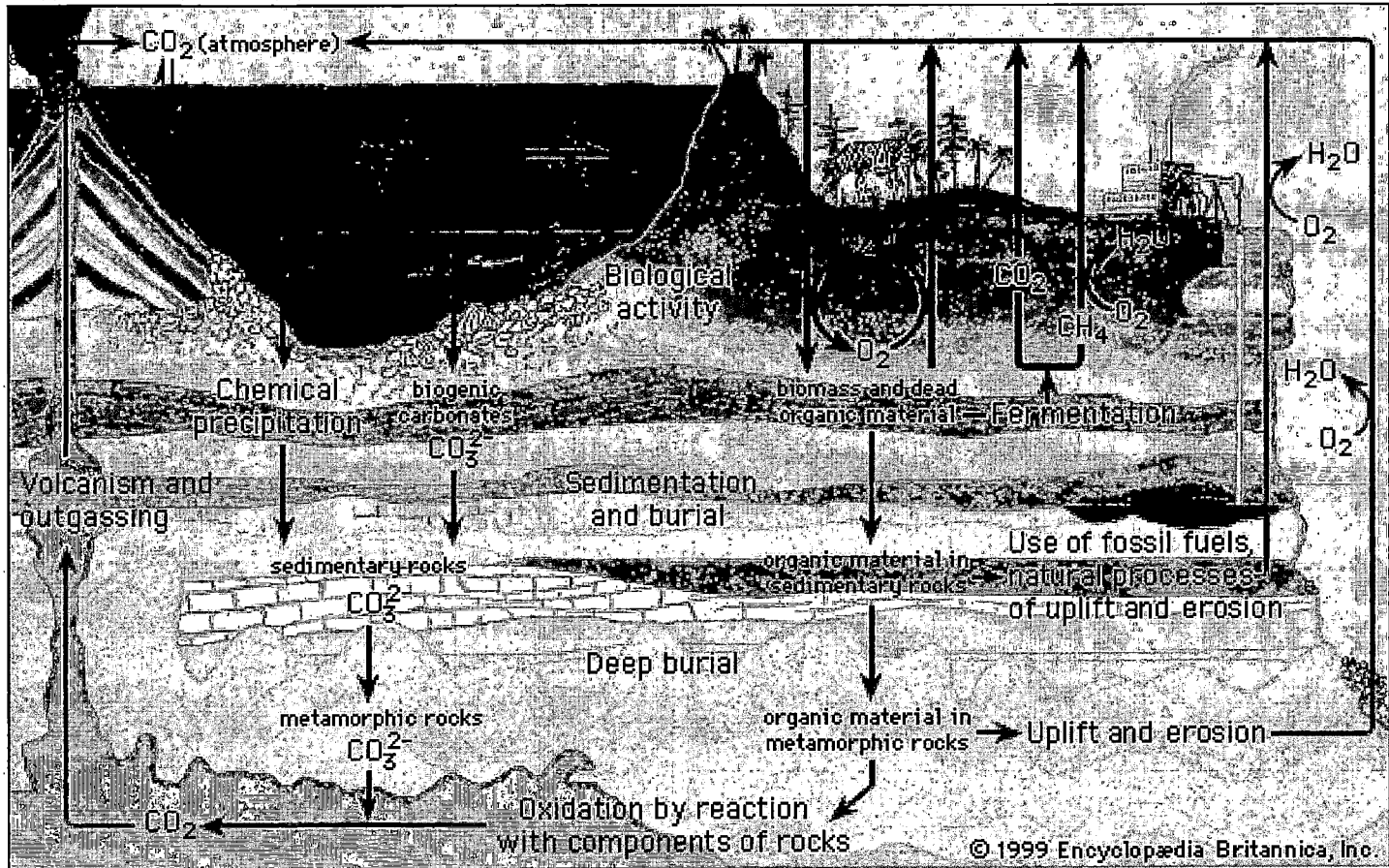


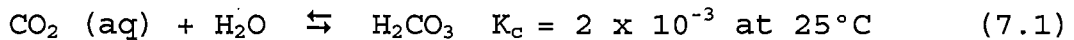
Figure 6. Global Carbon Cycle.

⁸ Source: Reprinted from Encyclopedia Britannica. <http://cache.eb.com/eb/image?id=2402&rendtypeID=4> (accessed August 17, 2007)

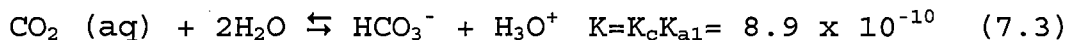
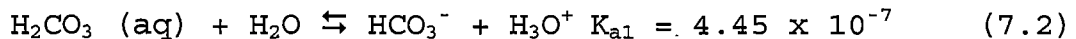
As depicted in the diagram, $\text{CO}_2(\text{g})$ interacts at the air/water interface, to represent the following equilibrium:



Once in its dissolved state it reacts with water to form carbonic acid, which dissociates into the bicarbonate ion and hydronium ion, thus accounting for the slightly acidic nature of natural waters:



The low K_c indicates that only a small fraction of the dissolved CO_2 is actually H_2CO_3 , although aqueous CO_2 is typically represented as carbonic acid (29). The actual pH of the environment is dependent on the prevalence of the species to favor the bicarbonate or carbonate ion, shown in the following reactions:



The reactions above demonstrate the disassociation of carbonic acid into the ionic species that are present at equilibrium. The presence of the hydronium ion (H^+) indicates an environment that would be acidic. The extent of the acidity is based on the particular acid present and its relative concentration. In the two preceding examples,

combining carbonic acid, a weak acid, and the bicarbonate ion, a weak base, results in a slightly acidic environment, as demonstrated in the following equilibrium reaction:

$$K_{a_1} = \frac{[H^+][HCO_3^-]}{[CO_2]} \quad (7.4)$$

$$K_{a_1} = 4.45 \times 10^{-7}$$

$$pK_{a_1} = -\log[K_{a_1}] \quad (7.5)$$

$$pK_{a_1} = 6.35$$

The concentration of CO₂ at 25°C can be determined utilizing Henry's Law. Once the saturation level of CO₂ in water is calculated, it can be used in conjunction with the pK_a to determine the pH of the natural waters:

$$P_{CO_2} = 3.7 \times 10^{-4} \quad (\text{Dry air});$$

$$P_{H_2O} = 0.0313 \text{ atm} = 23.79 \text{ torr at } 25^\circ\text{C}$$

$$P_{CO_2} = (760 \text{ torr} - 23.79 \text{ torr})(3.7 \times 10^{-4}) \quad (7.6)$$

$$P_{CO_2} = 0.258$$

$$\frac{(0.258 \text{ torr})(55.5 \text{ mol } H_2O)}{1.25 \times 10^6 \text{ torr}} = 1.146 \times 10^{-5} \text{ mol } CO_2 \quad (7.7)$$

With only one variable remaining, [H⁺], its corresponding pH can be ascertained:

$$K_{a_1} = \frac{[H^+][HCO_3^-]}{[CO_2]} = \frac{[H^+]^2}{1.146 \times 10^{-5}} \quad (7.8)$$

$$K_{a_1} = 4.45 \times 10^{-7}$$

$$[H^+] = [HCO_3^-] \quad (7.9)$$

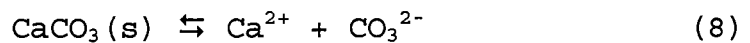
$$(1.146 \times 10^{-5})(4.45 \times 10^{-7})^{1/2} = 2.26 \times 10^{-6}$$

$$\text{pH} = -\log [H^+] \quad (7.10)$$

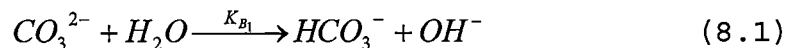
$$\text{pH} = -\log [2.26 \times 10^{-6}]$$

$$\text{pH} = 5.65$$

Just as the air/water interface influences the pH of water, due to the ability of CO_2 to react with water to make carbonic acid, the presence of carbonate (predominately from limestone, $CaCO_3$) also affects the pH of natural waters. Although relatively insoluble, $CaCO_3$ is prone to weathering due to the acidic nature of waterbodies. As a result, $CaCO_3$ will slowly dissolve, releasing the carbonate ion as low pH waters interact with it, as shown in equation 8.



These effects can be positive, functioning to neutralize acidic waters, or if in excess, it can raise the pH, resulting in alkaline conditions.



$$K_{b_1} = \frac{[HCO_3^-][OH^-]}{[CO_3^{2-}]} = K_{a_2} \quad (8.2)$$

$$K_{a_2} = 4.69 \times 10^{-11}$$

$$K_{b_1} = \frac{K_w}{K_{a_2}} \quad (8.3)$$

$$K_{b_1} = \frac{1.00 \times 10^{-14}}{4.69 \times 10^{-11}}$$

$$K_{b_1} = 2.13 \times 10^{-4}$$

$$pH = 14 - (-\log 2.13 \times 10^{-4}) \quad (8.4)$$

$$pH = 10.33$$

It should be noted that the formation of HCO_3^- and CO_3^{2-} increases the solubility of CO_2 . The actual speciation of carbon varies widely depending on its route of uptake, the prevalent species formed, and the pH of the system.

Aside from the dissolution of gaseous CO_2 occurring at the air/water interface, there are other sources of CO_2 in natural waters. A larger percentage of the CO_2 is due to the aerobic decomposition of organic matter, which will be discussed in further detail in the succeeding section on Biota.

The role that biota play in the decomposition of organic matter ultimately effects the cycling of carbon in

sediment, thereby influencing the geochemistry of natural soils, a more complete discussion of soils will be presented in the latter part of this chapter.

Nitrogenous Compounds

Since 78% of the atmosphere is largely comprised of nitrogen, it is expected that nitrogenous compounds would be found in natural waters. The oxidation state in which nitrogen is found is vital to the ecological balance of the waterbody, as redox reactions occurring within the nitrogen cycle are some of the most important bacteria-mediated processes in water and soil science. Hence, understanding the nitrogen cycle, its fixation, and the denitrification process is essential to watershed chemistry. As with other atmospheric gases, the introduction of nitrogen will begin at the air/water interface using Henry's law to determine the saturation level of N_2 at 25°C:

$$P_{N_2} = 0.78 \text{ (dry air)}$$

$$P_{H_2O} = 0.0313 \text{ atm} = 23.79 \text{ torr at } 25^\circ\text{C}$$

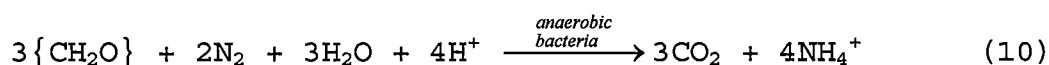
$$P_{N_2} = (760\text{torr} - 23.79\text{torr})(0.78) \quad (9.1)$$

$$P_{N_2} = 574.24 \text{ torr}$$

$$\frac{(574.24 \text{ torr})(55.5 \text{ mol/L } H_2O)}{1.25 \times 10^6 \text{ torr}} = 4.895 \times 10^{-4} M \text{ N}_2 \quad (9.2)$$

Using the molarity in equation 9.2, the saturation level of N₂ at 25°C can be converted to 13.72 ppm via dimensional analysis. Although the saturation is 13.72 ppm, N₂ must be fixed by microorganisms before it is useful to plants. However, only a select group of bacteria (e.g., *Azobacter*, *Clostridium*, *cyanobacteria*, and *Rhizobium*) can fix N₂, as it is a very stable molecule and requires significant energy to break its covalent triple bond.

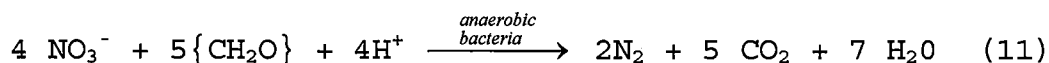
Fixating dinitrogen is considered the limiting step in the nitrogen cycle because the amount of nitrogen available for plant uptake is directly proportional to the ability of bacteria to fixate it. Since plants need bacteria to reduce the N₂ to NH₃, fixation is typically a symbiotic relationship shared between plants and photosynthetic bacteria as in Equation 10.



During the fixation process, the atmospheric N₂ is bound; special photosynthetic bacteria derive energy from plants to break the covalent bonds between nitrogen atoms (30). The nitrogen is then reduced to ammonia, which is an available

form plants can uptake (30). As the plant dies, the ammonia is released into the surrounding waters where soil bacteria, under aerobic conditions, oxidizes the ammonia (NH_3 or NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-).

The balance between the fixed nitrogen and atmospheric nitrogen is maintained via anaerobic conditions through the process known as denitrification shown in Equation 11.



During the denitrification process, NO_3^- is reduced to its non-toxic form, N_2 , allowing for the continued growth of bacteria under anaerobic conditions, and aiding the removal of nitrogen from the aquatic system by returning it to its gaseous state. One of the significant phenomena attributed to wetlands, making them especially useful as an advanced treatment facility for treated effluent, lies within the nitrogen cycle. Its abundant supply of vegetation and shallow and slow moving waters make it an ideal setting for denitrification, aiding in the removal of nitrate found in effluent.

Common oxidative states for nitrogen are provided in Table 3. Shown in Table 3 are the most common oxidative states of nitrogenous compounds. Of these, ammonia (NH_3) is

the most reduced form of all the nitrogen species. In this form, it exists in the -3 state, while the nitrate ion is the most oxidized form in the +5 state. In solution, the most important of the intermediates are nitrite (NO_2^-) and molecular nitrogen (N_2) (27).

Table 3. Nitrogen and its Oxidative States⁹.

	COMMON OXIDATIVE STATES OF NITROGEN						
	Increasing levels of nitrogen oxidation →						
Oxidation State of N	-3	0	+1	+2	+3	+4	+5
Aqueous Solution Salts	NH_4^+ NH_3				NO_2^-		NO_3^-
Gas Phase	NH_3	N_2	N_2O	NO		NO_2	

Speciation is significant since the species of the highest concern are the inorganic nitrogen compounds derived from the fixation and nitrification process, as they are in a form that is considered biologically available for uptake.

⁹ Source: Reproduced from Baird, Colin; and Cann, Michael. Oxidation-Reduction Chemistry in Natural Waters. *Environmental Chemistry*, Edition 2, W.H. Freeman and Company, NY, 2005. p 426.

If fixation occurs in excess it can result in toxic effects to fish, while excess concentrations of nutrients can stimulate the growth of unwanted aquatic plants.

Similar to other dissolved atmospheric gases, pH is very important in the speciation of nitrogenous compounds because fixation, nitrification, and denitrification are facilitated by bacteria that are sensitive to pH and temperature. Low pH environments favor reducing conditions, resulting in the reduced forms of ammonia and ammonium ion, while high pH environments typically result in oxidizing conditions forming the nitrate and nitrite compounds. Denitrification typically occurs between a pH of 6.0 and 8.0, making wetlands a prime denitrifying zone.

Negative Effects Associated with Inorganic Nitrogenous Compounds

Nitrogen is considered a limiting nutrient, meaning it is one of the nutrients that is responsible for and determines the amount of plant growth in aquatic systems. In aerobic environments, nitrogen exists in its fully oxidized form, NO_3^- , and is in the state that is most readily available for uptake by aquatic vegetation. Nitrate is an essential component of natural waterbodies for the health of

aquatic life, as it encourages the growth of plant life. In excess, vegetation flourishes and multiplies.

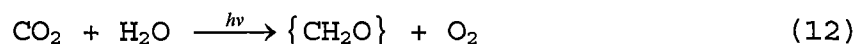
Microbial Processes

The first few sections of Chapter Two briefly highlighted the functions microorganisms serve in the decomposition of organic matter and the fixation, nitrification, and denitrification of nitrogen in aquatic systems. This section will focus on the types of microorganisms (bacteria, fungi, protozoa, and algae) and their specific tasks in facilitating chemical reactions. In this context, microorganisms can be classified as living catalysts programmed to ensure that chemical reactions occur. Microorganisms are in essence the driving forces behind why natural systems function the way they do.

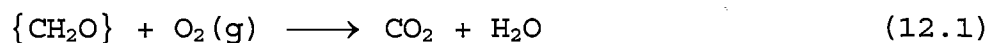
Despite the many varieties of microorganisms, they all fall into one of two classifications 1) reducers; and 2) producers. Reducers are the bacteria, fungi, and protozoa that would not qualify as photosynthetic species. They generate the energy needed for growth by extracting it from chemical components during the decomposition process. Fungi serve to break down cellulose in wood and other plant material, protozoa provide limestone deposits by the

deposition of their shells, as well as serving in the oxidation process of biomass, and bacteria break down biomass via anaerobic and aerobic processes (30).

Algae are classified as "producers", due to their ability to utilize and store chemical energy for the production of organic matter (30). In order for algae to store energy it requires the nutrients from oxidized species of carbon (CO_2), nitrogen (NO_3^{2-}), phosphorus (ortho-phosphate), and sulfur (SO_4^{2-}). The general reaction for the production of organic matter is represented in equation 12:



In the presence of light, photosynthetic algae functions very similarly to photosynthetic bacteria in that it uses the energy of the light for the reaction to proceed. In reaction 12, algae uses sunlight to convert CO_2 into carbohydrates by using the oxygen to oxidize carbon from the +4 state to the 0 state, while storing the energy gained in the carbohydrate. Upon the death of the bacteria, the reaction proceeds in the reverse direction releasing the stored energy into the surroundings, whereby oxygen is consumed in the process, shown in reaction 12.1:

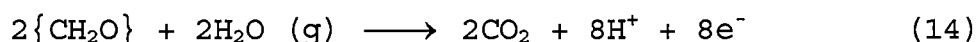


In the absence of light, the process shown in equation 12.1 follows non-photosynthetic pathways consuming oxygen to fully metabolize organic matter. For biota-rich environments, the breakdown of organic matter by bacteria during evening hours could lead to the depletion of DO. However, anaerobic bacteria promote the final step in the global cycling of carbon through the degassing of methane back into the atmosphere.

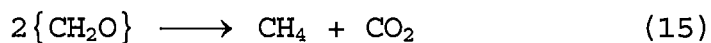
It is estimated that the degassing of methane from wetlands accounts for 80% of the natural global emissions of methane emitted into the atmosphere (30). Methane emissions are derived either from microbially produced methane or the fermentation of organic matter.



In reaction 13, methane-forming bacteria facilitates the formation of methane when CO_2 acts as an electron receptor. Just as carbon dioxide gets reduced in anaerobic conditions to methane (reaction 13) so can other compounds, such as, carbohydrates, shown in reaction 14:



The two half-reactions (equations 13 and 14) can be added together to get the overall reaction for the fermentation of organic matter via anaerobic decomposition:

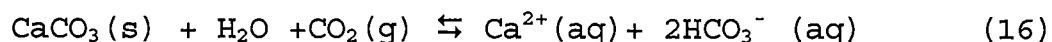


As overviewed in the section pertaining to nitrogenous compounds, bacteria has an active role in the cycling of nitrogen. In addition to carbon and nitrogen, bacteria aid in the reduction and oxidation of other compounds (sulfur, phosphorus, etc.) and play a significant role in the chemistry of sediment.

Geochemistry

The geosphere has a significant impact on the chemistry of natural waters in that it is in direct (sediment underlying the waterbody) and indirect (runoff from the applicable watershed) contact with natural waters. The geosphere is defined as the "solid earth" (31) and is comprised of minerals, rocks, soil, sediment, and clays. Within the minerals and rocks are inorganic solids that have the potential of leaching into the hydrosphere due to weathering. Weathering is described as the tendency of a mineral or rock to reach equilibrium and can be a result of

physical and chemical processes (31). Depending on the constituent that was once bound to the sediment, soil, and/or mineral the leached material can be toxic as it enters local waters via direct contact or through runoff. An example of a mineral that that is susceptible to weathering is calcium carbonate, depicted in reaction 16:



The dissolution of calcium carbonate is a result of chemical weathering from acidic rain or acidic surface waters. In this scenario, the calcium carbonate acts as buffer, assisting to neutralize the acidic waters. However, just as calcium carbonate undergoes weathering, so do other minerals, increasing the concentration of dissolved ions in the water. For areas enriched in arsenic or heavy metals, the dissolution, leaching, and oxidation of these compounds could result in adverse environmental health conditions.

Environmental geochemistry is the field of science that deals with the interactions between the hydrosphere, atmosphere, geosphere, and biosphere. However, due to the complexity of this topic and the vast number of elements and speciations involved, this topic will be addressed as necessary when discussing pollutants effecting Prado Basin,

and the ability of wetlands to mitigate for the involved constituents.

Internal and External Loading

Nutrient loading is the result of point source and non-point source pollutants, and occurs both externally and internally. External nutrient loading is primarily due to surface runoff from rain events and nuisance flows. Runoff containing nutrients increases the concentrations of phosphorus and nitrogen within the waterbody, while facilitating the increased growth of algal blooms. This contributes to the internal loading within the watershed, which as previously mentioned, alters the chemistry of the waterbody.

Internal loading is the loading that occurs within the waterbody resulting from the continued growth and decay of organic matter. Historically, the primary method employed to control internal and external loading involved the reduction or elimination of point source pollutants via diversion techniques.

Although cost effective, diversion is not a practical approach to watershed management; it merely transfers the problem downstream, rather than eliminating it. A more

popular approach for point source management is advanced wastewater treatment. Advanced treatment typically employs aluminum sulfate (alum) or calcium hydroxide (slaked lime) to precipitate phosphorus. This method is only effective if the waterbody undergoing treatment is eutrophied from phosphorous loading.

Prior to developing a management plan utilizing advanced treatment, it should be determined whether the receiving water body will benefit from the treatment, as the treatment will remain ineffective at treating eutrophication due to nitrogen loading if the source of the problem is phosphorus. Ensuring that the treatment facility is designed to treat the pollutants known for its drainage basin is of great importance due to the high initial capital and operational costs associated with tertiary treatment programs.

Advanced treatment for lakes containing phosphorus laden waters has been known to effectively remove 99% of the total phosphorus and has increased secchi disk depth by 50% (26) In addition to advanced treatment, lakes have greatly benefited from the use of created basins and pre-impoundments which allow time for nutrient rich particles to settle out prior to being discharged downstream.

For drainage basins dominated by agricultural activity, non-point source nutrient controls have proven difficult and users rely primarily on best management practices (BMPs) to reduce future loading to the watershed by controlling nutrients at the source. Such methods involve: 1) soil stabilization (chemical stabilizers, grassed outlets, revegetation, conservation tillage, buffer strips) designed to minimize the movement of soils and attached nutrients; 2) interruption of overland flow utilizing artificial wetlands to collect water and remove nutrients through aquatic plants and basins to collect runoff and allow settling of suspended sediment prior to discharge; 3) changes in chemical applications techniques to minimize excess nutrient availability; and 4) reduce nutrients at their source to increase the phosphorus absorption capacity in livestock making nutrients (i.e., phosphorus) more bioavailable for uptake (26).

Waterbodies that had previously succumbed to eutrophication due to internal loading have recovered, or are on their road to recovery, utilizing the following remediation methods: 1) biomanipulation of aquatic food chains; 2) mechanical harvesting of macrophytes or surface blooms (immediate relief, but is costly, and spreads the

problem over a long time); 3) chemical controls of phytoplankton to reduce biomass (requires continue treatment, releases organically bound phosphorus, and increases concerns of biota toxicity); 4) complete mechanical circulation of the water column (pushes phytoplankton to greater depths where light is insufficient for their growth); 5) phosphorus inactivation (extremely costly and only small lakes have potential for inactivation); 6) hypolimnetic oxygenation; and 7) mechanical removal of sediments by dredging (26). Although advances in technology has assisted in the recovery of once previously eutrophied lakes, the most effective method for managing drainage basins is to reduce future opportunities for nutrient loading, thereby, reducing opportunities for eutrophication, and eliminating the long, and costly, clean up process (26).

Influent/Effluent

The chemistry of waterbodies is greatly influenced by the rate of influent and effluent. That is, the rate at which water enters the system, the rate at which it leaves, and its storage capacity is known as the hydrological budget. The United States Geological Society, USGS,

estimates that 40,000 billion gallons per day (bgd) of water passes over the nation as water vapor. Of the 40,000 bgd circling the hydrological cycle, about "4,200 bgd falls to the earth in precipitation, and two-thirds is returned to the atmosphere by evaporation or by transpiration. The remaining 1,450 bgd is accounted for in storage (32)". The hydrologic budget or hydrological cycle is represented in Figure 7.

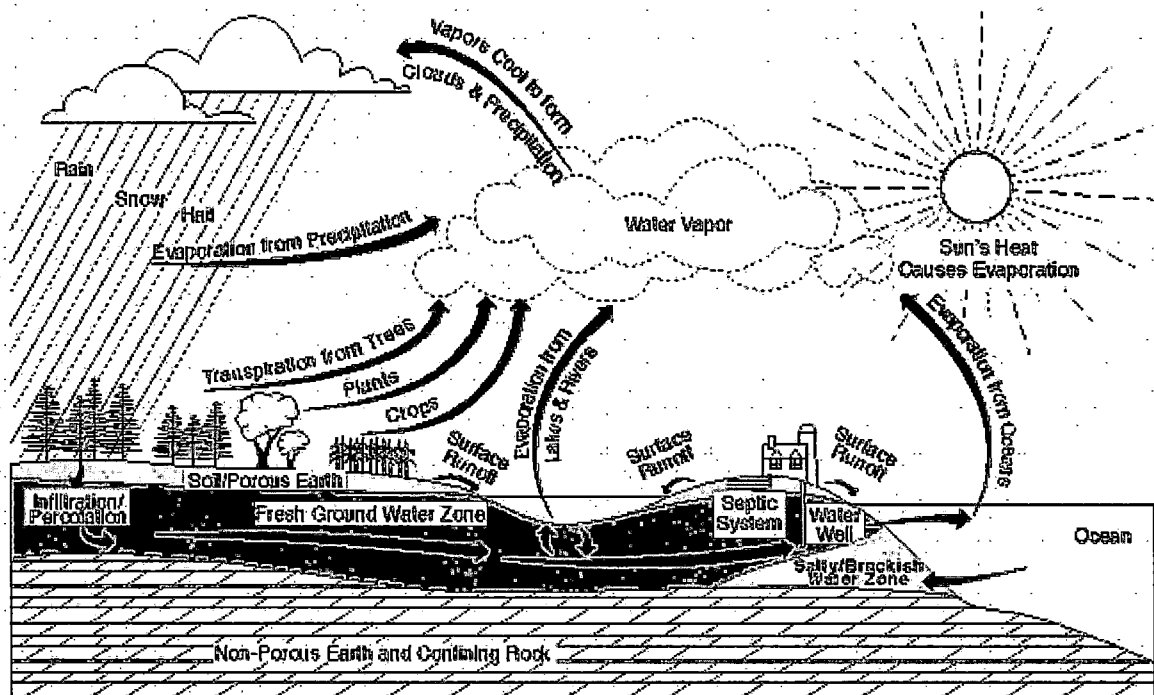


Figure 7. The Hydrologic Budget¹⁰

The hydrologic equation for surface flow is shown in the equations to follow, where T = transpiration, E = evaporation, P= precipitation, R = surface runoff, G = groundwater flow, I = infiltration, ΔS = change in storage, and subscripts s, g, 1, and 2 represent surface and underground components and influent and effluent, respectively (32).

$$P + R_1 - R_2 + R_G - E_S - T_S - I = \Delta S_S \quad (16)$$

¹⁰ Source: Reprinted from Ohio Department of Natural Resources. http://www.dnr.state.oh.us/Portals/7/pubs/fs_gifs/hydrocycl.gif (accessed February 2, 2008)

For underground flow, the equation for the hydrologic budget is as follows:

$$I + G_1 - G_2 - R_g - E_g - T_g = \Delta S_s \quad (17)$$

When equations 16 and 17 are combined the overall hydrologic budget is determined as follows:

$$P - (R_2 - R_1) - (E_s + E_g) - (T_s + T_g) - (G_2 - G_1) = \Delta(S_s + S_g) \quad (18)$$

By dropping out the subscripts and the quantities in the parenthesis of equation 18, the net equation (equation 19) results in the fundamental equation used for hydrological modeling:

$$P - R - E - T - G = \Delta S \quad (19)$$

The hydrological budget is especially significant during seasonal fluxes of extreme heat or during productive rainy season(s), and is greatly influenced by environmental factors, such as the rate of evaporation and transpiration.

If more water is leaving the system than entering, the vulnerability of the waterbody will be heightened due to temperature increases in the shallower waters. Increased temperatures can result in increased algal blooms as a result of the warmer waters, decreased DO due to saturation being temperature dependent and demand from plant growth and decay, pH variances, and increased BOD.

CHAPTER FOUR

MUNICIPAL WASTEWATER TREATMENT

History of Wastewater Disposal Methodologies

Throughout history, the disposal of waste has been a significant cultural and religious issue within a given society. Religious teaching required followers to remove and bury one's own waste, while cultural practices mandated more advanced systems. Ancient storm drains and sanitary sewer relics from the prehistoric cities of Crete and Assyrian, Figure 8 demonstrate the significance that wastewater disposal had on a society.

Between 1500 and 1700 BC, the Minoan culture of the Island of Crete developed and constructed a highly sophisticated sewage treatment system equipped with indoor plumbing, flushing toilets with wooden seats, and four large drainage systems emptying into a large sewer system made of stone (34). The Minoans were the last civilization to utilize flushing toilets until its re-development in 1596 (34).

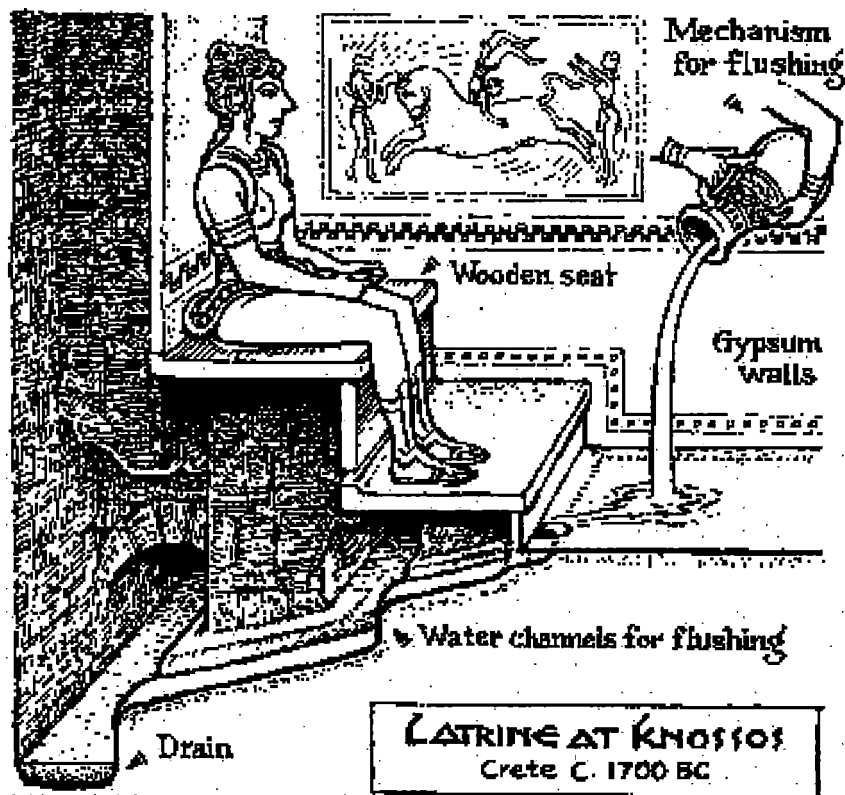


Figure 8. Minoan Sanitation System¹¹.

The rise of sanitation continued during the Greek era with the development of the first dump in 500 BC. Recognizing the role that human wastes had on the quality of water systems, the first law banning the disposal of wastes into streets was passed in Athens in 320 BC (34). By 300 BC the main role of Athens City/State was the removal of

¹¹Source: Reprinted from Onsite Wastewater Treatment Project. <http://www.cet.nau.edu/Projects/WDP/resources/History/History.htm> (Accessed February 2, 2008)

wastes. Revenues for this convenience was generated from levees by landowners (34). This system lasted for eight hundred years until the fall of the Greek civilization. However, the concern for water quality and public health was passed onto and further advanced under Roman civilization.

The Romans were considered the most advanced of early civilization and their waste handling practices were far superior to the practices of the middle ages. The Romans built large aqueducts connected to pure water sources, to provide their cities with clean water for baths, fountains, and flushing sewers (34). In having done so, the Roman Empire was able to double their water supply needs to meet the demands the ever-growing population placed on the society. However, even with the modern devices of underground sewer systems, Rome still experienced significant water quality issues; their city was considered to be unhealthy due to the practice of emptying the sewer system into the Tiber River (34). The fall of the Roman Empire during the fifth century brought an end to the advances of early civilization's sanitation efforts.

Although constructed for the primary purpose of drainage by the early Romans, the fall of the Roman Empire resulted in the complete demise of sanitary practices. For

the next thousand years, tap water was turned off and sanitation practices fell well below Roman standards (34).

Following the fall of the Roman Empire, "sanitation" referred to open trenches and outhouses that conveyed sewage directly into city streets and chamber pots that were dumped onto city streets. This "new" urban community often depended on their storm drain system to transport organic matter and refuse to the river via runoff. The Minoans used the Roman's trenches to transport human wastes directly from latrines to outside streets. Wastes would then remain in the streets where they provided a nutrient source for rodents until a rain event washed the organic matter away. The loss of sewer systems and hygienic practices during the Minoan age re-introduced water-borne illnesses and associated morbidity for all levels of society. The knowledge of excrement and its impact on water quality was lost.

The latter part of the middle ages brought about improvements to sanitation systems with the development of below-ground privy vaults and cesspools. Sanitation workers, paid for by property owners, would empty and dispose vault and cesspool contents onto farms, vacant lands, and watercourses. The following few centuries

focused on the re-development and protection of storm drain systems (i.e., open channels and street gutters), reintroducing laws that forbade the disposal of wastes into watercourses. During the 19th century, doctors discovered that the rapid removal of wastes improved public health, thereby, once again encouraging the disposal of waste materials into local rivers via storm drains.

The development of municipal water supply and household plumbing re-introduced flush toilets into homes and initiated the beginning of modern sewer systems. By 1910, there were about 25,000 miles of sewer lines within the United States municipal system (34).

At the beginning of the 20th century, it was discovered that the lengthy connecting systems led to the dumping of large quantities of human wastes into nearby streams resulting in water-borne illnesses and water-borne illness related deaths. The realization that human waste had the capability of contaminating local waterbodies ultimately led to the development and construction of sewage treatment facilities. However, construction was slow due to the invention of the septic system for the capture and containment of domestic supply, as well as, severe social

and economic factors taking precedence during the first half of the 20th century following World War II.

By the 1950's and 60's, the federal government acknowledged the need of increased municipal wastewater facilities for encouraging the prevention of pollution, by providing capital funding for their development and grant funding for water research and technical training.

Due to increased water research and technical training, new methodologies were developed for the analysis and treatment of wastewater. In addition, Congress established administrative agencies to enforce stricter regulations. On January 1, 1970, the National Environmental Policy Act (NEPA) was signed as a means of creating a coordinated effort to protect US environmental assets. In December of that same year, the EPA was created to act as the supervisory agency for all pollution control acts (e.g., air, water, and solid waste). Water pollution controls, Clean Water Act (CWA) were expanded in 1972 to include funding for increased waste water facilities. Today, wastewater regulations have been heightened to include discharge criteria and permits for discharge.

Wastewater Regulatory Permits

In 1987 the CWA was amended to include a regulatory framework for municipal and industrial stormwater discharges under the National Pollutant Discharge Elimination System (NPDES) permit by adding Section 402 (35). Under this amendment all facilities (municipal, industrial, and commercial) discharging wastewater into a conveyance channel that emptied into a waterbody were required to obtain a NPDES permit. California is a designated state that is required to implement the EPA's NPDES program. It is for this reason, that the NPDES permit is commonly referred to as the "regulatory speak" for the CWA.

The NPDES permit requires the principle permittee (typically the City for which the discharge activity will occur or the region the city is located depending on whether a regional or municipal permit was issued) to maintain the responsibility for managing its stormwater program.

Management of the stormwater program includes conducting water quality analyses, implementing monitoring programs, preparing and submitting annual reports to the Regional Board, conducting co-permittee (smaller entities holding a NPDES permit through the principal permittee)

meetings, providing technical and administrative support, and public education programs.

The co-permittee(s) (e.g., a wastewater treatment facility) is/are required to implement all programs and monitoring activities as required by their permit, establish and enforce policies for the protection of water quality as required by Section VI.1 of Order NO. R8-2002-0012, and as required by Federal Stormwater Regulations, 40CFR, Part 122.26(d)(2)(i)(A-F), take necessary enforcement actions on permittee violations, and prepare and submit all reports to the Regional Water Quality Control Board (Regional Board) in a timely manner (36).

In accordance with Section IV (Receiving Waters Limitations) of the NPDES permit, municipal separate storm sewer system (MS4) discharges shall not result in, or contribute to, exceedances of water quality standards as indicated by the Basin Plan's designated beneficial uses and water quality objectives. MS4s must be designed in such a manner that Best Management Practices (BMPs) implement control measures considered effective at reducing pollutants contributing to urban stormwater runoff, as a means of achieving compliance with receiving water limitations.

Wastewater Treatment - Primary Treatment

The actual treatment of wastewater is divided into several stages. The first stage of wastewater treatment is classified as primary treatment shown in Figure 9.

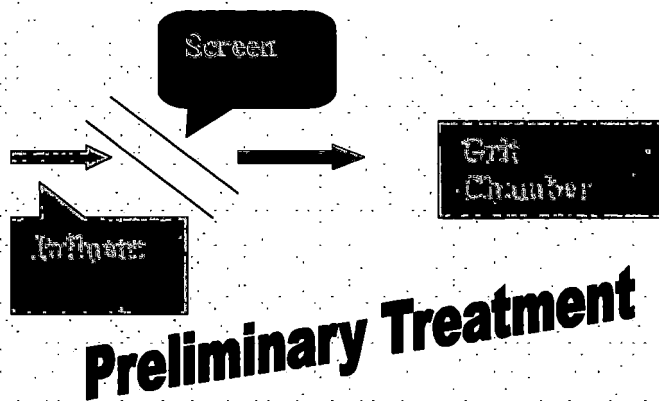


Figure 9. Preliminary Treatment Process¹².

The goal of primary treatment is to encourage the settling of suspended particles via physical and/or chemical processes, in order to remove insoluble materials. Although primary sedimentation has limited effectiveness due to the inability of over one half of waste to settle, it will reduce the amount of waste that moves through the

¹² Source: Reformatted from Baird, Colin; and Cann, Michael. Oxidation-Reduction Chemistry in Natural Waters. *Environmental Chemistry*, Edition 2, W.H. Freeman and Company, NY, 2005. p 426.

system. With this intent, the first step of primary treatment occurs as wastewater enters the plant and passes through a screen to catch large debris and trash. The screening process functions to reduce the size of debris entering the sewage system. Wastewater then flows through the grit chamber where low flow velocity allows grit (sand, seeds, coffee grounds, etc) to settle to the bottom of the tank preventing pipes from clogging and reducing abrasive wear on moving parts. The primary treatment process facilitates the settling of grit, which is then mechanically scraped from the bottom of the tank while floating debris is skimmed from the surface. The process of primary treatment reduces BOD by 35 percent and removes 60 percent of the suspended solids (37).

Wastewater Treatment - Secondary Treatment

Through the use of air and micro-organisms, secondary treatment encourages the decomposition of organic matter by creating conditions that optimize bacterial growth. The bacterial growth hydrolyzes organic-enriched waters, converting carbohydrates into soluble sugars, proteins into amino acids, and fats into fatty acids (38). If allowed to continue under aerobic conditions sugars will eventually

breakdown into carbon dioxide, water, and the nutrients derived from this process aids in the growth of new bacterial cells. By the time the organic matter has fully decomposed, the secondary treatment process will have removed an additional 50 percent of the remaining BOD and reduced suspended solids by an additional 33 percent.

The biological degradation of organic matter can be accomplished in various ways; the most common of these are through the use of film flow (e.g., trickling filters and rotating biological reactors) and suspension (fluidized cultures) processes.

Trickling Filters

The trickling filter is the most common film-flow type process used for the degradation of organic matter. As shown in Figure 10, wastewater is sprayed over a media bed (gravel rock or formed plastic) that is either enriched in micro-organisms or is overlaid with biological slime. The water then flows through the media, which extract organic matter and dissolved oxygen as it progresses through the layers. Bacteria within the slime extracts the organic material and inorganic nutrients, using the dissolved oxygen as it breaks down the raw material as an energy source for the synthesis of new cells. This process facilitates the

re-generates of new bacteria for the next influent application. The dissolved oxygen is then replaced in the void spaces of the media by absorption from the air.

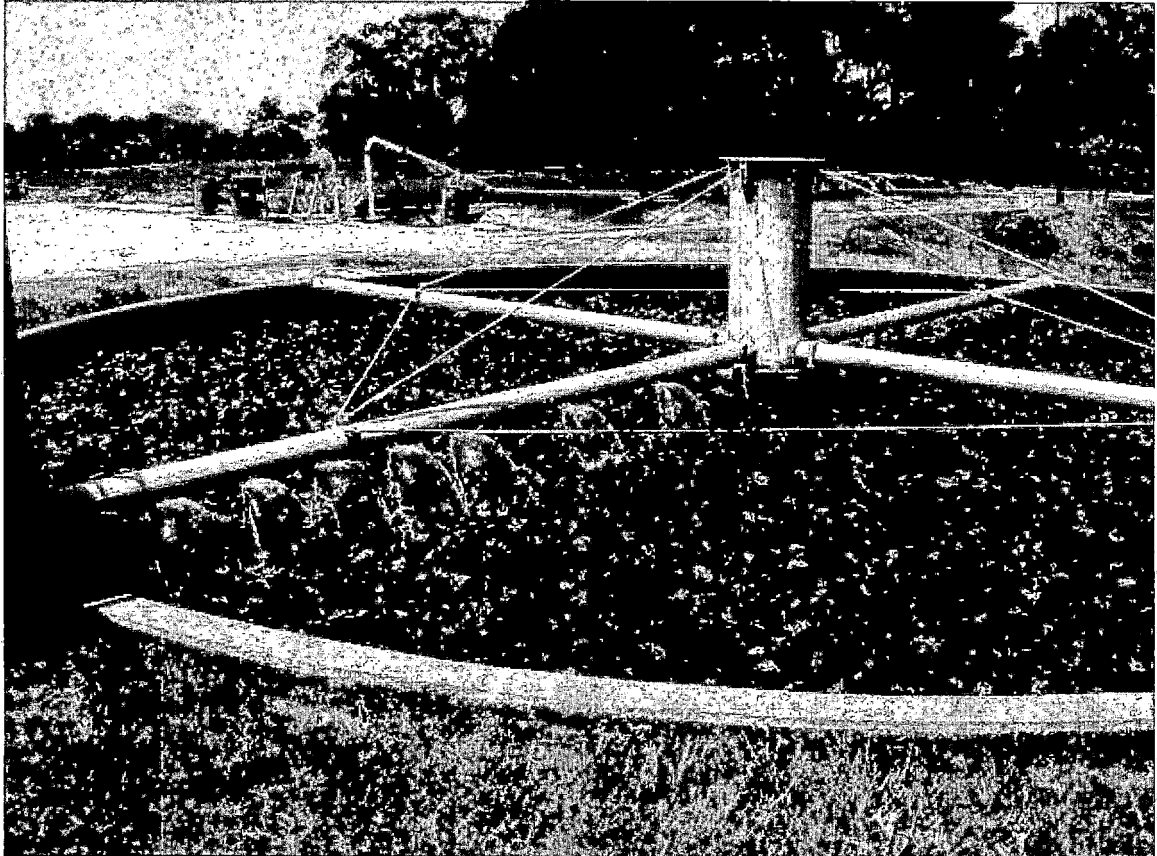


Figure 10. Trickling Filters¹³

¹³Wastewater Innovations, Inc.
[http://www.winnsystems.com/trickling%20filter%20\(600%20x%20450\).jpg](http://www.winnsystems.com/trickling%20filter%20(600%20x%20450).jpg)
(accessed September 12, 2007)

As the wastewater progresses deeper through the layers, the organic matter and dissolved oxygen decrease resulting in a starvation zone at the deepest layers of the tank. Although classified as an aerobic process, trickling filters are actually a facultative process incorporating both aerobic and anaerobic processes.

Rotating Biological Contactors

The rotating biological contactor differs from trickling filters in that the slime is supported on a lightweight material (e.g., Styrofoam) that moves through the water, treating the wastewater as it comes in contact with the slime. Aside from this difference, the biological media degrades organic material in the same manner as does the trickling filter.

Another biological method employed to meet secondary treatment protocols is the use of suspension processes in activated sludge aerated lagoons, oxidation ponds, and anaerobic treatment processes. Similar to that of trickling filters, activated sludge is an aerobic process utilizing a culture of agglomerated bacterial cells referred to as flocs (≥ 0.1 mm in diameter). In this system, microorganisms produce an extra-cellular slime functioning as a binding agent to facilitate floc formation. Diffused air is then

either added to the bottom of the tank or introduced via mechanical agitation to suspend the flocs in the media. Influent from the primary treatment process is aerated over the activated sludge lagoon, thus serving as the mixing device for this process. Cells, having a specific gravity slightly greater than water, can then be separated from the treated liquid by gravity settling and sedimentation. The removal of cells from water is important for the treatment to be considered complete, since the cells are organic, thus failure to completely remove the cellular walls adversely affects the measurement of the effluent's BOD (40). The degree of treatment achieved, and the clarity of the resulting water, is directly proportional to the settleability of the activated sludge. The settled cells are sent to the aeration-reaction tank to be recycled, while the supernatant passes through the system for further treatment.

Wastewater Treatment - Disinfection

Following secondary treatment, the supernatant undergoes disinfection to completely remove bacterial cells from the water and thereby completing the wastewater treatment process. For the purposes of this project

disinfection refers to the selective destruction of disease causing organisms, while sterilization is the complete destruction of all organisms. The process of disinfection employs one, or more, of the following mechanisms to destroy disease causing bacteria: 1) damage of the cell wall - results in cell lysis and death; 2) alteration of cell permeability - introduction of phenolic compounds and detergents changes the permeability of the cell, resulting in the escape of vital nutrients (e.g., nitrogen and phosphorus) from the cell; 3) alteration of the colloidal nature of the protoplasm - heat and radiation coagulates cell proteins, while pH changes denatures the proteins, each resulting in cellular death; and 4) altering the chemical arrangement of the cell's oxidizing agents inhibits enzyme activity. The amount or type of disinfection used is dependent on the final use of the water, the contact time for which it must be exposed, the concentration and type of chemical agent selected, intensity and nature of a selected physical agent, temperature, number of organisms, types of organisms, and nature of suspending liquid.

Contact time is an important variable when determining the most feasible chemical needed to kill bacteria.

According to Chick's law, $dN/dt = -kN_t$, the longer the

contact time at a given concentration, the greater the ability of the disinfection to kill (41). In Chick's law, N_t refers to the number of organisms at a given time (t) and k is the inactivation rate constant.

Deviations from this law are common and rates have been found to both increase and decrease with time. As a result, the assumption, $\ln(N_t/N_0) = -kt^m$, is typically made to formulate a relationship between the kill factor (the length of contact time required to kill bacteria) and applicable conditions (41). In this relationship, if $m \geq 1$ the rate of kill increases with time and if $m \leq 1$ the rate of kill decreases with time (41). The constants can be determined by plotting $-\ln(N_t/N_0)$ versus the contact time (t) on log-log paper with the equation of the line represented as:

$$(-\ln N_t/N_0) = \log k + m \log t \quad (20)$$

The concentration of the chemical agent used is strictly dependent on the toxicity of the chemical chosen; however, disinfection generally shares an empirical relationship with the concentration (C) of the disinfectant, $n = \text{constant}$, and $t_p = \text{time required to effect a constant percentage kill}$:

$$C^n t_p = \text{constant} \quad (21)$$

The constant can be determined via a log-log plot of concentration versus the time required to effect a given percentage kill will generate a slope value of $-1/n$, when $n > 1$ the contact time is more important than dosage, if $n = 1$, the effects of time and dosage are equal.

If physical agents (e.g., heat and light) are being used for disinfection, the intensity and nature of the physical agent is important. In general, it is recognized that the effectiveness of the disinfection process is a function of the intensity of the heat, or light being used, and is related to a first-order reaction for the decay of organisms (41). The dose required to effectively reach the kill factor is represented in equation 21.1, where $D = UV$ dose (mJ/cm^2), $I = UV$ intensity (mW/cm^2), and $t =$ exposure time (s) (41):

$$D = (I) (t) \quad 21.1$$

UV is analogous to chlorine disinfection (equation 21) and can be varied by changing either the intensity of the light or contact time (41).

The effect that temperature has on bacterial kill is represented by van't Hoff-Arrhenius equation(40), where increasing temperature increases the rate at which the kill occurs. In the equation 21.2, $t_1, t_2 =$ times for given kill

percentage at temperatures (in Kelvin) T_1 and T_2 , E = activation energy (J/mol), and R = gas constant (8.314 J/mol·K).

$$\ln (t_1/t_2) = E(T_2-T_1)/RT_1T_2 \quad (21.2)$$

The number of organisms present in solution is significant when there are unusually large concentrations of microorganisms present in the wastewater. In this situation, the time allocated to effectively kill all bacteria present would increase. The concentration of the disinfection used, and the intensity for which the disinfection is applied, directly corresponds to the number of organisms that will be eliminated during the disinfection process. Calculating the kill factor prior to disinfection and periodically re-evaluating disinfection needs is important to the budgetary needs of the treatment facility. The more chemicals used or greater energy required to meet treatment requirements greatly affects the costs associated with running the treatment facility.

The most common disinfection methods make use of chemical agents, physical agents, mechanical means, and radiation to treat the supernatant (40). Chemical agents (e.g., chlorine and chlorine based compounds, bromine, iodine, ozone, phenol and phenolic compounds, and alcohols)

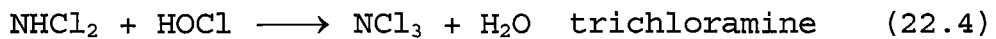
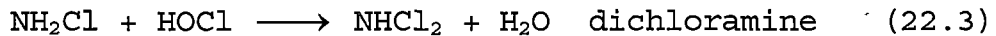
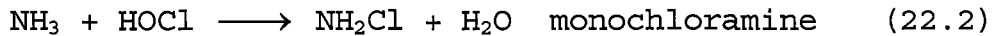
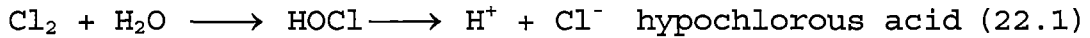
with strong oxidizing properties are generally chosen due to the high level of toxicity to bacteria, their residual nature, and cost effectiveness. Of these, the most widely used chemical agent for disinfection of drinking water is chlorine in the form of $\text{Cl}_2(\text{g})$, HOCl , and NaOCl . Ozone and UV radiation are generally chosen to disinfect waters that are designated for groundwater recharge or waters that will be discharged into local rivers to ensure that potential by-products created from the disinfection process do not interfere with aquatic organisms.

Wastewater Treatment - Denitrification

The removal of nitrogen from wastewater begins with the biological metabolic breakdown of organic matter and finishes with disinfection. Nitrogen is a vital nutrient in cellular activity. As such, microbial cells must extract some of the nitrogen from the organic matter for growth. In addition to the nitrogen (12 percent) removed during metabolic activities, a small percentage is incorporated into the floc as "biologically inert particulate matter" produced from the secondary treatment process (42).

The nitrogen that remains in the supernatant is removed during breakpoint chlorination. In the first step of

breakpoint chlorination, hypochlorous acid (HOCl) reacts with ammonia to form chloramines (equation 22.2, 22.3, and 22.4):



For an effective kill factor, Reactions 22.3-22.4 are dependent on pH, temperature, contact time, and the ratio of chlorine to ammonia (41). A molar ratio of 2:1 (chlorine to ammonia) increases the free available chlorine in the supernatant, oxidizing the chloramines to nitrous oxide (N₂O) and nitrogen (N₂), reducing the chlorine to the chloride ion, allowing the breakpoint to be reached, which results in the removal of ammonia from solution and free available chlorine in solution. The ability of chlorine to disinfect, or its oxidizing power, is based on the amount of free available chlorine in solution.

Raising the free available chlorine in solution ensures that disinfection has taken place, that ammonia has been removed from the system, and that there has not been an increased in potential by-products from the disinfection process being discharged into waters of the U.S. Systems

employing this technique on a continual basis would require significant quantities of chlorine to remove nitrogen, thereby increasing overall operational costs.

Wastewater Treatment - Tertiary Treatment

Tertiary treatment or advanced wastewater treatment refers to the additional measures taken to remove contaminants that would not ordinarily be removed during primary and secondary treatment processes. The term is applied to any course of treatment, in addition to, or modifications to, the conventional treatment system.

Tertiary treatment is only applied if treated effluent fails to meet compliance following the conventional system, and as a result, typically involves highly specialized systems aimed specifically at removing certain constituents to meet regulatory compliance needs. The most common of these processes involve filtration, phosphorus precipitation, and denitrification. Entities applying advanced treatment would typically have higher operating costs, negatively affecting their cost-benefit analysis. For the purposes of this paper, a cost-benefit analysis on the denitrification of wastewater (employing tertiary

treatment measures) will be performed utilizing natural versus conventional treatment systems.

CHAPTER FIVE
ALTERNATIVE TREATMENT SYSTEMS

Background

Technological advances due to increased sensitivities of analytical instrumentation and the ability to detect constituents at lower concentrations have heightened the public awareness of contaminants in the environment. Scientific journals publish advanced studies calling for stricter regulations on contaminants that were once undetected by regulatory agencies. Broadcasting highlights, the media educates the public of environmental concerns that may result in adverse human health effects, as local regulatory agencies scramble to shut down affected assets (i.e., wells, pumps, etc) until such time as new statutes are met. In an effort to remain in compliance while continuing to meet service needs, agencies may employ costly tertiary treatment measures to ensure that contaminants are reduced to a level that is within "limits", in an attempt to recover use of lost assets. In 1991, it was estimated that to meet the requirements set forth by the Regional Board for its maximum contaminant level (MCL) for nitrogen, 10 mg/L,

an average of 200 million dollars would be spent by treatment operators to upgrade their systems (43).

Receiving its principal water supply from an effluent dominated river typically high in nitrates, the Orange County Water District (OCWD) searched for a more cost-effective alternative to conventional nitrate controls. In response to studies conducted by Northwestern University and the University of California, Berkeley, and recent successes shown in the Hidden Valley Wetlands (local wetlands upstream of Prado) in removing nitrates, OCWD spent 5 million dollars developing a wetland project. These costs include mitigation measures required by USACOE, environmental compliance documentation(s), permits, and wetland design (18). OCWD owned 2,150 acres of property behind Prado Dam, and was able to maintain low initial start-up costs due to not having to allocate funds for land acquisition (13).

Operating since July of 1992, the Prado Wetlands has provided OCWD a cost-effective alternative for treating discharged wastewater and denitrifying river water by diverting 70 million gallons/day through 50 treatment ponds located on 465 acres of land (13). Through the construction and implementation of their wetlands, OCWD estimates nitrate removal expenditures of \$0.50/pound, compared to

\$15.00/pound they would have spent had they employed conventional treatment (44). At a savings of \$14.50/pound the Prado Wetlands removes approximately 20 tons of nitrates per month from 140,000 acre-feet of treated wastewater (13). During the dry summer months, treated wastewater comprises more than 90% of river's base flow (13).

Prado Wetlands not only functions to improve water quality, but it serves as an important layover to over 250 species of rare, threatened, and endangered migratory birds and water fowl (44). It is designated as environmentally sensitive habitat for indigenous species (e.g., least Bell's vireo, the western yellow-bellied cuckoo, and the Southwestern Willow Flycatcher) (44).

Providing mitigation for the opportunity to store water behind Prado Dam, OCWD in conjunction with USACOE and United States Fish and Wildlife Service (USFWS), increased the least Bell's vireo population from 20 to 200 breeding pairs through the restoration of current wetland habitat and allotting an additional 226 acres for habitat enhancement (13). Currently, OCWD is completing a three year study for the expansion of Prado Wetlands, which will make it the largest wetlands developed for water quality and habitat improvement in the United States (13).

Wetland Design-Feasibility

Prior to committing to the idea of utilizing wetlands as the preferred course of treatment a feasibility study should be conducted assessing the pollutants common to the watershed, project outcomes in terms of long term and short term goals, and the ability of the site to function as a wetlands.

Knowing which pollutants are common to the watershed and sub-watershed(s) are important when evaluating whether to construct a wetlands or a wastewater treatment facility for meeting treatment needs. Watershed managers should assess the area draining to the project site and determine if wetlands could mitigate the pollutants of concern (POCs) that were identified for the area. POCs are pollutant sources known to occur as a result of the activities of specific planning zones. If wetlands are designated as the primary treatment mode for the drainage areas, then the system will likely improve the overall quality of water. If wetlands are known for not treating the designated POCs, and it is believed that pollutant loading will concentrate, than wetlands are not the most beneficial treatment for that particular drainage basin. After all, it is not the goal of any watershed manager to spread water over soils enriched

with heavy metals or in areas identified as environmentally hazardous/sensitive.

Secondly, the watershed manager should identify project outcomes. These are the short and long term goals of project implementation. The manager should categorize all benefits to be gained (e.g., water quality, habitat, recreational attributes, aesthetics, open space) and the time frame for which they need to be implemented. Other factors that should be considered are the methods and technologies necessary to meet identified project outcomes and what cost(s) (financially, socially, environmentally, etc.) the project will incur if construction is undertaken.

Finally, the suitability of the site to function as wetlands must be evaluated. A key factor is site accessibility. Will the wetlands be able to easily and cost-effectively receive water all year? Is the source water sufficient in quantity to sustain the wetlands? What is the overall quality of the influent? Will the wetlands be able to treat and improve the overall quality of the influent? Wetlands require a significant amount of land to meet treatment requirements so the manager should assess whether sufficient open space is available. Not all soils can adequately retain water, so the soil type should be

evaluated to ensure that water can be held for an extended period of time. If not, how will modifications be made to meet this requirement? Does the site's natural topography encourage wetland habit by allowing water to gravity flow to the area? What other purposes will the wetlands serve (e.g., a wildlife corridor, nesting or resting area for migratory birds, etc., and will this require a maintenance agreement between DFG and FWS under the Safe Harbors Act)? Is adequate funding available to purchase the land, design, construct, and maintain the wetlands, and any habitat that may depend on it, once it is implemented?

As part of the feasibility study the type of wetlands to be used should be thoroughly investigated and the most appropriate option for meeting budgetary and treatment needs should be selected.

There are two types of wetlands, natural and constructed. The suitability of each to receive and treat wastewater must be considered prior to electing a natural treatment option. Typically, natural wetlands are classified as receiving waters or waters of the US. Which means, that the waters will ultimately drain to a waterbody that is considered "navigable" (i.e., oceans). These wetlands have beneficial use designations and would require

advanced treatment prior to discharging into a thriving ecosystem. If the wetlands are used as a more cost-effective alternative to advanced treatment facilities, discharging to natural wetlands would probably not be the preferred method, as monies would have already been allocated to meet specific treatment goals per regulatory standards and beneficial uses. Generally, when discharging to established natural wetlands the goal is for the enhancement of existing habitat, not to treat wastewater.

If electing to use a natural system, constructed wetlands are normally preferred for treating secondary treated effluent, as they tend to pose significant benefits over natural wetlands. Constructed wetlands do not typically have the same regulatory constraints and permits that are required for discharging to an established ecosystem because their predominant purpose is for the treatment of wastewater. However, if the wetlands become recognized as environmentally sensitive habitat, permitting may become more of an issue.

Constructed wetlands are advantageous, as they tend to have the same, if not better, treatment capabilities than natural wetlands. This is due to the ability to engineer and design the treatment system that best meets the

topography, hydrology, and soil characteristics of the site for attaining optimum treatment. When designing wetlands, engineers generally choose one of two types, (free water surface (FWS) system or subsurface flow system (SFS)) for treating wastewater.

If the objective of the wetlands is to provide or enhance habitat, as well as treating wastewater, then FWS systems are typically favored. FWS systems have relatively impermeable bottom sediment enabling them to hold water over an extended period of time, are shallow, with depths ranging from 0.33 to 2 ft, and are well vegetated. In this type of system, treated effluent is continuously fed into the system allowing water to slowly filter through the vegetation.

If the wetlands are strictly for advanced wastewater treatment, then SFS systems are favored due to their impermeable sand or rock bottom media that supports vegetation for filtration (40). Regardless of the system used, knowing the characteristics of the wastewater, all possible treatment mechanisms, current and past public health issues, and designing the wetlands in accordance with local, state, and federal regulatory requirements are fundamental to the successful operation of the constructed treatment system (40).

Wetland Design - Wastewater Characteristics

The soil-water-plant ecosystem is capable of removing or reducing the concentration of most constituents commonly found in wastewater (e.g., suspended solids, organic matter, nutrients (N & P), trace elements and organic compounds, and microorganisms). As mentioned previously, when designing wetlands, it is important to know the characteristics of the source waters and the degree to which it must be treated to ensure that the system designed is within treatment capabilities and provides treatment in a favorable capacity. It is for this reason that a general discussion of wastewater constituents is to follow.

Field Testing

To understand the effects that varying operating and environmental conditions have on a wetlands' hydrological residence time, vegetation coverage, and water temperature, changes to these variable were studied in three phases between 1992 and 1993 (47). Phase 1 was a nine weeks course, carried out between the months of July 18 and September 18 of 1992. During this time, 30% of SAR flows were diverted to the pond system at a rate of $20 \text{ ft}^3\text{s}^{-1}$. Phase 2 was a six week trial from October 26 to December 6, 1992. During this time, 40% of SAR flows were diverted to the pond system at a

rate of $30 \text{ ft}^3\text{s}^{-1}$. Phase 3 occurred over a twelve week period, September 12 to December 4, 1993. During this time, 50% of SAR flows were diverted to the pond system at a rate of $50 \text{ ft}^3\text{s}^{-1}$. The results of analytical data collected during this time are presented in the succeeding sections.

Suspended Solids

Suspended solids or total suspended solids (TSS) are defined as "the residue that remains after a wastewater sample has been evaporated and dried at a temperature of 103-105 °C" (46) and is depended on the pore size of the filter paper used for sample collection. Analyses of suspended solids are reported in terms of the result and the pore size of the filter paper used for the analysis.

Free Water Surface Systems. Constructed wetlands that are designed as a FWS system are ideal for treating suspended solids. FWS systems utilizing its shallow depth, slow moving waters, and abundant vegetation to filter particulate matter and allow time for heavier solids to settle. An example of a FWS system is Prado Wetlands.

Prado Wetlands. An analysis of the suspended solids entering Prado Wetlands' Study Site #1 showed that over the 30 day residence time, a reduction in suspended solids from 17.0 mg/L to 6.3 mg/L. Study Site #2 had a seven day

residence period, in which suspended solids were shown to reduce to 6.4 mg/L. Deviations in suspended solid result from the quantity and velocity of the influent on a day to day basis; however, the decrease in suspended solids demonstrates the ability of wetlands to encourage settleability.

Subsurface Flow Systems. SFS systems differ from that of FWS systems, in that it utilizes the sand or rock bed to settle particulate matter rather than vegetation. In this system, sedimentation occurs primarily through the inability of the solid matter to infiltrate through the sand or rock media. Remaining on the surface of the sand/rock matter, residue is removed from the water as the water infiltrates and percolates through the media.

Organic Matter

In a natural treatment type system, microorganisms are responsible for the breakdown of degradable organic matter. The breakdown of organic matter occurs both anaerobically and aerobically.

Prado Wetlands. The total organic carbon concentrations had the tendency to increase by 11 mg/L, 9 mg/L, and 5.7 mg/L as water moves through the wetland system (phases 1,2, & 3) due to the effects of evapotranspiration (EVT) and the conversion of organic carbon into soluble forms (humic acid and fulvic acid). This increase in the production of the humic and fulvic acids contributed to the decrease in pH of the waters leaving the wetlands, but is directly related to the ability of the system to denitrify the wastewaters. Studies seem to suggest that the higher the concentrations of organic carbon, the greater the rate at which denitrification occurs due to more "food" being available to microorganisms to break down nutrients (47).

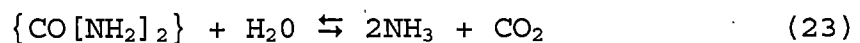
Nutrients

Wetlands are effective at reducing nutrients (nitrogen & phosphorous) under aerobic and anaerobic conditions as detailed in Chapter 3 of this project.

Nitrogen. Nitrogen is typically in the form of ammonia or organic nitrogen in wetlands unless it has undergone nitrification under advanced treatment processes. Nitrate is the dominant form of nitrogen in both the influent and effluent of Prado wetlands due to its ability to readily oxidize in turbulent river flow (18). Studies indicate that

the Prado Basin acts as an effective sink for nitrogen entering the Santa Ana River and its tributaries (18).

Organic Nitrogen. In the Prado wetlands, organic nitrogen is most associated with suspended particulate matter. In FWS systems, such as Prado, organic nitrogen would be predominately filtered by vegetation and heavier particulate matter would settle and bind with sediment. Organic nitrogen is formed in the plant biomass after it has been assimilated and taken up by plants and is then incorporated by the animal that eats the plant. Ammonification occurs when the organic nitrogen mineralizes as NH_3 is released during the decomposition of the organic nitrogen by heterotrophic bacteria (18). Heterotrophic bacteria has specialized enzymes that allows for the chemical breakdown of organic nitrogen.



The NH_3 is either released into the surrounding environment (wetlands) or is used in cellular metabolism and growth.

Ammonia Nitrogen. The presence of ammonia in natural treatment systems and natural waters are a result of discharged wastewaters, runoff containing ammonia, aquatic

animal excretions, ammonification of organic nitrogen, and fixation of nitrogen gas (18). Ammonia can exist in two forms, ionized ammonia (NH_4^+) and un-ionized ammonia gas (NH_3). Un-ionized gas form as a result of increasing temperatures and increasing pH and can result in volatilization (18).

Ammonia can follow several pathways once in a wetland system: 1) Soluble ammonia can be removed via volatilization as ammonia gas; 2) absorbed ammonia is available for uptake by plants and microorganisms; and 3) ammonia may be removed through the nitrification process under aerobic conditions.

In Prado Wetlands, under neutral pH and a temperature of 25°C , which are typical conditions for Prado, 99% of the ammonia exists as NH_4^+ (18). The ionic ammonia binds with negatively charged sediment particles and becomes immobilized (18).

Nitrate Nitrogen. If nitrate is not reduced and used by plants, its negative charge prevents it from taking part in anion exchange reactions with sediment. Nitrate will remain dissolved in the water as it percolates into the groundwater. If wastewaters (source water) are high in nitrate nitrogen, the wetlands must be designed in such a matter that encourages uptake, which occurs at the root zone

during the plant's active growing season, or the wetlands is designed to allow for biological denitrification to protect groundwater from high nitrate concentrations.

Prado Wetlands. Nitrate nitrogen is the predominate form of nitrogen found in Prado due to upstream users releasing it as nitrified effluent. Any remaining ammonia, following primary and secondary treatment, would have been oxidized to nitrate during its route downstream. Ammonia that is present in Prado in its reduced form can also undergo nitrification by autotrophic bacteria (*Nitrosomanonas* and *Nitrobacter*).

Table 4 provides a comparison of the speciation of nitrogen found in Prado Wetlands' with its relative concentrations. As can be seen in Table 4, wetlands are effective in reducing the concentration of nitrates to below 10 mg/L (parts per million or ppm).

Table 4. Comparison of Nitrogen Concentrations
for Average Phase 1, 2, and 3.

PHASE	NITROGEN CONCENTRATION (MG/L)									
	Inflow (site 1)					Outflow (sites 17, 18, 19, 20, &22)				
	NH ₄ ⁺	NO ₂ ⁻	NO ₃ ⁻	TIN	Org-N	NH ₄ ⁺	NO ₂ ⁻	NO ₃ ⁻	TIN	Org-N
1	<0.1	<0.5	8.0	8.3	0.3	0.1	<0.5	<0.1	0.4	0.6
2	<0.1	<0.5	8.6	8.9	0.4	0.2	<0.5	1.7	2.2	0.7
3	<0.1	<0.45	9.2	9.5	0.6	0.2	0.4	5.2	5.7	0.7 ¹⁴

¹⁴ Source: Reprinted from Santa Ana Watershed Project Authority (SAWPA). Investigation of the Fate of Nitrogen and Total Organic Carbon in the Prado Basin. L State Water Resources Control Board, 1995, p.1.

Aquatic vegetation has been known for its effective nitrogen removal rates (18). Certain types of vegetation have shown to be more apt to take up nitrogen (e.g., Bulrush 90%, reeds 78%, cattails 29%, compared to 11% for ponds without vegetation), as it can constitute up to 4% of a plant's biomass (18).

Phosphorus. Phosphorus, like nitrogen, is also considered to be a limiting nutrient. When found in high concentrations phosphorus can negatively affect the biochemical oxygen demand of an aquatic system. Wastewaters that are high in phosphate may use chemical precipitation and adsorption as their predominant means of removing

phosphorus to ensure that it doesn't negatively affect downstream waters.

Chemical Precipitation. Chemical precipitation is advantageous because it is easy and effective. Phosphate can be readily removed from water, as it will form precipitates with calcium at neutral to alkaline pH values and with iron and aluminum under acidic conditions.

Orthophosphate. A common species of phosphate found in natural waters is orthophosphate. It is generally removed from natural treatments systems through anion and cation exchange mechanisms. Phosphate is immobilized as it is adsorbed by clay particles within the sediment matrix.

Prado Dam. The predominate form of phosphorus in Prado wetlands is phosphate. Prado Wetlands have been successful in the reduction of phosphorus concentrations. As waters flow through the three phases, concentrations steadily decrease by 1.6 ppm, 0.9 ppm, and 1.2 ppm, respectively (18).

Trace Elements and Organic Compounds

Wetlands typically remove trace elements (metals) and other organic compounds through adsorption and precipitation reactions.

Major Ion Concentrations

Following Phase 1 and 2, sodium and calcium were the dominant cations present in diversion flows (approximately 90 ppm each) with chlorine and sulfate as the dominant anions (approximately 110 ppm each).

Treatment Mechanisms in Wetlands

The predominant mode of treatment in wetland systems are through biological processes of plant up-take and microorganism breakdown.

Microorganisms (bacteria and parasites) are naturally removed from these systems as a result of "die-off, straining, sedimentation, entrapment, predation, radiation, desiccation, and adsorption, while viruses are removed via adsorption and die-off (40)".

Public Health Issues

Treating wastewater for the subsequent purpose of recharging groundwater has created much concern amongst the general population due to the use of bacterial processes to

breakdown organics (that may contain human *E-coli* and/or virus known to cause water-borne diseases) and nutrients.

Microorganisms are often portrayed in a negative light. The negative aspects of bacteria are more heavily perceived than that of the positive ones. The public often sees treated effluent as nothing more than wastewater and they worry over the quality of the water that is being used to irrigate the crops they eat and recharge the groundwater they drink.

In response to public health concerns, OCWD conducted a comprehensive study titled "Santa Ana River Water Quality and Health" which characterized the quality of the SAR water and evaluated the impacts on groundwater quality (48). Positive results to this study have led to plans for future enhancement and expansion of the wetlands and the successful marketing of their "toilet to tap" campaign, which has been more well-received by the public than any other facility that has launched similar campaigns.

Wetland Design - Prado Wetlands

Once SAR flows reaches Prado Dam, 50% of the water is diverted to the Wetlands. There are four major basins, East (A' and A) 74.3-acres, North (B') 87.5-acres, South (B)

92.6-acres, and West (C) 78.8-acres, within the 360-acre wetlands and within each basin there are between six and eighteen sub-basins (47). Once diverted, the flows enter Prado Wetlands through the East basin traveling parallel with Basin A' (40% of the flow) and A (60% of the diverted flow), as water leaves these Basins, it gravity flows to North (B') and South (B) (47).

North (B') and South (B) contain ten sets of 2-foot deep (deeper through and shallow bars have been constructed to ensure vertical mixing) sub-basins that are arranged in such a manner that they receive 10% of the flows sequentially (47). Effluent from B and B' combines in the Cattail Channel where they flow to sub-basins C and finally discharge into Chino Creek. The flow rate through the wetlands is maintained at ~100 cubic feet per second (cfs) and takes about 62 hours to move through the entire basin system. The overall purpose of the system is to capture as much of the flows allocated to OCWD while providing ample residence time through the system to allow the natural purification process to occur. An overview of the wetlands and its basins are shown in Figure 11.

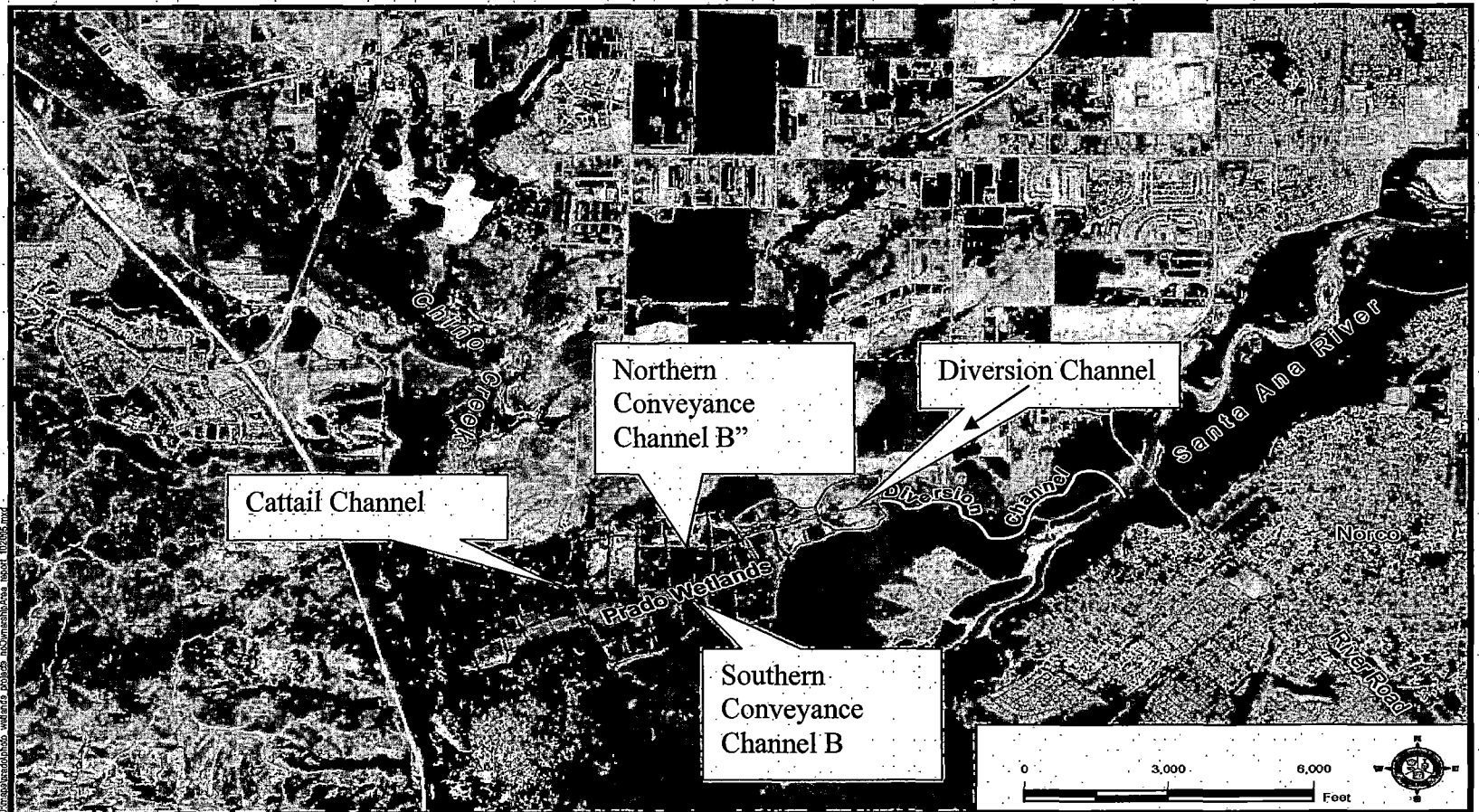


Figure 11. Vicinity Map of Prado Wetlands Detailing Basins

CHAPTER SIX

COST-BENEFIT ANALYSIS

Decision Making Process

The principles of a cost-benefit analysis (CBA) are not new, in fact, prior to making any decision of reasonable importance, the pros and cons are often weighted to some degree. When faced with an issue of uncertainty as a child, my parents repeatedly instructed me to divide a paper in half, labeling one side as "positive" and the other as "negative", sending me off to my room to appropriately fill down the columns until a respectable decision could be reached. In other words, the opportunity was given to recognize that the consequences generally outweighed that of the pros. Needless to say, I went about my youth and young adult years using a pencil as a decision making tool, often electing to opt out of the activity after having seen, in writing, under the negative heading, "my parents will kill me."

As an adult, I have become to realize that this novel concept or the "particular cleverness" of my parents was actually Benjamin Franklin's concept of Prudential Algebra - the act of applying the precision of algebraic quantities

to the weight of reason by breaking the problem up into separate and comparable parts (49).

Applying this algebraic approach to problem solving, Franklin would evaluate each side of the equation and cross out ideas that either had an equal negative and positive reason, or multiple reasons whose total sum would equal the weight of an idea on the opposite column, until such time that he could no longer cross cancel. At that point, Franklin felt a fair evaluation and judgment could be reached regarding the issue of importance (49).

Although this advice features steps that can be taken for making a decision of personal consequence, it highlights the strategy used for conducting a cost-benefit analysis. That is, "a systematic cataloguing of impacts as benefits (pros) and costs (cons), applying a monetary valuation (assigning weights), and finally assessing the net benefits of the proposal relative to the status quo (net benefits equal the benefits minus the costs) (49)". For a CBA to be effective, it must be non-biased, including all costs and benefits to the society as a whole, not simply isolated to the negative and positive feelings of the evaluator. As such, CBAs often referred to as social cost-benefit analyses because they quantify societal

priorities in monetary terms, while aiding the policy maker's decision making process by measuring the value of the policy. In other words, a CBA provides the decision maker with the power to elect the option offering the fewest consequences or the greatest foreseeable benefit to the most people. The mathematical expression, where B = social benefits, C = social costs, and NSB = net social benefits, is as follows (49):

$$NSB = B - C \quad (24)$$

As a means of quantifying the expenses involved in tertiary treatment, the previous chapters have detailed the chemistry of denitrification in terms of the processes involved in treatment. This chapter will focus on the costs associated with constructing new facilities, renovating old facilities to meet current regulatory standards, and the costs of treating wastewater. If we simply stopped here, there would be no question as to what treatment method (wetlands or the wastewater treatment facility) offered the most cost efficient means of denitrifying wastewater. However, the fiscal consideration of denitrification should not be the only item evaluated when performing a CBA, all benefits and cost must be weighted to provide a just assessment. As such, the

remainder of this project will use the knowledge gained from previous chapters to develop a CBA for the denitrification of wastewater utilizing wetlands vs. wastewater treatment facilities.

Although wetlands and publicly owned treatment works (POTWs or wastewater treatment facilities) are both effective at treating and removing constituents other than nitrogen, in an effort to simplify this study and to eliminate multi-facet variables, this project will narrow its scope to the removal of nitrogen from wastewater. All other constituent removal, from methods employed to remove nitrogen, will be considered a benefit that would ultimately reduce the operational costs of that particular facility.

To begin, the types of costs (implementation, ongoing, and intangibles) incurred by each facility will be assessed for the purposes of calculating net costs. Implementation costs, or one-time costs, are defined in terms of the design criteria or the monies allocated for the technological upgrade required of an existing treatment facility. Ongoing costs will be assigned to the continued "up-keep" of the facility (e.g., operation and maintenance, permitting, treatment costs, etc.). Intangible costs will

be designated to monies allocated for absorbing the cost of change (i.e., the budgetary sacrifices necessary to cover new costs) and the fees associated with land acquisition. Following a standard CBA model, benefits will be categorized into contingencies that reduce the costs, increase the revenue, improve the standard of living (intangible benefits), and/or reduce the risks associated with the project implementation.

Calculating Costs of Tertiary Treatment: Wastewater Treatment Facilities

As previously noted, implementation costs are the one-time fees needed to meet project start-up goals. One-time fees would include monies allocated for land acquisition, design, construction, and the attainment of permits. The average wastewater treatment facility typically spends \$200 million renovating their facility to meet current nitrate standards, while a facility opting to use wetlands as a means of denitrification can spend as little as \$400,000 on design and construction costs (45).

Since it is well understood that construction costs tend to vary significantly according to the intricacies involved with the system to be constructed, an overview of

various POTWs and wetlands are provided in the text to follow. Each of the treatment works discussed within this section and the subsequent sections are to provide examples as to how each facility has approached denitrification. Approaches to denitrification will range from facility upgrades to the complete design and construction of new treatment systems, including those facilities utilizing green technology.

Examples of Construction Costs: Wastewater Treatment Facilities

The State Water Resources Control Board (SWRCB) conducted a CBA on the fees associated with denitrification for the purposes of meeting current TMDL requirements for the Calleguas Watershed. From their study, it was determined that although the construction of new facilities was more costly than attempting to convert old facilities to current standards, the benefits offered by new facilities superseded the increased construction costs (50).

The studied found that to convert an existing POTW into a tertiary treatment facility for the denitrification of wastewater, the activated sludge processes, aeration speed, type of bacteria present within the sludge, and

solid residence times had to be adjusted each time nitrate levels exceeded discharge standards (50). Although the benefit associated with this type of conversion was cost effective (no new facilities were constructed and it did not result in a significant change to the overall operation and maintenance costs associated with the facility), operators experienced significant difficulties with conversion systems due to inconsistencies in removal rates and the inability to control the denitrification process (50). Each time denitrification was to be utilized, the system had to be "prepped" to handle the increased ammonia concentrations, unexpected increases resulted in large quantities of wastewater leaving the facility untreated. The conversion system was incapable of meeting instantaneous treatment needs resulting in exceedances to effluent water quality standards for nitrate (50).

Tables 5 and 6 provide a few additional examples of the monies appropriated within California's SWRCB, Region 4 watershed, for meeting nitrification and denitrification expenses. Variances in expenditures were due in part to the size of the treatment facility utilized, type of denitrification employed, and the energy consumption associated with treatment practices.

Table 5. Monetary Costs Associated with Nitrification.

POTW	PRESENT WORTH COSTS	CAPITAL COSTS	ANNUAL O&M
Hill Canyon	8,040,000	6,000,000	202,000
Simi Valley	8,100,000	6,000,000	211,000

Table 6. Monetary Costs Associated with Denitrification.

POTW	PRESENT WORTH COSTS	CAPITAL COSTS	ANNUAL O&M
Hill Canyon	14,020,000	4,170,000	930,000
Simi Valley	14,700,000	4,300,000	980,000
Camarillo	7,290,000	3,180,000	390,000 ¹⁵

¹⁵ Source: Tables 5 and 6 are reprinted from the State Water Resources Control Board.
http://swrcb.ca.gov/rwqcb4/html/meetings/tmdl/calleguas%20creek/02_0830/02_0830_Appendix_2.pdf (accessed October 27, 2007)

Indiana State Department of Health released a report in October of 2007 stating that homeowners and commercial business operators would bear the weight of replacing septic systems within the state to ensure that nitrate

standards were met. System wide septic upgrades, within Indiana, are expected to cost an average of 19.3 to 28.1 million dollars. The average homeowner (three-bedroom home) is expected to spend between \$6,500 and \$11,500, depending on the denitrification system that is to be implemented. Itemizations to the increased cost estimates are as follows:

- (1) New septic system design costs, \$8.3 M-8.5 M
- (2) Denitrification costs, \$10.6 M-\$15 M plus \$345,000 to \$430,000 per year for maintenance; and
- (3) Septic tank modification costs, \$93,500 - \$4.2 M (51).

Examples of Construction Costs - Green Technology:
Wastewater Treatment Facilities

The two facilities to follow, Washington DC's Blue Plains Wastewater Treatment Facility and Oklahoma's Biological Denitrification Plant, provide examples of a large and small facility utilizing green technologies for meeting current denitrification standards, while employing foresight into addressing emerging air quality regulations.

Washington D.C. The Blue Plains Wastewater Treatment Facility (BPWTF), shown in Figures 12a and 12b, is 150

acres and, at present time, is the largest wastewater treatment facility in the world (52). Its current treatment capacity is 370 million gallons per day, with a peak capacity of 107.6 billion gallons per day (52). Implementation of the \$101,200,000 EPA award winning methanol system reduced nitrogen levels by 49%, and reduced the cost of denitrification from \$4.00/lb to 0.50-0.60/lb (53). In having done so, the nitrogen load that Chesapeake Bay was expected to receive from 1995 to 2003 was reduced by 7 million pounds per year (52). The treatment works has been so successful that an additional \$76-80 million was appropriated to expand the facility to achieve greater nitrate reduction while heightening efficiency and lowering energy costs (52).



Figure 12a. Blue Plains Wastewater Treatment Facility.

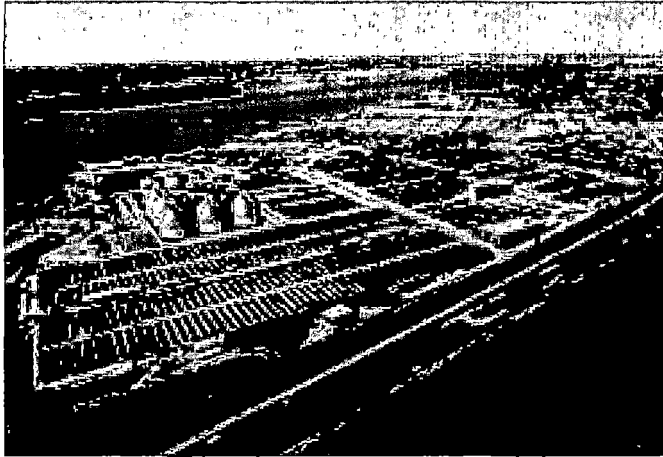


Figure 12b. Blue Plains Wastewater Treatment Facility¹⁶.

Coyle, Oklahoma. As a comparison, on a much smaller scale, the City of Coyle, Oklahoma, operates a 150 m³/day (39,626 gal/day) biological denitrification plant to meet the drinking water standards for a small community consisting of 290 residents and 400 school children. Since its operation, the denitrification plant has reduced nitrate levels from 16 ppm to <8ppm (55).

Between December 4, 1998 and February 24, 1999, total cost of water treated at the denitrification facility was \$0.21/cubic meter (0.79/1000 gallons) accounting for \$11,426/year (55). The average operation and maintenance

¹⁶ Source: Tables 12a and 12b are reprinted from DC Water and Sewer Authority. <http://www.dcwasa.com/about/facilities.cfm> (accessed February 23, 2008)

cost was \$0.15/cubic meter (0.56/1000 gallons) or \$8,100/year. Operation and maintenance for this facility includes general operation costs, energy, and drinking water disinfection costs (55). Figure 13 provides an overview of Coyle's water treatment system.

Table 7 provides a break down of the BPWTP and Coyle's Biological Denitrification Plant.

Table 7. Comparison of Blue Plains Wastewater Treatment Facility and Coyle Biological Denitrification Plant.

Facility	Treatment Capacity	Construction Costs	Nitrate Reduction	Operation and Maintenance	Method Employed
Washington	107.6 BGD	\$101,200,000	7 million lbs/yr	NA	Methanol Denitrification
Coyle	150 m ³ /day 39,626 GPD	NA	16-<8 ppm	\$8,100/year	Biological Denitrification

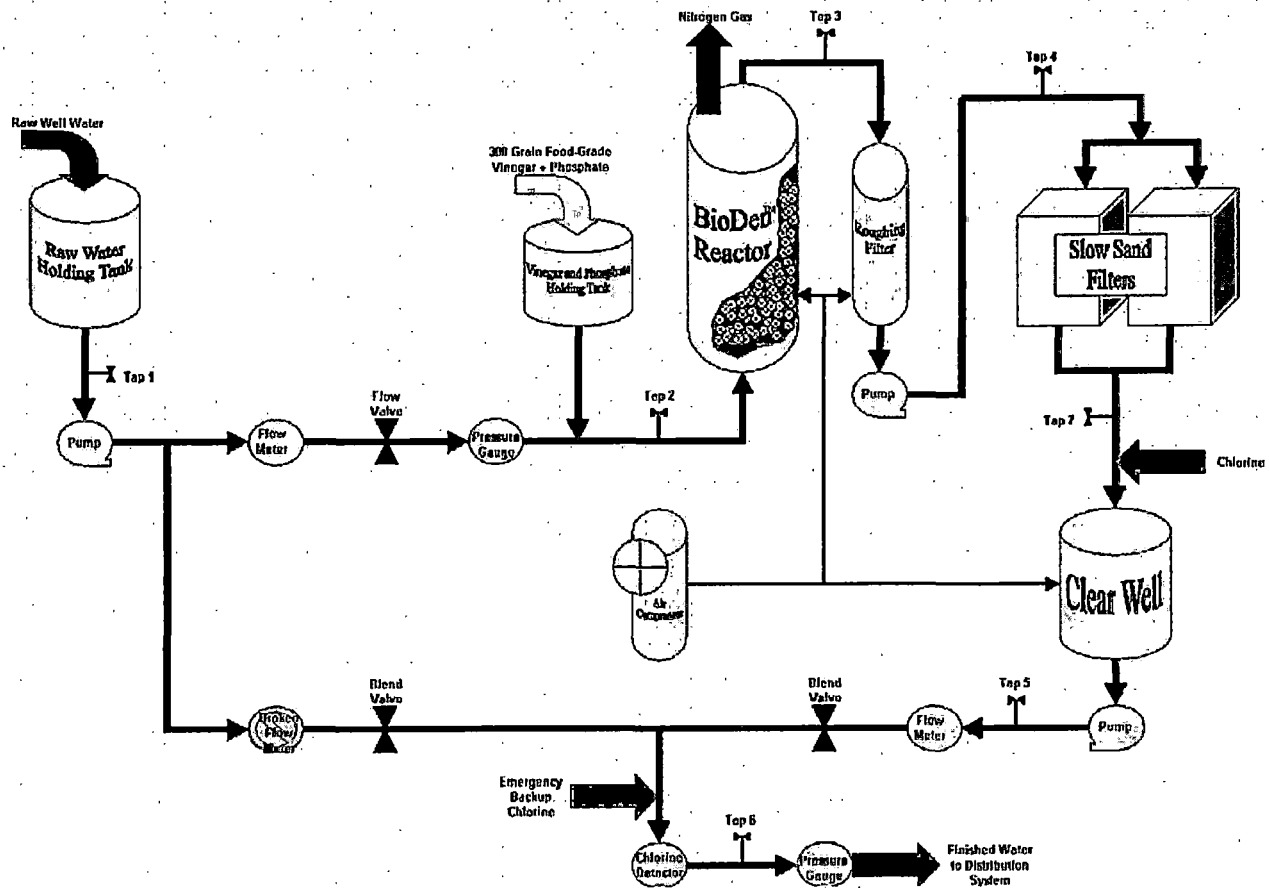


Figure 13. Coyle, Oklahoma, Water Treatment System¹⁷.

¹⁷ Source: Reprinted from Sanders, D.A.; Veenstra, J.N.; and Blair, C.D. Evaluation of a full Scale Biological Denitrification System for the Treatment of Drinking Water. Environmental Institute, Oklahoma State University.

Calculating Costs of Tertiary Treatment: Wetlands

It is typically more cost-effective to develop a treatment wetlands then it is to construct a POTW. On the average, agencies will spend 50-90% less on wetlands development than on the construction of a POTW due to the material savings (there is no concrete or steel to purchase) alone. Based on an economical and financial analysis of municipal systems employing tertiary treatment wetlands, conducted by the government of Canada, the construction of treatment wetlands generally ranged between \$6,000-\$300,000/hectare, with the average wetlands costing approximately \$100,000/hectare (1 hectare = 2.47 acres) (57).

Operation and maintenance of a wetlands generally pertains to restoration, however, depending its size, the average restoration could cost between \$3,500-80,000/acre (57). This includes the costs associated with soil and biomass replacement, grading, and repair of eroded slopes (57).

For the most part, the cost attributed to wetland construction is proportional to the number and size of treatment cells needing to be used. Cities within the

United States typically spend \$35,000-150,000/acre on wetland projects (58). Figure 14 shows the general schematics of treatment wetlands.

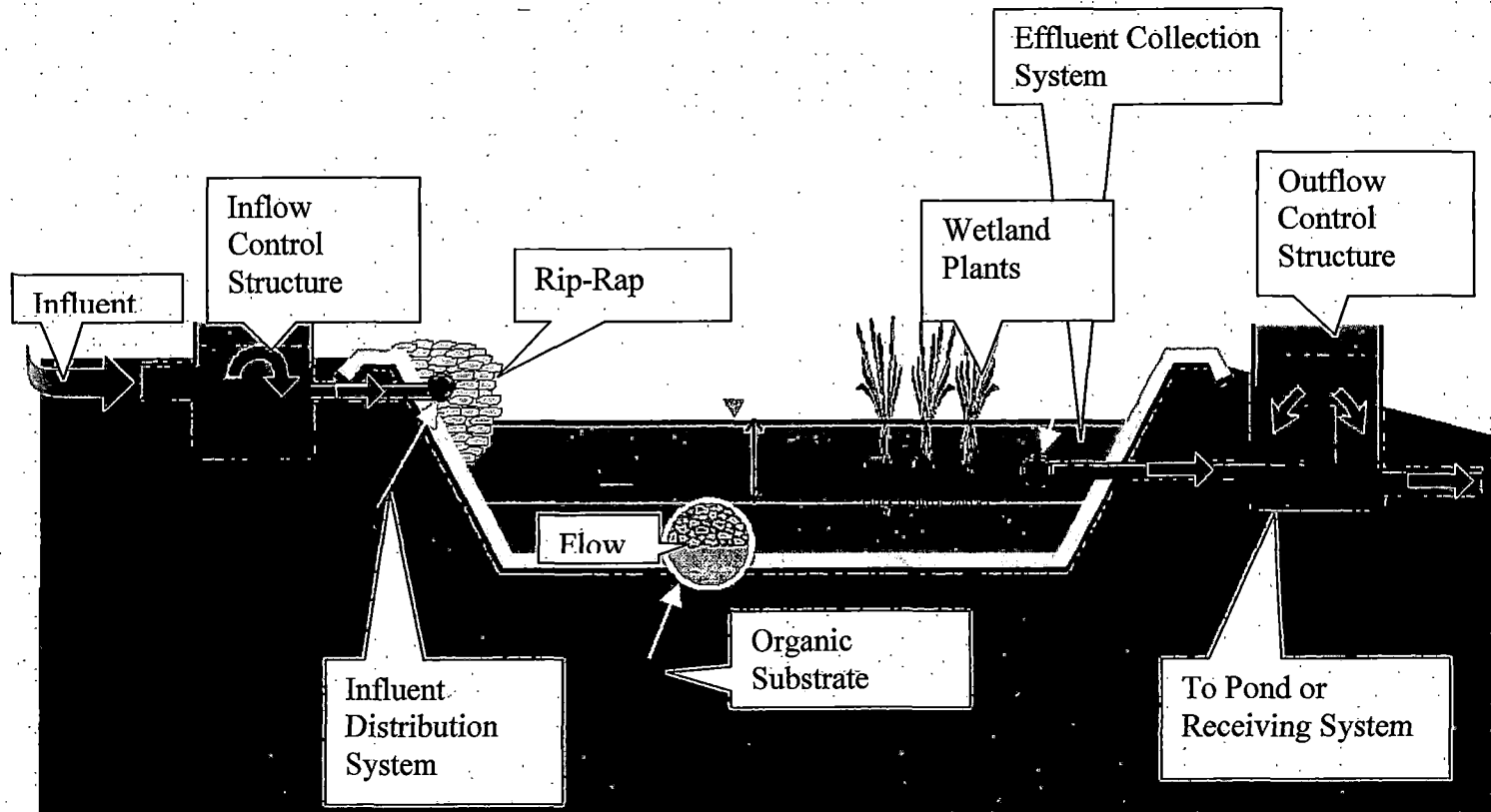


Figure 14. Free Water Surface Flow Wetlands¹⁸.

¹⁸ Source: Reprinted from Brookhaven National Laboratory. <http://www.bnl.gov/erd/peconic/factsheet/wetlands.pdf> (accessed October 28, 2007)

Examples of Construction Costs:
Constructed Treatment Wetlands

San Jacinto, California. Hemet San Jacinto Multi-Purpose Constructed Wetlands and Wetlands Research Facility, 45-acre wetlands, were designed to provide additional treatment to secondary wastewater from the San Jacinto Valley Regional Water Reclamation Facility. This wetland system was specifically designed to expand and enhance their reclaimed water program. Total project costs are presented in Table 8.

Table 8: Design and Construction Costs for the Hemet San Jacinto Multi-Purpose Constructed Wetlands and Wetland Research Facility.

COSTS ASSOICATED WITH INITIAL DESIGN AND CONSTRUCTION	COST
Multipurpose Wetlands	\$1,071,216
Multipurpose Wetlands Pipeline	\$24,753
Wetlands Planting	\$108,324
Wetlands Upland Area Landscaping	\$90,876
Wetlands, Water Hauling & Saline Marsh at WRF	\$136,971
Initial Design and Construction Costs	\$1,432,140 ¹⁹

¹⁹ Source: Reprinted from CDM. Background and Setting. *A User's Treatment Guide to Treatment Wetlands*; Santa Ana Watershed Project Authority: Riverside, CA 2004.

Subsequent modifications to the design resulted in an additional appropriation of \$412,000, bringing the overall project cost to \$1,844,000. Construction of this project was high due to the tremendous amounts of earthwork having to be completed to bring the deep storage ponds level with the landscape surface (12).

To assist with project start-up costs, Eastern Municipal Water District (EMWD) received grant funds totaling \$1,133,044 from the U.S. Bureau of Reclamation (12). Implementation of this wetlands cost EMWD \$710,956.00. Estimates for its continued upkeep include a bi-annual mechanical seals replacement of \$1,500 and weekly water sampling (\$170/week).

City of Ontario, California. The City of Ontario, California, is currently in the project approval phase of a \$20 million dollar natural treatment system for meeting stormwater quality objectives. The 200-acre, off-site, regional treatment facility will function to minimize long term water quality impacts attributed to impervious surfaces expected from new development and current water quality impacts associated with the existing community. Although not specifically designated for the treatment of nutrients,

the regional facility will mitigate stormwater runoff impacts, thereby improving downstream water quality.

Phoenix, Arizona. The Tres Rios Constructed Wetlands in Phoenix, Arizona, is an 11-acre pilot project/demonstration site for treating secondary effluent from the 91st Avenue Wastewater Treatment Plant and is the first step in a more expansive wetlands project. In 1995, estimates for facility upgrades were expected to cost the City \$628 million, as an alternative they opted to spend \$3.5 million building a wetlands demonstration site. Successes experienced with this site, and others like it within Arizona, have resulted in plans to allocate an additional \$80 million for its expansion, enabling it to accommodate wastewater from other facilities within the Phoenix vicinity.

Table 9 presents an overview of the construction and operational costs of the above referenced wetlands projects. Please note: Ontario Wetlands has not been constructed, the monetary values presented in Table 9 are proposed costs.

Table 9. Comparative Costs of Constructed Wetlands within Arizona and California

<i>WETLANDS</i>	<i>SIZE</i>	<i>COST/ACRE</i>	<i>O&M</i>	<i>TOTAL COST</i>
<i>Prado</i>	465-acres	\$10,753		5,000,000
<i>San Jacinto</i>	45-acres	\$41,000	\$12,000	\$1,844,000
<i>Ontario</i>	200-acres	\$100,000	Not yet implemented	\$20,000,000 (proposed)
<i>Tres Rios</i>	11-acres	\$318,181	NA	3,500,000

Calculating Costs of Tertiary Treatment:
Intangibles

Albeit that project design and construction can be quite costly, the process of acquiring land may be considered an intangible cost. At any point within the design phase, either facility may need to include the acquisition of land into their overall costs. This will be assessed as an intangible cost due to the inability to place a clear monetary figure on land given that its value varies significantly by geographical region and the current state of the housing market. It is for this reason that land acquisition has not been represented in the overall design and construction costs. It should be noted that regardless of the facility chosen for meeting tertiary

treatment standards, municipalities will generally utilize publicly owned lands that are heavily subsidized. As a result, the true value of publicly owned land cannot be assessed; therefore, monies designated for land acquisition will not be analyzed as a part of this project.

It is worth noting that depending on the size of the system being constructed, wetlands typically require more land than wastewater treatment facilities. This fact alone may make wetlands economically unfeasible for many municipalities due to the ever-increasing value of land, intense land usage within a city, and the competing need to utilize undeveloped land as a means of generating city revenue. However, alternatives may be available to offset some of these costs, such as the ability to sell mitigation credits to developers for some of the wetland acreage with a mitigation bank.

In this region, a developer whose site is environmentally sensitive can buy mitigation credits to offset environmental damage as a way of moving forward with their project. In the Santa Ana Watershed, the typical developer will pay an average of \$50,000 per acre of land requiring mitigation. Without the ability to apply this credit, increased restriction on environmentally sensitive

areas would render much of their site un-suitable for development.

Intangible Costs:

The Costs Associated with Methane Emissions

The incidence of global climate change may be counted as an intangible costs for both facilities due to their known contribution to the enhanced greenhouse effect.

WWTFs emit carbon dioxide, water vapor, and to some extent methane, while wetlands are known to be a significant source of methane emissions.

Wetlands are the largest natural source of methane to the atmosphere, accounting for approximately 20% of the global emissions of methane (59). The International Panel for Climate Change (IPCC) estimates that methane has a global warming potential (GPW) of 23 relative to CO₂ (60). With more facilities electing to use natural treatment for meeting denitrification objectives, the incidence of methane emissions are expected to increase.

As a component of the global budget of carbon, there are no feasible means of determining the costs associated with methane, as such; methane will be evaluated in term of energy consumption, given that most environmental problems can be attributed to energy usage. Since both facilities

have the capability of contributing significant quantities of greenhouse gases into the environment, wastewater treatment facilities designed to capture and reuse the methane generated from anaerobic digesters will be given a credit for the portion of their energy use that is involved in the reuse process.

Depending on whether the POTW utilizes anaerobic or aerobic processes determines whether the facility will generate methane gas. Anaerobic digesters utilize microorganisms to break down organic matter, in the absence of oxygen, methane is produced. Air quality standards require wastewater treatment plants, utilizing anaerobic digesters, to capture the methane produced from its anaerobic treatment processes. Once captured, the methane is either returned to the boiler to maintain the temperature of the digester or it is flamed. Products of the flaming process, shown in reaction 25 produce carbon dioxide and water vapor.



Each combustion product is considered a greenhouse gas that is capable of contributing to the enhanced greenhouse effect. If the remaining gas is burned at the flame the

carbon dioxide and water vapor would be subsequently released into the atmosphere. Since the capture and reuse of methane reduces the emission of greenhouse gases (methane, carbon dioxide, and water vapor), this will be evaluated as a cost reduction benefit for wastewater treatment facilities.

Intangible Costs:

The Costs Associated with Methane Emissions -
Wastewater Treatment Facilities

The facilities discussed within this section utilize green technology as a means of meeting treatment needs for denitrification and air quality standards. Typically green technology are associated with higher start-up costs, however, the monies saved on energy usage ultimately result in the payback of the increased expenditures.

Palmdale, California Palmdale Reclamation Plant (PRP), City of Palmdale, California, spent \$1.9 million on its combined heat and power (CHP), or cogeneration, fuel cell system to reduce the energy costs of operating its 10 million gallon per day (MGD) wastewater treatment facility. CHP systems are energy efficient and cost effective in that one source (anaerobic digester) is used to produce, catch, and reuse the power and heat attained from its (anaerobic digester) operation. PRP captures the biogas flow produced

from the digester and uses it as a "free" energy source to generate most of the fuel needed to operate its 250 kW fuel cell. Figure 15 provides a schematic of the typical cogeneration system.

Typical CHP System Configuration at WWTFs

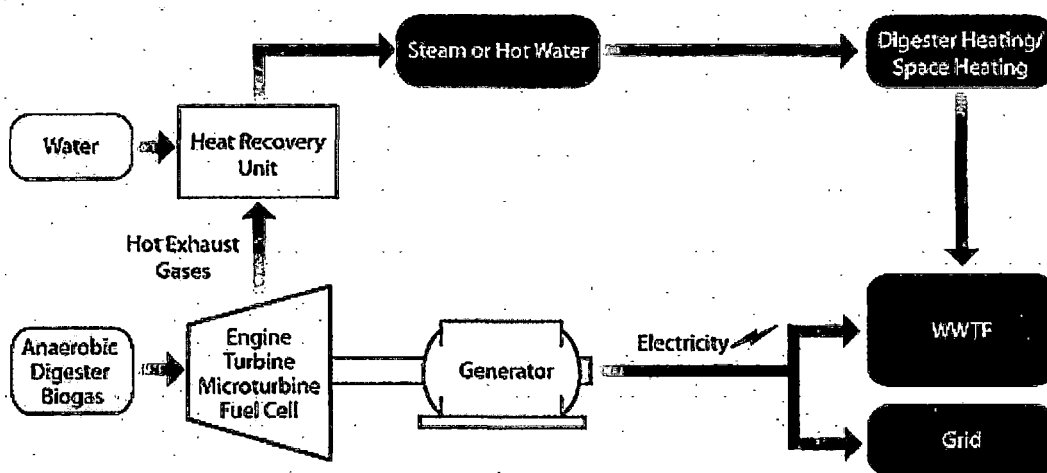


Figure 15. Combined Heat and Power System²⁰.

The general engineering rule of thumb is that for every 4.5 MGD of wastewater processed, 100 kW of electricity and 12.5 million British thermal units (Btu) can be produced per day (62). Generating 75 cubic feet of methane per minute, PRP uses approximately 60% of the

²⁰ Source: Reprinted from the EPA. Wastewater Fact Sheet. http://epa.gov/chp/markets/wastewater_fs.html (accessed February 23, 2008)

biogas produced to render 225kW of electricity per day
(63).

$$\left(75 \frac{ft^3}{min}\right) \left(60 \frac{min}{hr}\right) \left(24 \frac{hr}{day}\right) \left(365 \frac{day}{year}\right) = 39,420,000 \frac{ft^3}{year} \quad (26.1)$$

Of the $39,420,000 \frac{ft^3}{year}$ of biogas generated, 60% of this gas

can be reclaimed as usable methane gas:

$$(39,420,000 ft^3)(0.60) = 23,652,000 \frac{ft^3}{year} CH_4 \quad (26.2)$$

Therefore, $23,652,000 \frac{ft^3}{year}$ of methane have been

reclaimed through the use of the fuel cell. Reusing the methane prevents its subsequent release into the environment and reduces the GWP that would have been attributed to this facility had green technology not been used. Since this facility has protected the atmosphere from receiving approximately 24 million cubic feet of methane per year, this will be viewed as a benefit to PRP and a credit will be given to the facility for its innovativeness.

The fuel cell has been attributed to saving the City \$227,000.00 annually in energy costs, shown in equations 26.3-26.5 (64).

$$(225kW)\left(24\frac{hr}{day}\right) = 5400\frac{kWh}{day} \quad (26.3)$$

$$\left(5400\frac{kWh}{day}\right)\left(\frac{\$0.115}{kWh}\right) = \frac{\$621.00}{day} \quad (26.4)$$

$$\left(\frac{\$621.00}{day}\right)\left(365\frac{day}{year}\right) = \frac{\$226,665}{year} \quad (26.5)$$

Without the re-use of methane, at a net cost of \$0.115/kWh, the City's annual electrical bill would have been \$251,850.00 to operate their 250 kW cell. Instead, the City receives \$0.115 credit for its methane re-use and PRP pays a net cost of \$25,185.00/yr, demonstrated through the use of equations 26.6 to 26.9) to operate its combined heat and power plant.

$$\left(250\frac{kW}{day}\right)(24hr) = 6000\frac{kWh}{day} \quad (26.6)$$

$$\left(6000\frac{kWh}{day}\right)\left(\frac{\$0.115}{kWh}\right) = \frac{\$690.00}{day} \quad (26.7)$$

$$\left(\frac{\$690.00}{day}\right)\left(365\frac{day}{year}\right) = \frac{\$251,850.00}{year} \quad (26.8)$$

$$\text{Net Savings} = \$251,850.00 - 226,665.00 \quad (26.9)$$

$$\text{Net Savings} = \$25,185.00/\text{yr}$$

The remainder of the gas that does not escape the system and that was not utilized in the fuel cell is returned to the boiler as a means of maintaining the digester's

temperature. The fuel cell is attributed as having zero methane emissions, its capture and reuse has effectively reduced Palmdale's annual CO₂ emissions, from the burning of methane, by 778 tons (61).

Amberdeem, Minnesota. Albert Lea Wastewater Treatment Facility installed a 120 kW CHP system employing four Capstone C-30 microturbines to maintain the temperature of its anaerobic digester and some of the facility's space heating requirements (61). Prior to its \$250,000.00 implementation, the City's monthly electric bill for its 12 MGD facility was \$30,000.00. Of the 3,600,000 kWh/yr used, 800,000 kWh/yr (65) is gained from the reuse of 75,000 cubic feet per day of biogas (60% of this gas is methane).

$$\left(75,000 \frac{ft^3 \text{ biogas}}{day}\right) (60\% CH_4) = 45,500 \frac{ft^3}{day} CH_4 \quad (27.1)$$

The general engineering rule of thumb states, when employing the use of microturbines, every 1.0 ft³ of digester gas provides 2.2 watts of power generation (62). Using equation 27.2, the cubic feet of methane used was calculated.

$$\left(800,000 \frac{kWh}{yr}\right) \left(1000 \frac{watts}{kW}\right) \left(\frac{1.0 ft^3}{2.2 \text{ watts}}\right) \left(\frac{1 \text{ day}}{24 \text{ hr}}\right) \left(\frac{1 \text{ yr}}{365 \text{ days}}\right) = 41,511 \frac{ft^3}{day} \quad (27.2)$$

Of the 45,500 ft³ of methane produced, equation 27.2, 41,511 ft³ is reused at a net cost of \$0.05/kWh.

$$\left(41,511 \frac{ft^3}{day}\right) \left(\frac{2.2 \text{ watts}}{1 ft^3}\right) \left(\frac{1 kW}{1000 \text{ watts}}\right) = 91.3 \frac{kW}{day} \quad (27.3)$$

$$91.3 kW \left(24 \frac{hr}{day}\right) = 2191.2 \frac{kWh}{day} \quad (27.4)$$

$$\left(2191.2 \frac{kWh}{day}\right) \left(\frac{\$0.05}{kWh}\right) = \frac{\$109.56}{day} \quad (27.5)$$

$$\left(\frac{\$109.56}{day}\right) \left(365 \frac{days}{year}\right) = \frac{\$40,000}{year} \quad (27.6)$$

The use of the microturbine system is expected to result in a \$40,000-\$60,000 annual savings, with a two year payback to the city and 4-6 years payback for the total cost of the project (65).

Sioux Falls, South Dakota. Sioux Falls operates a 19.7 MGD electrical cogeneration plant, which utilizes methane gas from its sludge digestion system. In 2003, 22.5% of the total electrical power used at the facility was derived from its cogeneration plant. In 2006, the digester was effective at capturing 83,342,500 ft³ of gas, 80% methane, producing 3,371,285 kWh of power, accounting for 25% of the total electricity used at the facility (66). The Sioux Falls Treatment Facility typically uses 24,000-

32,000 kW/day, at an average cost of \$0.048 kWh (66). At this rate, the Sioux Treatment Facility would pay approximately \$1152.00-\$1536.00 per day in energy costs. Utilizing this system, the City is able to recover 25% of the energy used, saving \$105,120.00 to \$140,160.00 per year in energy costs and preventing the annual release of 1,416,049.04 m³ - 1,533,997.91 m³ of methane that would have otherwise contributed to the enhanced greenhouse effect.

Table 10 provides an overview of the WWTFs discussed in this section.

Table 10. Comparison of Combined Heat and Power Systems

POTW	Construction Costs	System Employed	Size (mgd)	Biogas Produced (ft ³ /year)	CH ₄ Produced (ft ³)	Energy Created (kWh/day)	Cost/(kWh)
PRP	\$1.9 million	CHP 250 kW Fuel Cell	10	39,420,000	27,594,000 ft ³ /yr - 31,536,000 ft ³ /yr	225	\$0.12
Albert Lea	\$250,000	microturbines	12	16,425,000	45,000 ft ³ /day	2200	\$0.05
Sioux	NA	Cogeneration	19.7	83,342,500	66,674,000 ft ³ /year	9236.4	\$0.048

As previously noted, wastewater treatment facilities are required to either capture and reuse or flare the methane produced by the digesters, as such, facilities employing capture and reuse techniques will be given a credit for the energy required to capture and reuse the gases that would have ordinarily been released as carbon dioxide.

The Sioux facility annually captures 83,342,500 ft³ of digester gas, 80% or 66,674,000 ft³, is available for use as methane gas. At \$0.048 dollars per kWhr, the City would have paid an additional \$161,821.68 to combust the methane to carbon dioxide and water. Incorporating their cogeneration plant, the Sioux Treatment Facility generated 3,371,285 kWh of electricity through the reuse program. However, the escape of 4.24×10^{-5} Tg of CO₂ equivalents reduces their savings by \$7132.27 resulting in a net saving of \$154,689.00.

The City will receive a credit of its net savings for the re-use of biogas in its cogeneration fuel cell facility. In addition to the savings earned from the reuse of methane, credit will also be awarded for the monies designated for the implementation of the co-generation plant.

Table 11 summarizes the annual and net savings, in terms of methane production and consumption, of each treatment facility outlined in this section.

Table 11. Costs of Operating an Anaerobic Digester

POTW	Implementation Fees	Size (mgd)	Methane Production	Tg of CO ₂ Equivalent	Net Savings
PRP	\$1.9 million	10	2.7X 10 ⁷ ft ³ /year	3.58X10 ⁻⁴	\$227,000
Albert Lea	\$250,000	12	4.5X10 ⁴ ft ³ /day	1.45X10 ⁻⁵	\$40,000
Sioux	NA	19.7	6.6X 10 ⁷ ft ³ /year	4.42X10 ⁻⁵	\$154,689

It should be noted that of the 1,066 wastewater treatment facilities in the US having capacities greater than 5 MGD, the suggested minimum size for mitigating implementation costs with cost/energy efficiency, only 50% operate anaerobic digesters. Of these, only 19% utilize their digester gas, it is assumed the remaining facilities flame their gas, emitting substantial quantities of CO₂ and H₂O vapor into the atmosphere.

With this in mind, treatment facilities of similar capacity to the Palmdale Reclamation Plant would emit 3.15×10^{-4} Tg of CO₂ equivalents, in addition to the methane that escapes the flame unburned. The 2006 EPAs inventory of US Greenhouse Gases report shows an annual average of methane emissions from POTWs in 2003 to be 36.8 TgCO₂, while wetlands accounted for approximately 145Tg of methane per year globally (67). As stated previously, wetlands account for 20% of the global emissions of methane and 76% of the natural sources of methane emissions.

Intangible Costs:

The Costs Associated with Methane Emissions -
Constructed Wetlands

The increased utilization of constructed wetlands as a cost-effective means of treating wastewater, has focused much attention on whether one environmental problem is taking precedence over that of another (i.e., is the prevention of water pollution taking priority over issues pertaining to increased emissions of greenhouse gases and their contribution to global warming?). Other concerns pertain to whether the nutrient enriched wastewaters would attenuate greenhouse gas emissions. However, studies (68) seem to indicate that increased nutrient loading does not seem to negatively affect greenhouse gas emission rates,

rather it is likely attributed to seasonal temperature changes (air, water, and soil), the types of plants utilized, depth, and algal cover. Albeit that seasonal temperature can not be changed, the findings do seem to indicate that wetland design and plant management can reduce the incidence of gas emissions by choosing plants that promote bacterial methane oxidation.

In its present state, that being without the use of algae emphasizing bacterial methane oxidation, the emission of greenhouse gases from constructed wetlands in Europe were studied. Results from these studies (69) demonstrate that Lakeus Wetland, Lakeus Central Treatment Plant in Kempele, Finland, contributes an average emission of 290mg/day/m² of methane during its seasonal high, the summer months.

For the purposes of comparing emission rates with that of wastewater treatment facilities, the Lakeus Wetlands was chosen due to it having the largest capacity of the lakes studied. Receiving chemically and biologically treated wastewater, the Lakeus Central Treatment Plant discharges 3,624 m³/day, approximately 1 million gallons per day, to the Lakeus Wetlands. The seasonal high was selected as a conservative number for estimating methane emissions, the

yearly emission rate. The conservative figure was calculated to be 1.059×10^{-10} Tg/year/m² CH₄.

$$\left(290 \frac{mg}{day}\right) \left(\frac{1g}{1000mg}\right) \left(\frac{1Tg}{1 \times 10^{12}g}\right) \left(365 \frac{days}{1year}\right) = 1.059 \times 10^{-10} \frac{Tg}{(yr)(m^2)} CH_4 \quad (28)$$

Multiplying by 23, the relative CO₂ equivalents was calculated to be 2.43×10^{-9} Tg/yr/m². Since the smallest wastewater facility evaluated was 10MGD, the CO₂ equivalent was multiplied by a factor of ten to approximate the expected emission rates from wetlands treating a comparable effluent load.

The expected emission rate from a similar size wetlands, during the summer months, would be 1.05×10^{-9} Tg/yr/m² of CH₄ or 2.43×10^{-8} Tg/yr/m² CO₂ equivalents. This calculated figure is extremely conservative and represents the worst case scenario of methane emissions from constructed treatment wetlands. To convert this amount of methane to CO₂ and H₂O would cost a treatment facility \$5.79/yr/m².

$$\left(1.059 \times 10^{-9} \frac{Tg}{(yr)(m^2)}\right) \left(\frac{1.0 \times 10^{12}g}{1Tg}\right) \left(\frac{1moleCH_4}{16.043g}\right) = 66.01 \frac{mol}{(yr)(m^2)} CH_4 \quad (28.1)$$

$$PV=nRT \quad (28.2)$$

$$V = \frac{\left(66.01 \frac{\text{mol}}{(\text{yr})(\text{m}^2)}\right) \left(0.08206 \frac{(\text{L})(\text{atm})}{(\text{mol})(\text{K})}\right) (309.48\text{K})}{0.027\text{atm}} = 62,088 \frac{\text{L}}{(\text{yr})(\text{m}^2)} \quad (28.3)$$

$$\left(62,088 \frac{\text{L}}{(\text{yr})(\text{m}^2)}\right) \left(\frac{1000\text{mL}}{\text{L}}\right) \left(\frac{1\text{cm}^3}{1\text{mL}}\right) \left(\frac{1\text{in}}{2.54\text{cm}^3}\right) \left(\frac{1\text{ft}^3}{12\text{in}^3}\right) = 2,193 \frac{\text{ft}^3}{(\text{yr})(\text{m}^2)} \quad (28.4)$$

$$\left(2,193 \frac{\text{ft}^3}{(\text{yr})(\text{m}^2)}\right) \left(\frac{2.2\text{watts}}{1(\text{ft}^3)(\text{day})}\right) \left(\frac{1\text{kW}}{1000\text{watts}}\right) = 4.82 \frac{\text{kWday}}{(\text{yr})(\text{m}^2)} \quad (28.5)$$

$$\left(4.82 \frac{\text{kWday}}{(\text{yr})(\text{m}^2)}\right) \left(24 \frac{\text{hr}}{\text{day}}\right) = 115.8 \frac{\text{kWh}}{(\text{yr})(\text{m}^2)} \quad (28.6)$$

$$\left(115.8 \frac{\text{kWh}}{\text{day}}\right) \left(\frac{\$0.05}{\text{kWh}}\right) = \frac{\$5.79}{(\text{yr})(\text{m}^2)} \quad (28.7)$$

Therefore, \$5.79/yr/m² of a given wetlands, under the worst case scenario, Table 12, would be considered as an intangible cost assigned to wetlands.

Table 12. Costs of Operating A Wetlands

Wetlands	Size (mgd)	Methane Production	Tg of CO ₂ Equivalent	Net Cost/yr/m ²
Lakeus	10	1.05x10 ⁻⁹	2.43x10 ⁻⁸	\$5.79
Wetland	(adj)	Tg/yr/m ²	Tg/yr/m ²	

The figures presented for Lakeus Wetlands are methane emissions during the seasonal high (average emissions for

the summer months) under poor maintenance conditions. Using the geometric mean as a way of normalizing the data, the average 10MGD wetlands, accounting for the wetlands with the smallest contribution versus the largest contributor, would be 26.9 mg/day at a net estimated electricity cost of \$3,200/yr.

Table 13 provides a summary of the associated costs and benefits of methane treatment. The WWTFs received a credit for the monies allocated to methane capture, while the wetlands incurred a cost for the emission of methane into the environment.

Table 13. Costs of Operating an Anaerobic Digester

Treatment Facility	Implementation Fees	Size (mgd)	Methane Production	Tg of CO ₂ Equivalent	Net Savings/yr	Net Costs
PRP	\$1.9 million	10	2.7X 10 ⁷ ft ³ /yr	3.58X10 ⁻⁴ /day	\$227,000	
Albert Lea	\$250,000	12	4.5X10 ⁴ ft ³ /day	1.45X10 ⁻⁵ /day	\$40,000	
Sioux	Not Available	19.7	6.6X 10 ⁷ ft ³ /yr	4.42X10 ⁻⁵ /yr	\$154,689	
Lakeus Wetland	Not Available	10 (adj)	1.05x10 ⁻⁹ Tg/yr/m ^{2r}	2.43x10 ⁻⁸ /yr/m ²		\$5.79/yr/m ²

Intangible Costs:
The Costs Associated with National Pollutant
Discharge Elimination System Permits -
Wastewater Treatment Facilities

Additional costs that were classified under the category of "intangibles" were the fees associated with the NPDES permit. A wastewater treatment facility is designated as a point and non-point source pollutant. POTWs are classified as a non-point source due to its storm drain system. The collection system itself, storm drain, is considered a non point source since it receives runoff from various points within the City. Because POTWs and MS4s discharge into the river, and many rivers are 303(d) listed, they become a point source pollutant at their point of discharge, and are required to obtain an NPDES permit. The city's ability to participate in dual roles is especially significant since the construction of additional facilities increases impermeable surfaces resulting in excess stormwater runoff.

The City of San Bernardino, California, appropriated \$66,350.00 of its 2006-07 fiscal year budget for renewal of its NPDES permit, implementation of best management practices, and other costs associated with the permit, such as implementing and maintaining a stormwater education

program (70). Agencies holding a NPDES permit are required to designate a percentage of their budget for a stormwater education program. Depending on the permit and the state for which the permit is issued, stormwater education has the potential of being quite costly.

In California, the NPDES permit is the regulatory speak for the Clean Water Act, as such, agencies holding a California NPDES permit will spend a considerable amount of monies on their permit. To provide a comparison, the Neuse Wastewater Treatment Plant, Raleigh, North Carolina, is not required to implement a stormwater education program and only pays \$3,440.00 on the yearly renewal of their NPDES permit. Table 14 provides a range of the costs associated with NPDES permits.

Table 14. Costs Associated with National Pollutant Discharge Elimination System Permits

CITY	STATE	ANNUAL NPDES PERMIT COSTS
San Bernardino	California	\$66,350.00
Raleigh	North Carolina	\$3,440.00

Intangible Costs:

The Costs Associated with Impervious Surfaces -
Wastewater Treatment Facilities

Other cost associated with POTWs is its creation of impervious surfaces and its contribution to the heat island effect. As service areas are expanding due to increasing populations, POTWs have to treat larger quantities of wastewater under more stringent regulations. Consequently, facilities have to increase capacity to accommodate greater treatment needs and more specialized equipment. With each expansion the impervious area created by the larger facility attributes to excess runoff loaded with sediment and debris. Increased sediment loading negatively affects the assimilative capacity of waterways, thereby resulting in additional adverse harm to the watershed.

Unlike other land uses, POTWs are not required to maximize permeability and minimize impervious connectivity; thus acres of impervious surfaces are not only carrying sediment to storm drains, but areas also absorb tremendous quantities of heat ultimately contributing to the increased heat island effect. The increase in impervious footprint and the enhanced heat island effect are additional intangible costs attributed to POTWs, however, monies allocated to NPDES permits and construction will

effectively absorb this cost and it will not further be assessed.

Intangible Costs:

The Costs Associated with Vector Control -
Constructed Wetlands

Additional costs primarily associated with wetlands are those fees designated to vector control. The shallow stagnant water that characterizes wetlands is ideal for the breeding of mosquitoes. If left unabated, large populations of disease-carrying mosquitoes could result in adverse health effects and increased medical costs. Proper facility design, vegetative management, and facility maintenance can effectively reduce the occurrence of mosquitoes. As a result, monies allocated for operation and maintenance will include the cost of mosquito management and it will not further be assessed.

Calculating the Benefits of Tertiary Treatment:
Wetlands

Through the construction and implementation of Prado Wetlands, OCWD estimates nitrate removal expenditures of \$0.50/pound, compared to \$15.00/pound they would have spent had they employed conventional treatment (45). At a savings of \$14.50/pound the Prado Wetlands removes approximately 20

tons of nitrates per month from the 140,000 acre-feet of treated wastewater at an annual cost of \$120,000.00. Using nitrate removal technologies available to wastewater treatment facilities, OCWD would have allocated \$7,200,000.

Intangible Benefits:
Valuating Wildlife and Aesthetics -
Constructed Wetlands

Prado Wetlands not only functions to improve water quality, but it serves as an important layover to over 250 species of rare, threatened, and endangered migratory birds and water fowl and is environmentally sensitive habitat for indigenous species (e.g., least Bell's vireo, the western yellow-bellied cuckoo, and the Southwestern Willow Flycatcher). Providing mitigation for the opportunity to store water behind Prado Dam, OCWD in conjunction with USACOE and United States Fish and Wildlife Service (USFWS), increased the least Bell's vireo population from 20 to 200 breeding pairs through the restoration of current wetland habitat and allotting an additional 226 acres for habitat enhancement.

Given the inherent difficulty of assigning a monetary figure to aesthetics, recreation, and wildlife, a similar approach taken for methane emissions is used for wetlands.

Each year billions are spent on wildlife related activities, such as hunting, fishing, camping, etc. The 2006 National Survey of Fishing, Hunting, and Wildlife - Associated Recreation National Overview found that 87 million Americans (16 and over) participated in some type of wildlife related activity. The study found that 34 million Americans participated in fishing and hunting activities, which accounts for \$120.1 billion or 1% of the gross national product (71). Of the 34 million that were fishing and hunting, \$40.3 billion was spent on equipment, \$25 billion on trip related expenses, and \$10.6 billion on entrance fees, licenses, membership dues, and land leasing (71). The US Fish and Wildlife Service estimate that each sportsperson(s) spent an average of \$2,225.00 in 2006, while another \$45 billion was spent on activities relating to wildlife appreciation.

Although these figures include all fee related recreational activities, they do not simply state the importance of a single wetland on a region. However, it does emphasize the importance that recreation plays in our society and our economy. Wetlands are an important source of this revenue, as they provide homes to many of the game animals and are vital nesting grounds to migratory birds.

Intangible Benefits:
Valuating Wildlife and Aesthetics -
Florida Everglades

The Florida Everglades are one of the most recognized wetlands and ecological preserves in the nation, with over 1 million visitors a year; the local economy is boosted by the \$120 million that is generated from tourism (72) and another \$2.6 million from revenues gained from the Florida Everglades United States Postal Service stamp collection (73).

Intangible Benefits:
Valuating Wildlife and Aesthetics -
Prado Wetlands

Prado Park is one of nine regional parks in San Bernardino County, and the largest constructed wetlands in the United States, total combine park revenues from tourism account for \$6,282,959.00/year (74). The ability of wetlands to generate revenue assists in offsetting their operational costs and in some cases, may even assist in raising extra monies for projects within the watershed.

Intangible Benefits:
Valuating Wildlife and Aesthetics -
The Commercial Fishing Industry

Wetlands are an important element to the general health of the nation's economy. Accounting for \$19.8 billion of the US Gross National Product and 924,600 US jobs, 75% of the fish and shellfish supporting the fishing industry depend on estuaries at some point of their life cycle (75). Wetlands support estuaries by providing the basis of the food chain, maintaining the water quality, and providing a nursery for young fry. Without wetlands to protect fry, the fishing industry and a significant portion of the American economy could crumble. As such, wetlands can be assigned a dollar value of \$14.9 billion (75% of the income derived) from the commercial fishing industry and another \$14.4 billion (75% of the earned income) from the 924,600 employees who gain their livelihood from the fish and shellfish that take refuge in these waters.

This is especially significant to northern California and Idaho, as 30,000 employees have lost their jobs due to the declination of salmon populations. Salmon depend on wetlands for the protection of their fingerlings, fry, and salmonoids. Habitat loss has resulted in the thinning of

salmon runs, less salmon resulted in the loss of many American jobs.

Intangible Benefits: Flood Attenuation

Wetlands are well-known for the ability to protect against flooding, which is rated as one of most costly natural disasters (76). Recent studies indicate that wetlands are able to hold more water than previously believed. A 5.7 acre marsh is capable of retaining the natural runoff of a 410 acre watershed (76). Results to this study indicate that 13 million acres of wetland (3% of Mississippi watershed) could have prevented the flood of 1993 (76, 77). An estimated 53% of the total wetlands lost in the United States were due to anthropogenic activities (76, 78).

The declination of wetland habitat, and the rise of construction on flood plains, has resulted in the increase in the incidence of flooding in the United States. The Association of State Floodplain Mangers (79) has estimated that damages from floods account for \$5-8 billion annually and \$196 billion in property damage (80). Although the USACOE have spent over \$120 billion since the late 1940's on flood control projects (81), flood events are still capable of exceeding the capacity of the flood control

structure with damages tending to exceed the costs of unprotected areas (82, 83). Since 53% of the Nation's wetlands have been lost due to anthropogenic practices, then the losses associated with the declination of wetlands will be counted as an intangible cost to society. Table 15 summarizes expenditures allocated to wildlife and recreation. Since 75% of earned income is directly depended on wetlands, this percentage was used to calculate wetlands contribution to the US economy. Table 16 summarizes revenues loss due to the Nation's declination of wetlands.

Table 15. Economical Benefits Associated with Wetlands.

UNITED STATES	DESCRIPTION	BENEFITS TO US	WETLAND BENEFITS
87 Million Americans	Wildlife Activities	\$120.1 Billion	\$90.1 Billion
34 Million Americans	Fishing/Hunting	\$75.9 Billion	\$56.9 Billion
	<ul style="list-style-type: none"> • Equipment • Trip Expenses • Entrance Fees 	<ul style="list-style-type: none"> • \$40.3 Billion • \$25.0 Billion • \$10.6 Billion 	<ul style="list-style-type: none"> • \$30 Billion • \$18.8 Billion • \$7.95 Billion
924,000 jobs	Wildlife Appreciation	\$45 Billion	\$33.8 Billion
	Commercial Fishing and Shellfish Industry	\$19.8 Billion	\$14.9 Billion
Individual	Expenditures	\$2,225.00	\$1,668.75
Florida	Tourism	\$120 Million	\$120 Million
1 Million People	US Stamp Collection	\$2.6 Million	\$2.6 Million
San Bernardino County	Tourism	6 million	\$4.5 Million
	Net Benefits:	\$336.5 Billion	252.6 Billion

Table 16. Costs Incurred Due to the Declination
of the Nation's Wetlands

UNITED STATES	DESCRIPTION	COST OF LOSING WETLANDS
Wetland Declination	53% loss to Nations Wetlands	\$175.4 Billion
Flood Control Projects Property Loss	Monies Spent to mitigate wetland losses	\$330 Million \$4.5 Billion
California/Idaho 30,000 jobs	Commercial Salmon Industry	\$482.3 Million
Net Loss:		\$182.4 Billion

Intangible Benefits:
Valuating Public Health -
Wastewater Treatment Facilities

Comparing the advantages gained from nature and those gained from modern society (advanced wastewater treatment facilities) are essentially as relative as comparing apples and oranges. Modern practices of collecting raw sewage and physically treating the waste products of an ever growing society have protected the watershed from various water-borne related diseases, saving billions in medical expenses. An advantage to the use of wastewater treatment facilities are that more control is gained by the operator in the outcome of the water. At any stage along the purification path, problems that arise can be immediately dealt with. An advanced treatment facility can be specifically designed to treat the problems that are unique to a given watershed, thereby improving the overall water quality of the particular watershed.

CHAPTER SEVEN

SUMMARY/CONCLUSION/RECOMMENDATIONS

There is a place for both wetlands and wastewater treatment facilities in society; each serves an important capacity that always must be considered prior to their implementation. A Summary in Table 17 demonstrates the value that the nation places on wetland resources. From this summary it can be seen that the overall monetary benefit wetlands provide to the Nation's economy is \$67.8 billion.

Table 18 provides an overview of all the facilities that were discussed in this CBA. It is interesting to note that just by summing the figures that were compiled for green technology based WWTFs, 107.7 billion gallons of raw wastewater is treated on a daily basis at a net savings of \$421,689.00. Of the 107.7 million gallons, 4.16×10^{-4} Tg of CO₂ equivalents are captured and not emitted into the atmosphere (the work of only three treatment facilities at an treatment cost of less than 5 million dollars/year). It is overwhelming to imagine the amount of CO₂ that could be prevented from entering the atmosphere if more facilities utilized green technologies.

Further, the amount of revenue (\$136 Billion) that is annually lost due to the declination of the Nation's wetlands is astounding. Although wetlands account for 20% of the global emissions of methane, the significance of these emissions are minuscule (\$3200/yr for the average 10MGD wetlands) compared to the flooding devastation that can occur from their disappearance and the revenue and jobs lost from the slump or collapse of the commercial fishing industry and the tourism associated with its recreational uses.

Although, inherent difficulties occur when attempting to apply a monetary figure to social issues, some valuation can be assigned to habitat based on the role it plays in a given society. It can not be definitively stated that one facility is superior to that of another. Each facility has its place in society.

WWTF are ideal for cities that do not have the physical or monetary ability to utilize wetlands. As discussed in Chapter 2, specific conditions must exist for wetlands to be beneficial in a given area. As discussed in Chapter 4, the suitability of the site to function as wetlands must be evaluated. Key factors are site accessibility, source waters quality and quantity, the ability to treat POCs, the

availability of land, soil conditions, necessary modifications needed to meet wetland requirements, the site's natural topography (that is, its ability to encourage wetland habit by allowing water to gravity flow to the area), other purposes served by implementation of treatment wetlands (e.g., a wildlife corridor, nesting or resting area for migratory birds, etc), and availability of funding to purchase the land, as well as to design, construct, and maintain the wetlands (and any habitat that may depend on it, once it is implemented).

It is recommended that a feasibility study be conducted prior to choosing a treatment option. As part of this study, the type of wetlands to be used should be well thought-out and the most appropriate one chosen for meeting budgetary and treatment needs. If these conditions do not exist, it may be more costly over time to construct wetlands on a site with poor soil conditions or known contaminants

Should a new treatment facility be built, significant considerations should be made into utilizing BAT technologies, as it will save substantial money over time.

This analysis has taken an employee/employer relationship for applying a monetary component to nature. That is, rather than attempting to place a dollar value on

nature, a value has been assigned to the functions and jobs that nature participates in to enhance the quality of life, just as society applies a monetary value to the jobs that we perform.

Using this analytical scheme, wetlands seem to be the more cost-effective means of treating secondary wastewater provided that the right conditions exist for their use.

Table 17. National Benefits and Costs Provided by Wetlands Resources

UNITED STATES	DESCRIPTION	US INCURRED COSTS	WETLAND COSTS
87 Million Americans	Wildlife Activities	\$120.1 Billion	\$90.1 Billion
34 Million Americans	Fishing/Hunting	\$75.9 Billion	\$56.9 Billion
	Wildlife Appreciation	\$45 Billion	\$33.8 Billion
924,000 jobs	Commercial Fishing and Shellfish Industry	\$19.8 Billion	\$14.9 Billion
Individual	Expenditures	\$2,225.00	\$1,668.75
Florida	Tourism	\$120 Million	\$120 Million
1 Million People	US Stamp Collection	\$2.6 Million	\$2.6 Million
San Bernardino County	Tourism	\$6 million	\$4.5 Million
	Benefits:	\$260.9 Billion	\$248.4 Billion
Wetland Declination	53% loss to Nations Wetlands	-\$175.4 Billion	-\$175.4 Billion
Flood Control Projects	Monies Spent to mitigate wetland losses	-\$330 Million	-\$247.5 Million
Property Loss		-\$6 Billion	-\$4.5 Billion
California/Idaho	Commercial Salmon Industry	-\$643 Million	-\$482.3 million
30,000 jobs			
	Costs:	\$182.4 Billion	\$180.6 Billion
Net Benefits		\$78.5 Billion	\$67.8 Billion

Table 18. Summarization of Known Costs Associated with Wastewater Treatment Facilities and Wetlands

Treatment Facility	Implementation Fees	O&M	Cost/yr Denitrification	Size	Methane Production	Tg of CO ₂ Equivalent	Net Savings	Net Costs
Hill Canyon	\$14,020,000	\$930,000						
Simi Valley	\$14,700,000	\$980,000						
Camarillo	\$7,290,000	\$390,000						
BPWTF	\$101 million		4.2 million	107.6 BGD				
Coyle		\$8,100	\$11,426	36,626 G/D				
PRP	\$1.9 million			10 MGD	2.7X 10 ⁷ ft ³ /yr ³	3.58X10 ⁻⁴	\$227,000	
Albert Lea	\$250,000			12 MGD	4.5X10 ⁴ ft/day ³	1.45X10 ⁻⁵	\$40,000	
Sioux	NA			19.7 MGD	6.6X 10 ⁷ ft ³ /yr ³	4.42X10 ⁻⁵	\$154,689	
Permits								3,500-70,000
WWTF (nationally)	\$137 million	\$2.3 million	\$4.2 million	107.7BGD	9.3X10 ⁷ ft ³	4.16X10 ⁻⁴	421,689	-\$70,000
Prado		\$59,759	\$120,000	70 MGD				
San Jacinto	\$1,844,000.00	12,000		45 acres				
Ontario	\$20 million		NA	200-acres				
Tres Rios	3.5 million		NA	11 acres				
Lakeus Wetland Recreation	NA			10 MGD (adj)	1.05x10 ⁻⁹ Tg/yr	2.43x10 ⁻⁸		\$2,112.81
Wetlands (nationally)	\$25.5 million	\$72,000	\$120,000	80 MGD	1.05x10 ⁻⁹ Tg/yr	2.43x10 ⁻⁸	\$67.8 Billion	-\$180.7 Billion

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