ABSTRACT

Modeling the Effects of Low Flow Augmentation by Discharge from a Wastewater Treatment Plant on Dissolved Oxygen Concentration in Leon Creek, San Antonio, Texas. (December 2000)

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A GIS-based hydrological/water quality model called Non Point Source Model (NPSM) was used to simulate various physical, chemical and biological processes taking place in the Leon Creek Watershed, near San Antonio, Texas. The model was then used to evaluate base flow augmentation scenarios to remedy dissolved oxygen problems during dry, low-flow periods. The effects were demonstrated by increasing base flow in a stream by discharging recycled water from Leon Creek Wastewater Treatment Plant during a three month low-flow period in 1993, 1994 and 1995 respectively. Five scenarios were evaluated in addition to the control scenario (no flow augmentation). Each of the five scenarios represented an increase in base flow by a factor of 0.25, 0.5, 1, 2 and 4 respectively.

The study indicated that increasing base flow in the stream increased the mean daily DO concentration in the stream. The most significant effect was observed when the base flow was increased by a factor of 1 onwards, with no data point falling below the DO criterion of 5 mg/l. From the results of DO modeling developed for this project and from the scenario analysis, it can be concluded that a minimum flow augmentation of one times base flow (i.e. doubling the base flow) is required in order to see a significant increase in mean daily DO concentration in Leon Creek and associated tributaries and remedy DO problems during low-flow periods. Since there is uncertainty involved in the modeling process, it is recommended that a higher flow augmentation of two times base flow or four times base flow be implemented in order to reduce uncertainty and significantly improve water quality of Leon Creek.

DEDICATION

To my parents and sister, who never once doubted my abilities and whom I cherish.

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TABLE OF CONTENTS

Page

CHAPTER

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 Background

Land use by humans in the form of agriculture, transportation, manufacturing, mining and construction invariably has an impact on the surrounding ecosystem. This includes increased nutrient loads from point and non-point sources (NPS), toxic loading from point sources, increase or decrease in the stream flows - all of which might lead to a decline in the overall water quality of the streams and make then unfit for recreation or human and wildlife consumption.

A 1996 Texas Natural Resources Conservation Commission (TNRCC) study indicated that water quality in Leon and Salado Creeks in the San Antonio River Basin is impaired due to elevated concentrated of nutrients, fecal coliform bacteria and violation of DO. Subsequently, these water bodies have been included in the Federal Clean Water Act Section 303 (d) listing of impaired water bodies for Texas. The United States Environmental Protection Agency (US EPA) under its Clean Water Action Plan of 1998 is emphasizing the need for State, local and tribal authorities to carry out a watershed level study and management approach in order to address the issues of nonpoint source runoff and pollution and restore the health of impaired waters.

This thesis follows the style and format of *Water Research.*

The San Antonio River Basin traverses at least three eco-regions in Texas: the Central Texas Plateau, the Texas Blackland Prairies, and the Western Gulf Coastal Plain (See Map 1 of Appendix A). This basin is dominated by urban and industrial development from the city of San Antonio but agriculture is also a major economic source in the region. Since there is diverse economic activity in this region, the sources of pollution are also diverse. To add to this is the increasing ethnic diversity and income levels. The social and economic diversity in this watershed makes it a classic case study for urban areas. It is critical to analyze the ecological risks that various factors such as land use change and nonpoint source pollution pose to these ecosystems in order to restore them.

The major streams in this basin include Salado Creek, the Upper San Antonio River and Leon Creek. Map 2 of Appendix A shows the location of Leon and Salado creeks. Both creeks originate in the north central region of the basin. Leon creek flows in the western region of the San Antonio metropolitan area whereas Salado creek flows in the eastern region of the San Antonio metropolitan area. Both eventually join the San Antonio River south of the city. Map 3 of Appendix A shows Leon Creek and associated tributaries.

The Leon Creek Watershed is fed by runoff, springs and small, undesignated streams. The drainage area crosses the Edwards Aquifer Recharge Zone, spanning from the Hill Country northwest of San Antonio through the western edge of the City of San Antonio to its convergence with the San Antonio River southeast of the city. Although the northern half of the segment is normally dry, this water body is a major source of aquifer recharge during heavy storm events, potentially including urban runoff and leaks from sewage collection (Harris, 2000). Water quality in these river segments must be restored by 2003 under the TNRCC Statewide Basin Management Schedule (TNRCC, 1997). Under the Federal Clean Water Act of 1972, restoration of these water bodies requires development of a Total Maximum daily Load (TMDL) for each component not in compliance.

1.2 Problem Statement

In keeping with the above-defined management objectives, it becomes imperative to understand the various physical, chemical and biological processes (anthropogenic as well as non-anthropogenic) that occur at the watershed level and their effects on various indicators of ecosystem health. Nonpoint source (NPS) pollution is of vital importance to water resources and land management activities. This is because the sources of nonpoint pollution are distributed over a landscape, both spatially as well as temporally. It is very difficult to pin point all sources of nonpoint pollution because it arises from varied land usage, which are spatially distributed over a geographic region. Also, there is no defined pattern for the release of this type of pollution. All this makes it very important to study and understand the spatial as well as temporal patterns of nonpoint source pollution in order to determine and reduce its impact on the ecosystem.

The concentration of DO in natural waters is a primary indicator of overall water quality and the viability of the aquatic habitat (Melching and Flores, 1999). A number of abiotic and biotic factors, such as reaeration, stream respiration, nutrient and organic loading affect DO concentration in streams. Hence DO is considered a non-conservative constituent (Greb *et al*., 1995). Low base-flow in streams can also aggravate DO problems. Various point and nonpoint sources of pollution such as wastewater treatment plant (WWTP) discharges and agricultural runoffs can affect DO concentration in streams. At the watershed level, DO is a key indicator of water quality in the receiving waters that can characterize risks sufficiently. Hence, understanding the impact of various anthropogenic as well as non-anthropogenic processes on the DO concentration in water bodies becomes imperative in any watershed management/rehabilitation plan.

1.3 Objectives

The objective of this study was to use a complex GIS-based hydrological/water quality model in order to simulate various physical, chemical and biological processes occurring in the Leon Creek Watershed, to simulate hourly DO concentrations in Leon Creek and to study the effect of water reuse on DO concentration in the creek and its tributaries.

Specifically, the model was used to evaluate stream flow augmentation as an alternative management practice for improving the water quality in Leon Creek and associated tributaries. The hypothesis tested in this study was that increasing the base flow during low-flow periods increases the mean daily DO concentration in the streams.

CHAPTER II

LITERATURE REVIEW

2.1 GIS and Hydrological/Water Quality Modeling

Introduction

Geographic Information Systems (GIS) are gaining wide popularity in the field of environmental modeling because of their superior data processing and analytical capabilities and state of the art visual representation techniques. GIS can be described as a computer system for entering, storing, managing, processing, analyzing and visually representing geographic or spatial and attribute data. To put it in layman's terms, it is a system that put layers of data on a series of base maps, and relates things geographically.

Why GIS in environmental modeling?

One of the important aspects of environmental engineering is developing mathematical models to describe various phenomenon related to the environment, to simulate these models, predict environmental impacts with the help of statistical and other analyses, and make decisions based on the outcome of these models. Almost all of these models have a temporal and spatial component attached to them. GIS and remote sensor data can greatly facilitate modeling in such endeavors by providing primary input data, estimating model coefficients and performing statistical analysis (Lyon and McCarthy, 1995). GIS allow the users to overlay coverage, analyze and determine pollutant loading, and prioritize and identify critical areas very efficiently and economically (Tsihrintzis *et al.*, 1997). Integration of a nonpoint source model and a GIS enhances and supports decision-making concerning watershed-based distributed processes (Tsihrintzis *et al.*, 1996). Use of GIS can enhance the knowledge of spatial variation and reduce the uncertainty caused by spatial averaging. As an example, change in the land use affects surface run off volume, which in turn has an effect on surface water quality (Tsihrintzis *et al.*, 1996).

Types of model and data required

There are two types of models used in NPS pollution analysis. A screening level model is used as an indexing tool to characterize current watershed conditions based on simple algorithms that are derived from basic watershed characteristics such as land use, topography and soils among others. These models serve as a general indicator to policy makers and government officials of the watershed condition in their region and point out to areas of concerns and further studies. For example, a screening level model of a geographic region can graphically indicate (by overlaying of land use and water quality layers) poor water quality levels in areas of high percentage imperviousness and as such can identify critical watersheds for further study. Such models use less exhaustive and low-resolution data i.e. at 1:1,000,000 or 1:2,500,000 scale. At this scale, reasonable data is available. Sometimes national databases at 1:5,000,000 scale are also used (Hamlett and Petersen, 1995). More detailed assessment models of specific watersheds use data of a higher resolution (1:24,000 scale or higher). These models use complex and exhaustive algorithms based on detailed watershed characteristics such as runoff, sediment production, chemical and pesticide loading, precipitation, slope and land management practices among others. GIS plays an important role in these models in handling graphical information and providing quick results in parameter estimations to simulate a number of scenarios.

Models used in research

Appendix B gives a list of some of the models used in nonpoint pollution studies. Many other models like these can be cited through extensive survey of literature. The list gives an indication of how some of the models have been interfaced with GIS for NPS pollution studies.

2.2 History of DO Modeling

Introduction

Assessing the impact of sewage on receiving waters was the first water-quality modeling endeavor taken up by engineers (Chapra, 1997). The immediate impact of raw sewage discharge on water bodies such as streams and rivers is the depletion of dissolved oxygen, since the aquatic microorganisms utilize dissolved oxygen for decomposing the degradable part of sewage. In addition, a sediment oxygen demand supplements the decay in the water. As oxygen level drops, atmospheric oxygen enters the water to compensate for the imbalance. Initially, oxygen consumption in the water and to the sediments is more that reaeration, but after sometime, the reaeration rate becomes equal to the depletion rate. At this point the critical level of oxygen in the water is reached. This is the lowest level of oxygen in the water. Beyond this point, reaeration rate overcomes the depletion rate and the oxygen level in the water starts increasing. At some point downstream of the “oxygen sag”, the level of dissolved oxygen returns to initial values. This is the zone of recovery and is characterized by the growth of plants on the nutrients released from the decomposition process. Reaeration is the most important natural means of DO recovery for polluted streams (Melching and Flores, 1999). Besides reaeration, aquatic plant photosynthesis and respiration are a major source and sink of oxygen in water bodies respectively.

Nutrient inputs may stimulate excessive autotrophic growth in rivers and streams. Water quality in streams is influenced not by the mere presence of autotrophic organisms as such, but rather in the way these organisms affect the DO balance (Hajda and Novotny, 1996). Thus autotrophs also influence DO balance in streams and primary production forms the link between nutrient loads and degradation of water quality. The imbalance between the light requirements of the major sources and sink processes associated with primary production may seriously affect water quality in streams (Hajda and Novotny, 1996). The major DO sink processes, respiration and decomposition are independent of light, whereas the source photosynthesis is dependant on light. Consequently, DO loss due to respiration and decomposition may take place at different times than photosynthesis and as a result, diurnal variation of DO in streams is observed. Low flow seems to aggravate the diurnal DO depression (Hajda and Novotny, 1996). The reasons may include limited nutrient dilutions, decreased turbidities and increased residence times (Hajda and Novotny, 1996). Thus, the process of DO dynamics is not a simple balance of biochemical oxygen demand (BOD) decay and reaeration, but also involves other anthropogenic factors such as nutrient loading and the subsequent eutrophication (primary production of autotrophs such as algae), and demands from sediment decays and benthic respiration. Table 1 gives in brief the various sources and sinks of DO in a stream.

Table 1. Sources and sinks of DO in streams

Sources	**Sinks**
1. Reaeration	1. BOD (Biochemical oxygen demand)
2. Algal photosynthesis	3. Algal respiration
	4. Nitrification (Nitrogenous BOD)
	5. Macrophyte respiration
	6. Benthic oxygen demand
	7. Sediment oxygen demand

Mathematical models: History and development

Dissolved oxygen is an indicator to judge the health of ecosystems. Mathematical models are effective means of predicting DO concentrations in streams. These mathematical models are differential equations that simulate the transport and effect of BOD exerting organic matter on a stream’s DO (Tyagi *et al.,* 1999).

Streeter and Phelps did the pioneering work in the field of dissolved oxygen modeling in 1925. They developed the relationship between BOD and DO resources of the river, producing the classical DO sag model (Adrian and Sanders, 1998). Theriault in 1927 and Fair in 1939 summarized the methods for estimating the model’s parameters and Thomas accounted for settleable BOD in the DO sag equation (Adrian and Sanders, 1998). In 1956, Odum comprehensively described the interaction of photosynthesis, respiration and reaeration that cause diurnal DO variations in streams. O'Connor and DiToro incorporated these factors into a computer model for calculating DO concentrations in surface waters in 1970 (Ansa-Asare *et al.*, 2000). Hann (1962) was one of the first to apply digital computers to calculate waste assimilation capacity of a stream in terms of BOD.

The classic Streeter-Phelps BOD and DO model modified for plug flow, simulating a point discharge of BOD in a stream can be written as follows (Chapra, 1997):

$$L = L_O e^{-\frac{k_r}{U} X} \qquad (1)$$

and

$$D = D_O e^{-\frac{k_a}{U} x} + \frac{k_d L_O}{k_a - k_r} \left[e^{-\frac{k_r}{U} x} - e^{-\frac{k_a}{U} x} \right] \qquad (2)$$

where:

$k_r = k_d + k_s$ = rate of BOD removal (d^{-1})

k_d = decomposition rate in the stream (d^{-1})

k_s = settling removal rate (d^{-1})

$k_s = \frac{v_s}{H}$

v_s = BOD settling velocity ($m\ d^{-1}$)

H = water depth (m)

k_a = reaeration rate (d^{-1})

L_O = ultimate BOD (mg-O L^{-1})

L = BOD remaining at a distance x downstream from the point source

D = DO deficit at a distance x downstream from the point source (mg L^{-1})

D_O = initial DO deficit in the stream (mg L^{-1})

x = distance downstream from the BOD point discharge (m)

U = mean stream velocity (m s^{-1})

On similar lines, the Streeter-Phelps equations for a plug-flow system with distributed sources can be represented as follows (Chapra, 1997):

$$L = \frac{S_L}{k_r}(1 - e^{-k_r t}) \qquad (3)$$

and

$$D = \frac{k_d S_L}{k_r k_a}(1 - e^{-k_a t}) - \frac{k_d S_L}{k_r (k_a - k_r)}(e^{-k_r t} - e^{k_a t}) \qquad (4)$$

where:

S_L = rate of BOD distributed source (g m^{-3} d^{-1})

t = time (s)

Remaining terms are as explained earlier.

The above equation accounts for oxygen deficit due to distributed BOD loading. For distributed effects of plants and sediment oxygen demands, Chapra (1997) gives another equation:

$$\overline{D} = \frac{-P + R + (\frac{S'_B}{H})}{k_a} \tag{5}$$

where:

$\overline{D}$ = oxygen deficit due to distributed effect of plants and sediments (mgL^{-1})

P , R = volumetric rates of plant photosynthesis and respiration, respectively (g.m^{-3}d^{-1})

S'_B = areal rate of sediment oxygen demand (g m^{-2} d^{-1})

ddddd Finally, the combined Streeter-Phelps model for point and non-point (distributed) sources is given as follows (Chapra, 1997):

$$L = L_0 e^{-k_r t} + \frac{S_L}{k_r}(1 - e^{-k_r t}) \tag{6}$$

and

$$D = D_0 e^{-k_r t} + \frac{k_d L_0}{k_a - k_r}(e^{-k_r t} - e^{-k_a t}) + \frac{-P + R + (S'_B / H)}{k_a}(1 - e^{-k_a t}) + \frac{k_d S_L}{k_r k_a}(1 - e^{-k_a t}) - \frac{k_d S_L}{k_r (k_a - k_r)}(e^{-k_r t} - e^{-k_a t}) \tag{7}$$

This equation can now be used for a realistic representation of the steady-state processes taking place in the system as it incorporates both point and non-point sources of loading to a stream. However, the above equations indicate the response of a stream to diffuse sources that do not contribute significant flow. Although this has been the standard approach in traditional stream oxygen modeling, recent concern over nonpoint –source pollution has directed attention to distributed sources that contribute flow (Chapra, 1997). Analytical approaches for this situation have been found to be inadequate as compared to computer-based numerical method for more general applications (Chapra, 1997). Today, engineers use computerized models that incorporate numerical methods for analyzing and providing alternative solutions involving arbitrary geometries and flow conditions (Bravo, 1998). Moreover, some of the recent go beyond describing the traditional processes of advection, dispersion and basic kinetics to include the effects of other factors such as, nutrient loading, nitrification, eutrophication, sediment oxygen demand and benthic oxygen demand. Thus, such models give a more detailed and realistic assessment of water quality in terms of DO, as they incorporate most of the sources and sinks of oxygen in streams. For example, the QUAL2E model (Brown and Barnwell, 1987) incorporates the following equation for DO balance in a stream:

$$\frac{udo}{dx^*} = K_2(O^* - O) + (\alpha_3\mu - \alpha_4\rho)A - K_d L - K_4 / D^* - \alpha_5\beta_1 N_1 - \alpha_6\beta_2 N_2 \qquad (8)$$

where:

u = stream velocity (m d^1)

dd x^* = stream distance (m)

O = concentration of dissolved oxygen (mgL^{-1})

O^* = saturation concentration of dissolved oxygen at the local temperature and pressure (mgL^{-1})

α_3 = rate of oxygen production per unit of algal photosynthesis (mg-O/mg-A)

α_4 = rate of oxygen uptake per unit of per unit of algae respired (mg-O/mg-A)

α_5 = rate of oxygen uptake per unit of ammonia nitrogen oxidation (mg-O/mg-N)

α_6 = rate of oxygen uptake per unit of nitrite nitrogen (mg-O/mg-N)

μ = algal growth rate (d^{-1})

ρ = algal respiration rate (d^{-1})

A = algal biomass concentration (mg-A/L)

L^* = ultimate concentration of carbonaceous BOD (mgL^{-1})

K_d = carbonaceous deoxygenation rate based on BOD stream profile (d^{-1})

K_2 = reaeration rate (d^{-1})

K_4 = sediment oxygen demand ($g\text{-}O/m^2\text{-}d$)

D^* = stream depth (m)

β_1 = ammonia oxidation rate coefficient (d^{-1})

β_2 = nitrite oxidation rate coefficient (d^{-1})

N_1 = ammonia nitrogen concentration (mg-N/L)

N_2 = nitrite nitrogen concentration (mg-N/L)

The growth and decay kinetics of algal biomass are complex and involve many parameters in the mathematical formulations. Chlorophyll-a, component of algal biomass is used as an indicator to simulate algal biomass (Chaudhary *et al.*, 1998). In the HSPF model (Bicknell *et al.,* 1996), the DO balance is calculated by similar equations and considers the following basics sources and sinks:

1. longitudinal advection of DO and BOD
2. sinking of BOD material
3. benthal oxygen demand
4. benthal release of BOD material
5. reaeration
6. oxygen depletion of due to decay of BOD materials

Additional sources and sinks of DO and BOD are simulated in other optional sections of the model. Depending on the depth of study that the modeler is interested in, the model can simulate the effects of nitrification on DO and denitrification on BOD. The DO balance can be adjusted to account for photosynthetic and respiratory activity by phytoplankton and/or benthic algae and respiration by zooplankton (Bicknell *et al.*, 1996).

Some DO models in use

QUAL2E model developed by the U.S Environmental Protection Agency is widely used for conventional pollutant impact evaluation (Drolc and Kon_an, 1999). It is a steady state stream water quality model that primarily simulates DO and DO influencing parameters of water quality (Chaudhary *et al.,* 1998). A complete description of the model methodology is available in the user documentation (Brown and Barnwell, 1987). The QUAL2E model in basically an in-stream water quality model that simulates the fate and transport of water quality constituents mostly during low-flow steady state conditions existing in streams. It is therefore a “receiving water model”. It does not have the capability of simulating the fate and transport of pollutants on land surfaces and their deposition either in large or small water bodies or their infiltration through soil into groundwater. HSPF on the other hand combines the capability of handling NPS pollution generation and transport on land surfaces, as well as the fate and transport in receiving water bodies. It is therefore a NPS pollution model as well as a receiving water model. It is a quasi-dynamic model capable of simulating fate and transport of pollutants in a continuous non-steady environment that is more representative of the complex watershed-level processes. Data requirements for the model are significant and running costs are high. Despite this, HSPF is thought to be the most accurate and appropriate modeling tool presently available for a watershed level simulation of hydrology and water quality (Bicknell *et al.,* 1996).

2.3 Total Maximum Daily Load (TMDL)

Definition

A TMDL or Total Maximum Daily Load is defined as the maximum amount of a pollutant that a water body can receive without violating water quality standards, and an allocation of that amount to the pollutant's sources (EPA, 1999). It is based on the relationship between polluting sources and in-stream water quality conditions (Cote, 1998). A TMDL must take into account considerations of seasonal variability and provide for a margin of safety (MOS) that accounts for uncertainties in the way the pollutants are loaded into the system and future increase in pollutant loadings. To put it simplistically:

$$\text{TMDL} = \text{WLAs} + \text{LAs} + \text{Background} + \text{MOS} \qquad (8)$$

where:

TMDL = Total Maximum Daily Load

WLAs = Waste Load Allocations for point sources

LAs = load Allocations for nonpoint sources

Background = background concentration of pollutant in the system

MOS = Margin of Safety

Hann (1962) devised computer methods to determine the ultimate BOD loading which a stream can take without violating River Quality Standards. His work is an early precursor to the TMDL concept that took shape 10 years later.

History

The actual history of TMDL goes back almost 30 years. In the early 1970s, the American public urged Congress to tackle the gross misuse and pollution of the Nation's waters, which lead to the birth of the Federal Water Pollution Control Act Amendments of 1972 (more popularly known as the Federal Clean Water Act of 1972). The Act focused on technology-based solutions for reducing the pollution of waters by prescribing Best Available Treatment (BAT) or Best Practicable Treatment (BPT) methods to municipal and industrial wastewater discharges above a certain minimum threshold. This approach worked well and was responsible for preventing billions of pounds of pollution from fouling the water and doubled the number of waterways safe for fishing and swimming. The impetus of this approach was in the creation of permits under the National Pollutant Discharge Elimination System (NPDES).

Despite this tremendous progress in reducing water pollution, almost 40 percent of the Nation's waters assessed by States still do not meet water quality goals. (Browner, 2000). In fact, at present, only about 10 percent of the Nation's water bodies are polluted due to point sources of municipal and industrial wastewater discharge. About 43 percent of the pollution comes from diffused or nonpoint sources of such as agricultural runoff of nutrients and sediments. The authors of the 1972 Clean Water Act envisioned a time when a more focused approach to restoring the remaining polluted waters would be needed and they created a much under-utilized and until recently, unknown provision: the TMDL program in section 303(d) of the Act (Browner, 2000). In summary, section 303(d) requires the States to:

1. Identify waters that do not meet water quality standards adopted by that State;
2. Prioritize these waters depending upon the severity of their pollution; and
3. Establish “total maximum daily loads” for these waters taking into account the seasonal variability of water quality and account for a margin of safety to reflect the uncertainty involved in assessing discharges and water quality.

The basis for establishing the TMDL process was to provide for more stringent water quality based controls when water quality goals cannot be met using technology based controls (Novotny, 1996). The States are required to submit the 303(d) list and TMDLs upon completion, once every two years to the EPA for approval. Failure to comply or gain approval will result in the EPA taking over the state TMDL process and developing the same. On the other hand, failure by EPA to enforce section 303(d) can result in a lawsuit. To date, citizen action groups have brought legal actions against EPA that has resulted in the resolution of 17 cases so far (Browner, 2000). These lawsuits have acted as a wake-up call to the EPA for pressurizing the States to produce the lists of impaired waters and step up the TMDL process. The EPA under its Clean Water Action Plan of 1998 is emphasizing the need for State, local and tribal authorities to carry out a watershed level study and management approach in order to address the issues of nonpoint source runoff and pollution and restore the health of impaired waters.

Current status

In 1997, the EPA asked the States to speed up their process and set an 8-13 years time-frame in which to develop TMDLs for all listed water bodies, beginning with the list due on April 1, 1998. In response to EPA’s action, the States have made good progress in developing a list of polluted waters. All States submitted the 1998 lists and the EPA has approves all but one of these lists. Between 1972 and 1999, States and EPA developed approximately 1000 TMDLs. Since October 1999, States have established over 600 TMDLs with the approval of EPA (Browner, 2000). Over 2000 TMDLs are now under development across the country (Browner, 2000).

TMDL strategies for DO

Lasting solutions to water quality problems are best achieved by considering all activities in a watershed. This means that both point and non-point sources of pollutant generation should be assessed. Specifically for DO, this means that all oxygen demanding sources from point and nonpoint sources should be assessed. Point sources include BOD, ammonia, nitrogen and high temperature discharges from municipal and industrial wastewater treatment plants. Nonpoint sources include nutrient and sediment runoff from agricultural lands, sediment wash-offs during storm events and bacteria loadings. Once the sources are assessed and quantified, a TMDL for each pollutant can be established based on the standard DO criteria of 5.0 mg/L. Additional control of both point (regulated) and nonpoint (unregulated) sources can effect the desired pollutant load reduction (Novotny, 1996).

The EPA (1983b) Use Attainability regulations suggest that water body improvements that could remedy the cause of impairment should be considered (Novotny, 1996). Waste assimilative enhancement of a stream include in-stream aeration to remedy low DO concentrations and remediation of contaminated sediments among others (Novotny, 1996). Waste assimilative capacity of a stream can be increased by flow augmentation (Hann, 1962). On a watershed level, water quality restoration has two major management facets. One is the implementation of Best Available Treatment (BAT) or Best Practicable Treatment (BPT) for point sources and the other is the implementation of Best Management Practices (BMPs) for nonpoint sources. BMPs include reducing agricultural run-offs from farmlands by better scientific application of fertilizers to crops and better house keeping practices.

An alternative management practice could be low flow augmentation to dilute the concentration of oxygen demanding pollutants and to increase the assimilative capacity of DO for the water body. The aim of this project was to study the effect of this practice on receiving stream by evaluating scenarios.

Thus, while this project did not focus on the development of TMDLs for DO criteria, it aimed to evaluate an alternative management practice for water quality restoration thereby acting as a stepping stone towards the development of TMDL and BMPs for Leon Creek Watershed.

CHAPTER III

MATERIALS AND METHODS

3.1 Introduction

This project used historical and current water quality and quantity data from the San Antonio River Authority (SARA) and the United States Geological Survey (USGS) monitoring stations on Leon Creek. Watershed land use was determined using the USGS Geographic Information Retrieval Analysis System (GIRAS) land use classification database.

The US EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS, version 3-Beta) environmental modeling software was used for used for modeling purposes. BASINS brings key data and analytical components together in one framework. This is consistent with the new holistic approach, which makes watershed and water quality studies much easier. BASINS uses Arc View-Geographic Information System (GIS) as the integrating framework to provide the user with a fully comprehensive, state of the art watershed management tool for developing TMDLs that require the integration of both point and nonpoint sources (Battin *et al.*, 1999*).*

BASINS addresses three objectives: 1) to facilitate examination of environmental information, 2) to provide an integrated watershed and modeling framework, and 3) to support analysis of point and nonpoint source management alternatives (Battin *et al.*, 1999). Originally released in September 1996 (BASINS version 1.0), heart of BASINS version 2.0 is its suite of interrelated components essential for performing watershed and water quality analysis. These components are grouped into five categories:

- National databases with local data import tools;
- Assessment tools (TARGET, ASSESS and Data Mining) that address needs ranging from large-scale to small-scale and Watershed Characterization Reports;
- Utilities including Data import, Land use Reclassification, Digital Elevation (DEM) Reclassification, Watershed Delineation and Water Quality Observations Data Management Utilities;
- Watershed and water quality models including NPSM (HSPF), TOXIROUTE and QUAL2E; and
- Post-processing output tools.

BASINS (version 3-Beta) includes additions like an automated watershed delineation tool and an additional model SWAT. The final version of BASINS 3.0 is expected in October 2000.

Among the various models available within the BASINS suite, the Non Point Source Model (NPSM) model was used for the present study. NPSM can integrate watershed-based point and nonpoint loading and transport. NPSM is basically an abbreviated version of the HSPF (Hydrological Simulation Program-FORTRAN) model, with the added convenience of a graphical user interface (GUI). HSPF is a combined watershed based point and non-point source and receiving-water model that has been under development since the early 1980s with the help of U.S EPA grants.

Appendix C gives a brief overview of HSPF. This project will use NPSM (HSPF) for its watershed based water quality modeling needs.

3.2 Building the Project for NPSM

Building the project for NPSM model run involves creating the input files for the selected watershed by using the US EPA's RF1 (reach file version 1) as a stream network, extracting information on point sources from its database and calculating what percent of the land surface belongs to each category. This is done in the ArcView-GIS environment within BASINS and the steps involved are discussed below.

Watershed delineation

The first step in setting up the project is to delineate the sub-watersheds to be modeled. This first involves creation of a study area (i.e. main watershed) that will be delineated into sub-watersheds. EPA's River Reach Files Version 1 (RF1) provided the stream network information for Leon Creek and its major tributaries – Helotes Creek and Culebra Creek. This data was developed for stream routing for modeling at 1:500,000 scale (Lahlou *et al.,* 1998). The study area for this project was determined by visualizing the RF1 stream network and making sure that all major streams that contribute flows to Leon Creek were included. The next logical step is to divide the study area into sub-watersheds that contribute flows to each of the stream segments. The quick and easy way to do this is to use the automated watershed delineation tool available with BASINS. This tool allows for rapid definition of sub-watersheds based on user supplied coverages or point and click selection. Streams, DEM or even aerial photographs can be used to assist in delineation. Map 4 of Appendix A shows the study area and the delineated sub-watersheds contributing flows to Leon Creek.

As can be seen, each sub-watershed is associated with a single stream segment and each stream segment is associated with a single “pour point” at its most down-stream location. NPSM calculates various quantities such as pollutant loading, surface-runoff, and sediment transport within each sub-watershed and “dumps” these at the most upstream point of the associated stream segment. The quantities are then routed through the length of the stream segment and the output is a concentration/flow measured at the most downstream point (pour point) in the modeled sub-watershed. NPSM is therefore a lumped-catchment model in the sense that it does not allow for a longitudinal resolution of flow or pollutant loading and output measurement. Hence, one must make the assumption that the output concentration or any other physical quantity is representative of the entire reach (stream segment). This assumption is more valid when considering only nonpoint sources as opposed to both point and nonpoint pollutant sources. This is because the point sources may have more localized effects on water quality.

BASINS allows the users to add/remove pour points before it delineates sub-watersheds. Taking advantage of this option a pour point was added to coincide with the location of USGS gauge station on Leon Creek at Interstate Highway 35. This will ensure that when the model is calibrated for flows, the observed and simulated values are for the same output point.

Invoking NPSM

With the sub-watersheds delineated, the next step is to select the sub-watersheds and invoke NPSM within BASINS. When invoked, NPSM first creates the base project file by taking the input files created in earlier steps and incorporating data such as parameter values for various watershed level and in-stream processes, stream cross-sections and land use contributions among others.

The user then calls the project file within NPSM and uses the GUI to set up the input file for simulation. Appendix D gives details of the NPSM GUI and its functions.

3.3 Watershed Modeling: Application of the NPSM/HSPF Model

The BASINS software was downloaded from the EPA website and also obtained via CDROM. All the necessary data for Leon Creek was extracted within BASINS and projected using the following parameters:

Projection: UTM Zone 14
Spheroid: GRS 80
Central Meridian: -99
Reference Latitude: 0
Northing:0
Easting: 500000
Scale Factor: 0.9996

This projection provided land use data and maps for the Leon Creek area and an U.S EPA RF3 reach file for the stream channel that is more detailed than the RF1 reach files. However, to keep things simple, the RF1 file was used for delineation and modeling purposes. An image theme of USGS topographic map called Digital Elevation Model (DEM) having 30m resolution was added to the GIS environment to aid in the delineation of watershed. This image theme was obtained from the website of Pacific Environmental Services, Inc. (http://home.pes.com/demprog.html).

Watershed characteristics

The total length of the creek from its headwaters in the north central part of the San Antonio Basin to its confluence with the Medina River, south of the city of San Antonio, is about 36 miles. The Leon Creek watershed, as delineated by the BASINS software has mixed land use. Map 4 of Appendix A shows Leon Creek and its associated sub-watersheds. The total area of the delineated watershed is 131906 acres. Map 5 of Appendix A shows the land use characteristics of the watershed based on the Anderson Level II classification available in BASINS. The upper half of the watershed area is mostly evergreen forest. Crop land and pasture land covers the central and the lower region of the watershed. Most of the urban, built-up and commercial land is spread in the lower half of the watershed. Roughly, the upper 1/3rd of the watershed lies in the Edwards Aquifer recharge zone. Table 2 gives the area based land use characteristics of the entire watershed.

Table 2. Land use characteristics of Leon Creek Watershed

Sub-watershed	**Urban or built-up land (acres)**	**Agricultural Land (acres)**	**Forest Land (acres)**	**Range Land (acres)**	**Barren Land (acres)**	**Total by sub-watershed (acres)**
001	1950	2267	20904	451	1483	27055
002	1193	3804	16277	652	684	22610
003	146	7496	15879	1792	534	25847
004	2334	4351	15010	458	1069	23222
005	0	992	770	121	77	1960
006	13652	7376	5156	3476	1552	31212
Total by land use type (acres)	**19275**	**26286**	**73996**	**6950**	**5399**	**131906**
Percentage area by land use type	**14.6%**	**19.93%**	**56.1%**	**5.27%**	**4.1%**	**100%**

This land use inventory is from the 1996 data available within BASINS. NPSM requires specification of the percent impervious cover for various land use category. So all of the impervious area is lumped into the urban land use assignment. For the present study, the impervious cover was defined as 70 percent of the urban land use category. Similarly, impervious cover for agricultural land was defined as 5 percent of the total agricultural land. Table 3 gives the impervious cover defined for each type of land use based on literature values.

Table 3. Percent impervious cover for each land use type

Land-use type	**Percent impervious**
Residential	25
Open Land	5
Forest	0
Commercial	70
Agricultural	5
Barren	0

Source: Brun *et al.*, 2000

Reach physiography

NPSM requires reach physiography to be defined in order to do the in-stream mass balance and routing calculations. The date required is depth of flow, surface area, volume and outflow for each reach. These data are contained in an “F-table” within the model. BASINS 3-Beta has the capability of automatically generating F-tables for each stream reach for use within NPSM. NPSM does not actually consider the cross-section of reaches for hydrodynamic calculations. Instead, it uses the depth, volume and surface area of each reach for flow and mass routing.

Water quality data collection

Historical water quality data for dissolved oxygen was found to be limited. The San Antonio River Authority (SARA) maintains water quality data from 1990 onwards at several locations on Leon Creek. However, the SARA water quality data consists of “grab samples” collected at a specific time of the day during low flow periods, normal flows or storm events. For studying DO in a stream, continuous 15-minute or hourly data is required in order to capture the diurnal variation of DO concentrations in a stream. As such, the water quality data from SARA was limited in scope and usability.

Supplementary water quality data was collected by deploying electronic Yellow Spring Instruments (YSI) Datasondes at two locations along the creek. Map 5 of Appendix A shows the location of the two monitoring sites on Leon creek. Water quality data was collected at 15-minute intervals for a period of two weeks in August 1999, January 2000 and July 2000 on both sites. Table 4 shows the various water quality constituents monitored during the two-week periods.

Table 4. Water quality constituents monitored by YSI Datasondes

Constituent	Units of measurement
Temperature	^{o}C
Specific Conductivity	mS/cm
DO	mg/L
DO % saturation	-
Depth	feet
PH	-

This water quality data was later used in the modeling exercise to observe daily trends of DO and for the purpose of rough calibration.

3.4 Calibration, Validation and Sensitivity Analysis

The first step in using a hydrological/water quality model is to calibrate it for hydrology. Hydrology drives all other processes in a watershed. Part of the precipitation that impinges on the land surfaces infiltrates into the soil, a part of it evaporates and the remaining flows as surface runoff. Out of the fraction that infiltrates, a part of it may be lost to deep percolation and the remaining recharges an underground spring and/or aquifer. This shows up later as base flow when the aquifer/spring recharges a stream. The surface runoff flows on the land and finally finds its way to a receiving stream, river or a lake.

Calibration of hydrology in NPSM (HSPF) involves the adjustment of parameters that govern watershed response to precipitation and comparing simulated flows versus measured flows in streams. Hydrologic calibration is performed for long-term simulation (base flow) and for specific storm events depending upon the needs of the modeler. For the present project, long term simulation of the model for base flows was important since most of the DO problems occur during low base flows in the streams. Hence it was decided that the model be calibrated for long-term simulation only. The long-term simulation involves establishing an annual water balance and estimating initial storage conditions. If the estimated runoff over a time period is within reasonable limits of the observed runoff for that time period, the model is said to be well calibrated. A well calibrated model also takes into account seasonal variability in flow conditions.

Data

For the present project, historical daily mean stream flow data was obtained for USGS gauging station number 08181480 located on Leon Creek at Interstate Highway 35. Map 6 of Appendix A shows the location of the gauging station on Leon Creek. While creating the NPSM project, care was taken to include this geographic point as the last "pour point" for the entire watershed. NPSM simulates flows at each user-defined pour points within a watershed, which are located on the stream being modeled. Thus, by ensuring that the most downstream pour point of the entire watershed coincides with a USGS gauging station, the calibration exercise becomes accurate. Incidentally, the drainage area delineated by BASINS for that pour point is within 6 percent of the drainage area reported by USGS for their gauging station. Table 5 gives the details of the USGS gauging station used for hydrological calibration purposes.

Table 5. Details of USGS gauge station number 08181480 on Leon Creek

Station name	Leon Creek At I.H. 35 At San Antonio, TX

Station number	08181480
Latitude (ddmmss)	291947
Longitude (dddmmss)	0983502
State code	48
County	Bexar
Hydrologic unit code	12100302
Basin name	Medina
Drainage area (square miles)	219
Gage datum (feet above NGVD[*])	573.49

[*]See APPENDIX M

NPSM hydrological concepts

The user’s manual for HSPF (Bicknell *et al.*, 1996) describes the hydrological concepts in NPSM. The water balance is denoted by a simple equation:

$$P^{*} - ET - PERC - \Delta SM = RO \qquad (9)$$

where:

P^{*} = precipitation (inches)

ET =evapotranspiration (inches)

$PERC$ =deep percolation (inches)

SM =soil moisture storage (inches)

RO =runoff (inches)

This simple relationship has been characterized in NPSM (HSPF) via numerous variables and storage compartments. Precipitation that falls on an impervious surface can either runoff, be stored in a storage compartment and evaporate, or be temporarily stored in a storage compartment and runoff later. On a pervious surface, the response to precipitation is a bit more complex. On impingement, it can either runoff, be stored in a temporary compartment and evaporate, be retained in a storage compartment temporarily and flow later as interflow or enter the subsurface via infiltration. NPSM divides the sub-surface into three zones: the upper zone, the lower zone and the deep groundwater zone. Upon entering the upper zone via infiltration, the water can remain in storage, be available for evapotranspiration or enter the lower zone via infiltration. In the lower zone, water can remain as storage, be available for evapotranspiration or enter the deep groundwater zone via infiltration. Upon entering the deep groundwater zone, the water can remain as groundwater storage, exit as groundwater outflow, be available for evapotranspiration or be lost from the system due to deep percolation. All the above processes have an initial value or rate. These values and/or rates govern the flow of water on pervious or impervious surfaces. It is observed that runoff from pervious surfaces is more complicated than runoff from impervious surfaces. Runoff from impervious surfaces directly affects the peak flows and volumes where as runoff from pervious surfaces affect base flow in stream. From the standpoint of long-term calibration a sensitivity analysis was performed on three parameter variables that directly affect base flow and the overall annual water balance for the simulation period. These will be discussed in a later section. Appendix E gives the hydrological parameter definition table for NPSM.

Hydrology calibration

Calibration was performed for the year 1994. 1994 represents a moderate year with above average annual precipitation for the region. 1992 represents an extremely wet period due to a very high annual precipitation and hence was not used for calibration purposes. Similarly, 1995 was a record drought year for the region and hence was not used for calibration purposes. Initial parameter estimates for hydrology were made based on the BASINS Technical Note 6 that is available from EPA's BASINS web page (http://www.epa.gov/ost/basins/bsnsdocs.html). These initial parameter estimates were then revised iteratively to arrive at the final values. The model was set to simulate flows from the period 1987-95. In doing so, a sufficient lead-time was given to reach dynamic equilibrium for various storage variables. For the initial runs, the estimated initial storage parameters at the start of the simulation period were checked against equilibrated values during a similar period a few years later. The initial estimates were then revised for the start of the simulation period and further simulations done. Four steps were followed for the final calibration exercise:

1. Development of an overall mass balance for the watershed by adjusting overall gains and losses from the watershed due to precipitation, evapotranspiration and loss to deep groundwater. This water balance should be compared to the observed flow data.
2. Adjusting the low-flow high flow distribution as compared to observed data by adjusting the rate at which the water infiltrates the soil, enters groundwater and recharges the streams.
3. Roughly match peak flows and adjust recession rates so that the peaks recede to normal levels as observed.

4. Fit the seasonal distribution of flow, taking into account seasonal distribution of evapotranspiration, soil moisture and changes in groundwater recharge to streams.

The first step was to achieve an overall annual water balance by reasonable distribution of gains and losses in the watershed. It has been reported that the eastern region of Edwards Aquifer receives up to 50 percent more rainfall at some places as compared to the western region of the aquifer. The weather station used for modeling purposes is located to the east of the aquifer region and the Leon Creek Watershed is located to the west of the aquifer region. Moreover, the weather station is about 16 miles away from the USGS flow gauging station under consideration. The farthest reaches of the watershed are about 21 miles away fro m the weather station. Owing to the above facts, it was concluded that the precipitation observed at the weather station is not representative of the precipitation over the entire watershed and hence a multiplication factor of 0.5 was incorporated in the input precipitation data. Deep percolation losses were increased by adjusting a parameter DEEPFR to 0.4. These deep percolation losses denote permanent losses from the watershed. Such losses might include lateral outflow of groundwater from one aquifer to another low-lying aquifer outside the watershed area. Sometimes, groundwater flows beneath the gauging station and shows up as base flow at a point downstream. This flows is not accounted for at the gauging station reading and hence constitutes a loss from the system. There is reason to believe that such losses are taking place in the Leon creek Watershed, since the geology of Edwards Aquifer Recharge Zone consists of extremely porous limestone formations.

All these losses are incorporated into one parameter called DEEPFR in NPSM. Actual evapotranspiration was observed to be close to potential evapotranspiration and hence no factor was incorporated for evaporation data. After doing the above adjustments, the overall annual runoff volume was observed to be over-predicted by about 39 percent. This water balance can be improved by incorporating better precipitation data and by studying the evapotranspiration parameters in detail.

The second step in the calibration process was to compare high-flow low-flow distribution with the observed data. This was achieved by adjusting model parameters representing infiltration (INFILT), interflow (INTFW) and groundwater recession (AGWRC).

The third step was to roughly compare the simulated peaks and observed peaks (not extreme storm events) for shape and recession. The model parameters adjusted in this step were interflow recession constant (IRC), and surface flow parameters (LSUR, NSUR and SLSUR).

The final step in hydrology calibration was to match the monthly flow distribution. It was observed that the model overestimated winter month base flow and underestimated summer month base flow. Adjusting monthly parameters for evapotranspiration (MON-INTERCEPT, MON-LZETPARM), upper zone storage (UZSN), evapotranspiration from base flow (BASETP) and groundwater recession (KVARY) reduced this difference. The resulting values for each model parameter are given in Appendix F. The table shows default values, calibrated values and the minimum and maximum possible values as defined in the BASINS user’s manual

(EPA, 1996). A complete description of each parameter is provided in BASINS Technical Note 6, which is available from the BASINS web page (http://www.epa.gov/ost/basins/bsnsdocs.html). Figure 1 shows a graph of the observed vs. predicted flows at USGS gauging station on Leon Creek near I.H. 35 for the year 1994.

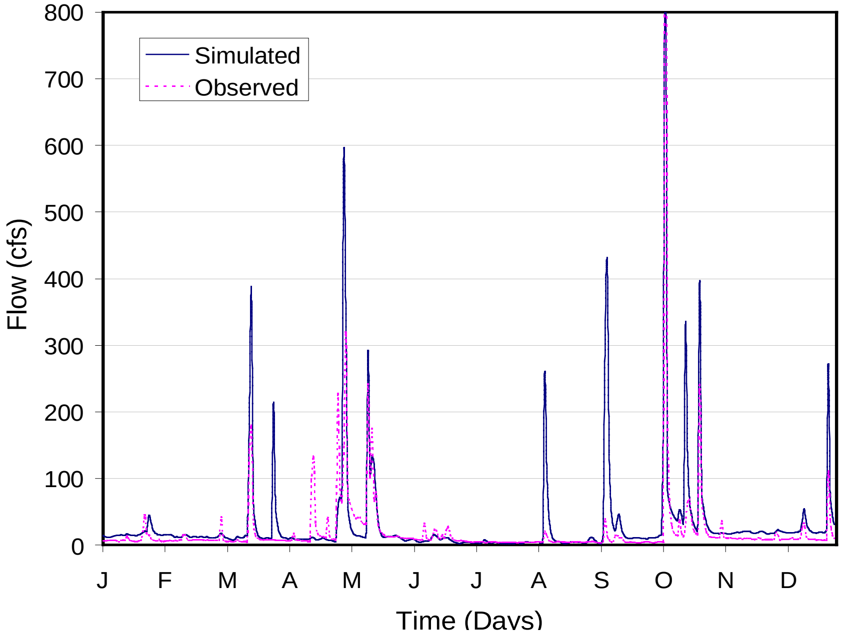

Figure 1. 1994 simulated and observed flow

The following observations can be made from the graph. Base flow is over-predicted for some winter and spring months. Extreme storm events are not well predicted by the model. These deficiencies can be attributed to the following:

1. Data from only one gauging station was available for calibration of the entire watershed. This considerably limits the extent to which calibration can be done,

especially of a watershed covering an area of about 130,000 acres. Technical experts suggest using at least 5 gauging stations for good calibration.

2. Weather data that is representative of the watershed area under study was lacking. Data from a weather station that is 20 miles away from the gauging station was used. Moreover, the precipitation was assumed to be uniform over the entire watershed, which in reality might not be the case for a big watershed. This introduces an uncertainty in the modeling process as some localized events get wrongly introduced in the simulation. A distributed data covering the entire watershed area is needed for good calibration.
3. Calibration was attempted using the “lumped parameter” approach. In other words, all types of land segments were assigned same parameter values. Assigning parameter values based on type of land-use and/or location could have improved calibration. However, this involves a detailed study of the land-use characteristics and thorough knowledge of local conditions in the watershed, which was beyond the scope of this project.

Figure 2 shows a scatter plot of observed vs. predicted flows at USGS gauging station 08181480 on Leon Creek. R-squared value of 0.657 indicates a fairly reasonable prediction for hydrology. The slope of the line is about 0.9.

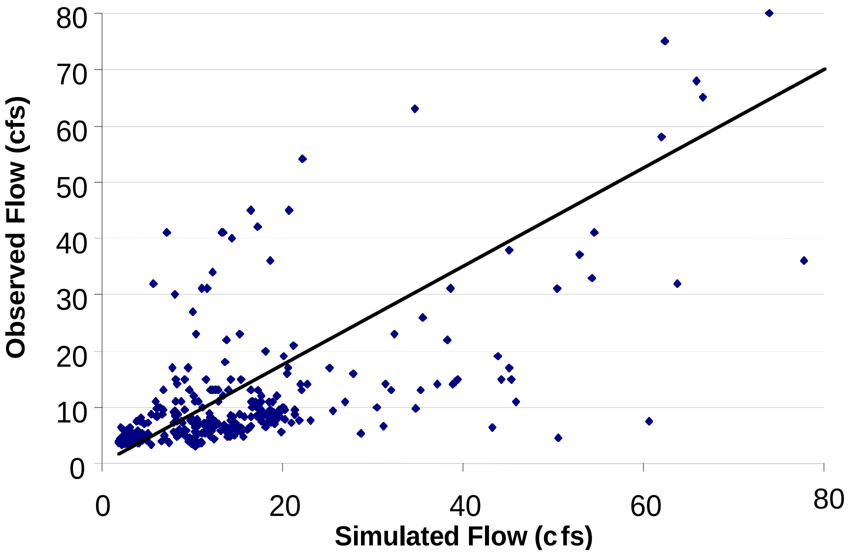

Figure 2. 1994 scatter plot of observed vs. simulated flow (R^2 = 0.647; m = 0.875)

Validation

The model was validated for the year 1990, which represents a similar year to 1994 in terms of precipitation. Figure 3 shows a graph of the observed vs. predicted flows at USGS gauging station on Leon Creek near I.H. 35 for the year 1990. Figure 4 shows a scatter plot of observed vs. predicted flows at USGS gauging station 08181480 on Leon Creek for the year 1990. The R-squared value is about 0.59, which indicates a fairly reasonable validation. The slope of the line is about 1.1.

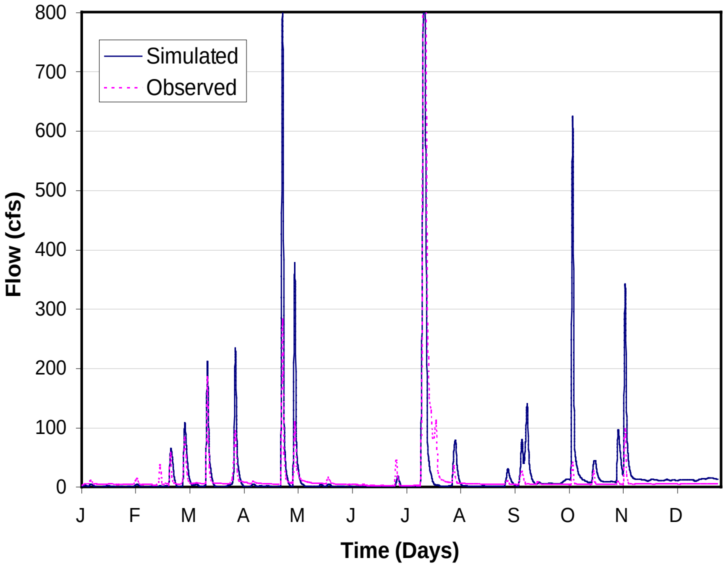

Figure 3. 1990 simulated and observed flow

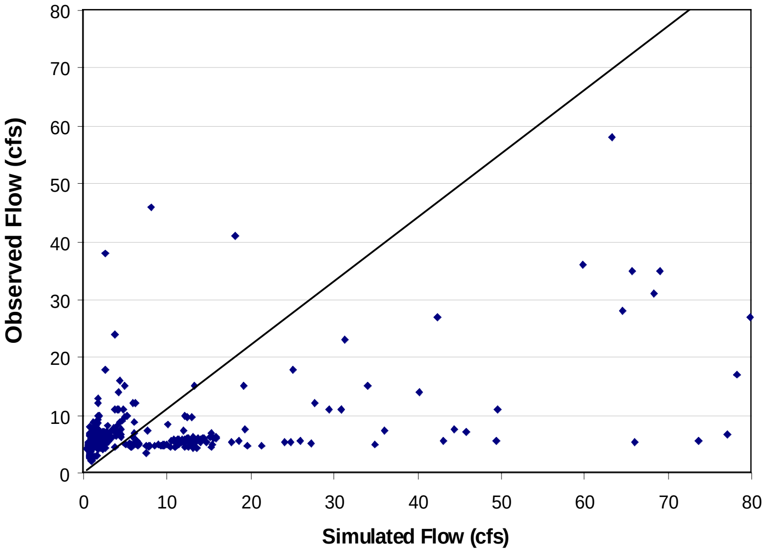

Figure 4. 1990 scatter plot of observed vs. simulated flow (R^2 = 0.59; m = 1.112)

Hydrology sensitivity analysis

Three model parameters that affect base flow and overall water balance respectively were considered for sensitivity analysis. These parameters were soil infiltration capacity (INFILT) and deep percolation losses (DEEPFR) in the Pervious Land Module (PERLND) and retention storage capacity (RETSC) in the Impervious Land Module (IMPLND). A simple sensitivity analysis was performed by varying the parameters by +/- 50 percent of the calibrated values.

In NPSM/HSPF, INFILT is the parameter that controls the division of precipitation into surface and sub-surface flow and storage compartments (BASINS Tech. Note). Higher INFILT values means higher base flow in streams as more water goes to the sub-surface. Lower INFILT values mean that more water flows as surface runoff and less water percolates, leading to lower base flow. Infiltration also affects the overall runoff volume. The more the infiltration, the higher the chance for evapotraspiration losses from soil layers. Similarly, in conjunction with DEEPFR (deep percolation), higher INFILT values lead to larger permanent losses from the watershed. It was found that increasing the INFILT value by 50 percent lead to an increase of 23 percent in the overall runoff volume and an increase of 87 percent in average base flow for the year 1994. Decreasing the INFILT value by 50 percent decreased the overall runoff volume by 22 percent and the average base flow by 74 percent for the year 1994.

DEEPFR in NPSM/HSPF is the fraction of infiltrating water that is lost to deep percolation. 1-DEEPFR then is the fraction available as active groundwater storage and hence contributes to base flow in the streams. Portions of a watershed at higher elevations are more prone to groundwater losses since there might be lateral outflows to low-lying aquifers outsides the watershed. An example of this inter-watershed transfer is the significant flow from Edward's Aquifer to Comal Springs. During 1980, nearly 48 percent of the spring discharge form Edwards Aquifer was from Comal Springs in Comal County (Ryder, 1996). DEEPFR is also used to denote losses that may not be measured at the flow gage used for calibration, such as flow around or under the gage site. On account of the above reasons, DEEFR was set to 0.4, which is a rather high value. However, it gave a reasonable water balance. A detailed study of groundwater conditions is needed to verify this value. A 50 percent increase in DEEPFR led to a 29.6 percent decrease in overall runoff volume for the year 1994. Decreasing DEEPFR by 50 percent increased the overall runoff volume by 41 percent for the year 1993.

RETSC is the depth of water that collects on the impervious surface before any runoff occurs. This directly affects the amount of storm water runoff in streams and hence the overall runoff volume. A 50 percent increase in RETSC led to a 10 percent decrease in overall runoff volume for the year 1993. Decreasing RETSC by 50 percent increased overall runoff volume by 14.3 percent for the year 1993. It should be noted that RETSC does not affect base flow in the streams, but only the surface runoff from impervious land.

Temperature

Temperature plays a significant role in the solubility of oxygen in water. Oxygen, being a non-polar molecular compound is not highly soluble in water.

Solubility of oxygen depends on water temperature and salinity among others and can range from 4ppm[1] to 15ppm. Higher water temperatures demonstrate lower solubility of oxygen and vice-versa. However, water temperature and DO are not related linearly. To account for temperature therefore, it is necessary to consider the percentage saturation. DO is then denoted as a percentage of the saturation value for a particular temperature. For example, a DO concentration of 7.5 mg/l (or ppm) might represent a 90 percent saturation, which means a good turnover for DO at that particular temperature. However the same concentration of 7.5 mg/l might represent 60 percent saturation, thus indicating a poor turnover for that particular temperature.

Temperature of water is a linear regression function of air temperature in NPSM. It was observed that simulated water temperature followed the air temperature curve and was lower than the air temperature, which is usually the case for small streams. As the volume of water is not large compared to a reservoir or lake, the water is expected to gain and lose heat quickly and hence follow the air temperature curve in shape. For this project, calibration for water temperature was found to be difficult for the following reasons:

1. No hourly-observed data was available for the simulation period. Hourly data was available for a period of two weeks in August 2000, January 2000 and July 2000 from the water quality Datasondes deployed in the creek. The data availability constraints within BASINS and NPSM restrict the simulation of the

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[1] parts per million

model up to the year 1995. Hence, it was not possible to simulate the model for the year 2000.

2. Some “grab sample” data was available from SARA for the years 1994-97. However, the quantity of data was very less. For example, only 16 readings were available for the year 1994 at the SARA monitoring site near Leon Creek Wastewater Treatment Plant. These readings represent a “snap-shot” of the water conditions at a particular time of the day and by no means represent the hourly values or even daily means. Thus, this data set is of practically no use for calibration purposes. Moreover, the location of data collection was different from the location of the calibration point, although it was on the same stream segment as the calibration point. Depending on the conditions surrounding the sampling points, the data can vary considerably within the same reach segment. For example, the water temperatures at a location surrounded by shade can be lower than a down stream or upstream location where there is no shade.

Considering the above factors, it is evident that calibration for temperature is a not possible for the present study. The same holds true for DO. Moreover, the aim of the project was not to use the model for deterministic analysis, but rather to analyze trends. Using a complex and highly parameterized model such as NPSM (HSPF) itself involves a big learning curve, much less using it to simulate such a complex constituent as DO. The objective of the project was to be able to use NPSM to successfully simulate the various physical, chemical and biological processes taking place in the watershed and to compare simulated trends with the trends actually observed. In other words, the objective was to see how effective the model simulates complex processes, rather than how accurately it does it. Extensive calibration therefore was neither a priority nor a possibility within the given time frame and data constraints. In absence of calibration, a trend analysis is the best option to determine whether the model is doing what it is supposed to do.

Dissolved Oxygen

As pointed in the earlier section, calibration for DO is not possible for the present study. From the standpoint of the NPSM model, what is of importance however is whether that model can simulate diurnal DO variations within a stream segment. For the purpose of trend analysis, the data collected using Datasondes at the sampling site on Lackland Airforce Base was used. January and July 2000 data was chosen to represent cold and hot weather conditions. As explained in the previous section, the model could not be setup for year 2000 simulation period. Hence, the 1994 water year was chosen for simulation of DO with the model. 1994 happens to be the most recent year that has similar precipitation and flow trends as the year 2000. The following criteria were used:

1. Annual precipitation comparison
2. Monthly precipitation comparison
3. Mean daily stream flow comparison during the period for which data was collected using Datasondes.

Appendix G shows the comparison charts for the above criteria. Various module sections within NPSM were chosen to simulate DO. These represent to a large extent, almost all of the complex processes taking place in the watershed and in the streams. These processes include fate and transport of BOD and nutrient loading on land surfaces, benthal oxygen demand, phytoplankton influences, alga respiration and sediment oxygen demand among others. Appendix H shows the NPSM simulation module matrix for DO simulation. Appendix I shows the DO parameter definition table for NPSM. The table also gives the default values and the maximum and minimum values as defined for the model. A few parameters were changed from their default values. Their values are also given in Appendix I. Quantities such as BOD and nutrient application rates were supplied by the user since there were no default values. Nutrient application rates were estimated from a report of the United States Department of Agriculture (UDSA) (Lander and Moffit, 1996). These rates were chosen just to demonstrate that nutrient and BOD loading processes could be simulated by NPSM. The model was then run for the simulation period 1994. Figure 5 shows simulated hourly DO for January 1994 as compared to observed hourly DO for January 2000 during the period starting 26th January and ending 31st January. Similarly, Figure 6 shows simulated hourly DO for July 1994 as compared to observed hourly DO for July 2000 during the period starting 26th July and ending 29th July.

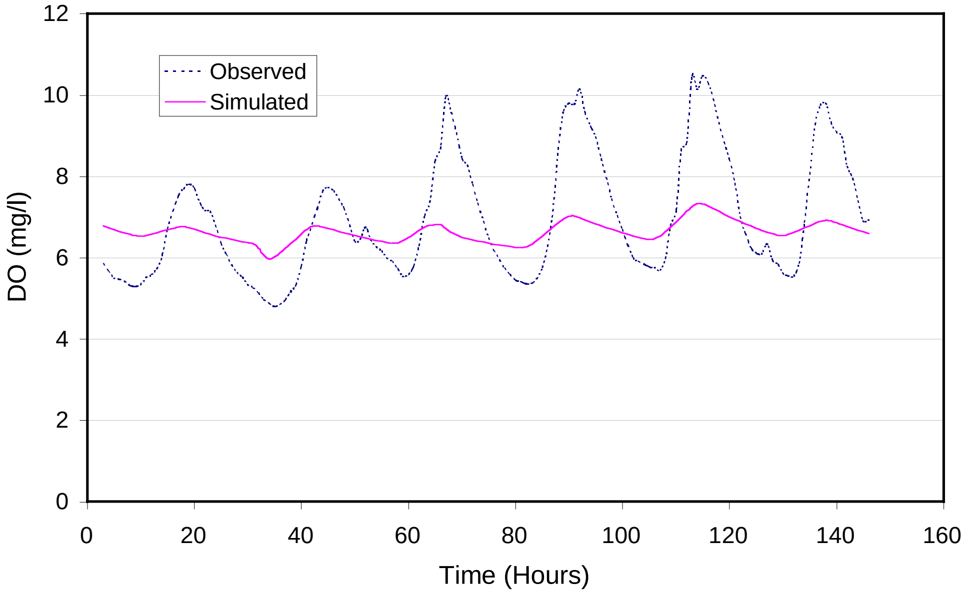

Figure 5. 1994 simulated and 2000 observed hourly DO during Jan. 26 to Jan. 31

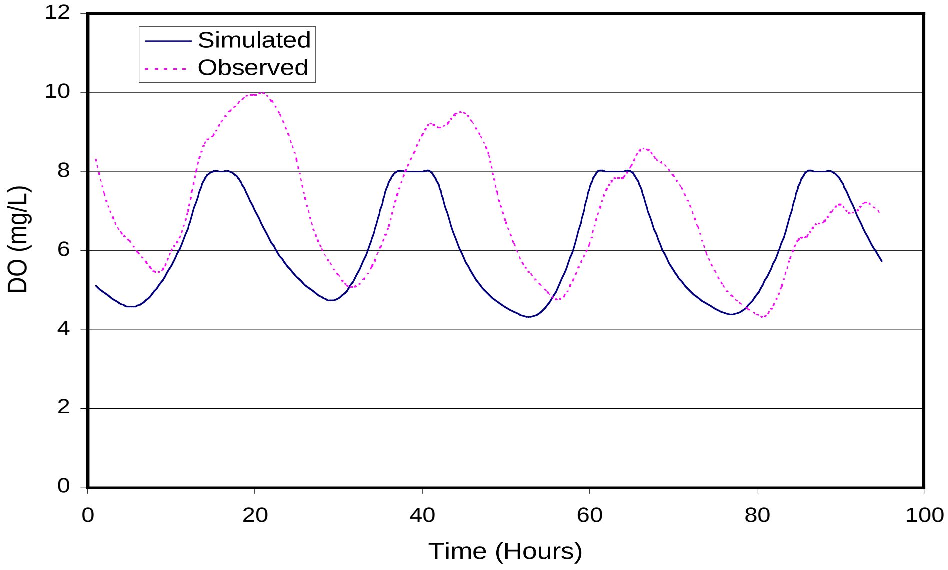

Figure 6. 1994 simulated and 2000 observed hourly DO during Jul. 26 to Jul. 29

The following points need to be considered before analyzing trends:

1. The simulation site and the sampling site are located on the same stream reach as designated by NPSM and are roughly 8 miles apart. The simulation site is the most downstream point of stream no. 6 as designated by NPSM and as shown in Map 7.
2. There could be differences in water temperatures, flows, shading, riparian vegetation and algae concentration at the simulation site and the sampling site.

Two means of trend analysis were used for comparison of data. The first was a visual analysis of the curves and the second was a comparison of the mean daily DO values. The following observations were made:

1. The simulated DO curve follows the observed DO curve in shape. Its peaks roughly at the same time that the observed curve peaks and sags roughly at the same time that the observed curve sags.
2. The daily variation of simulated DO is within the same range as the daily variation of observed DO.
3. The daily mean simulated DO is within 11 percent of the daily mean observed DO for January period and within 21 percent of the daily mean observed DO .for July period.

Based on the above observations, the following conclusions can be drawn:

1. The model is capable of simulating the diurnal variation of DO for a stream segment.
2. For the scope of the present study, the DO simulation done by the model is satisfactory.
3. The model presently cannot accurately reproduce the diurnal swings in DO in amplitude. This might be due to the fact that simulated organic loading, nutrient loading and algal concentrations in the streams is not representative of real conditions. With extensive calibration and continuous sampling data, the simulation curve could be improved to represent actual conditions.

Sensitivity analysis for DO

Simulation of the entire DO source and sink cycle in a stream is highly complex and requires an in-depth understanding of in-stream processes. These include BOD, BOD settling, sediment oxygen demand, benthic influences, algal respiration and photosynthesis among others. Besides, these processes can vary significantly along the length of a stream depending on local conditions such as flow, land-use, shading and nutrient loading. Surface processes such as the BOD loading and washoff, nutrient application and washoff, plant uptake of nutrients and atmospheric deposition of nitrogen compounds also indirectly affect the in-stream processes. NPSM has the capability of simulating all these processes involving a large number of parameters. Understanding enough about these parameters in order to get calibrated values involves extensive research that is often not possible due to time constraints or lack of data. As such, there is an inherent uncertainty built in the model because of over-parameterization.

Due to the above reasons, it was though best to keep default values for most in-stream parameters that affect DO. A few parameters were changed from their default values and their values are given in Appendix I. Performing a detailed sensitivity analysis was beyond the scope of this project. It was however found that in-stream DO concentration was extremely sensitive to groundwater concentration of DO. This is reasonable since groundwater recharges Leon Creek via springs. A simple sensitive analysis was performed by varying the groundwater DO concentration (GRNDDOX) by +/-50 percent from the calibrated monthly values. An increase of 50 percent in GRNDDOX led to an average increase of 35 percent in the predicted average daily DO concentration during the period January 26, 1994 to January 31 1994. Decreasing GRNNDOX by 50 percent led to a 44.5 percent decrease in average daily DO concentration over the same period. Similarly, an increase of 50 percent in GRNDDOX led to an average increase of 12.7 percent in the predicted average daily DO concentration during the period July 26, 1994 to July 29, 1994. Decreasing GRNNDOX by 50 percent led to a 20.8 percent decrease in average daily DO concentration over the same period.

3.5 Low-flow Augmentation to Rectify DO Problems: A Rehabilitation Approach

Introduction

The ultimate objective of this project was to evaluate the effects of low flow augmentation on the DO concentration of Leon Creek. As stated earlier, most of the DO problems in streams occur during low flow conditions when the water is stagnant, the concentration of nutrients, algae and BOD is high and the reaeration rate is low. The July 2000 observed DO graph (Figure 6) is an example of such conditions. It shows that the DO criterion was violated at many instances with concentrations as low as 4.3 mg/l. Such low flow conditions usually occur during dry periods when there is no rainfall and the temperatures are hot. It should be noted that Texas experienced one of the hottest summers that year with record temperatures and record number of consecutive days without significant precipitation.

The city of San Antonio boasts of a history of water recycling dating back to the 1960s when the city public service (CPS), the electric utility started using treated wastewater from the Calaveras and Braunig lakes in its cooling towers (Texas Water Savers, 1998). In the recent years, in an effort to maintain the sustainability of Edward’s Aquifer, SAWS started to develop the San Antonio Water Recycling Project. As part of this project, treated wastewater from the Leon Creek Waste Water Treatment Plant (see map 8 of Appendix A) will be used for irrigation, instream flows and industrial purposes. Pipelines painted in purple have already been installed. In a pilot project in 1996, water treated at the Leon Creek plant and stored at Lake Mitchell was delivered to Mission del Lago Golf Course for irrigation purposes. The Water

Recycling Project is expected to save about 11 billion gallons of Edwards Aquifer water annually for potable use (Texas Water Savers, 1998).

Approach

For the present study, a hypothetical quantity of water having quality representative of the Leon Creek Wastewater Treatment Plant discharge was assumed to be conveyed from the plant to an upstream site via the recycling pipe. This treated wastewater was discharged at an arbitrarily chosen upstream point to augment in-stream flow. This scenario can be represented in NPSM by adding a "point source" to the stream of interest. The exact location of the point source can be specified by entering a "mile point" number i.e. the number of miles from the most downstream point on the stream of interest. For the present study, stream segment number 5 (Culebra Creek) in NPSM was chosen as the receiving stream for flow augmentation. The mile point for the point source was fixed at 3.75 miles, which is the headwater for the creek. Map 8 of Appendix A shows the point of application of flow and the point at which water quality was measured by the model. Four parameters were chosen to represent the quality of water entering as point source in NPSM. These were nitrate-nitrogen, phosphate (dissolved ortho-phosphorus), DO and BOD. Representative values for nitrate-nitrogen and phosphate were obtained from the data obtained from SARA at its monitoring site located near the treatment plant. No data for BOD concentration were available from SARA. BOD data was acquired from effluent data collected by the San Antonio Water System (SAWS) monitoring site near the treatment plant. Annual average BOD concentration for the 6-year period 1992-98 was used as a representative value. Table 6 shows the representative values for water quality for the Leon Creek Wastewater Treatment Plant discharge.

Table 6. Representative values for water quality constituents at Leon Creek WWTP

Constituent	**Concentration/Value**
BOD	2.25 mg/l
Nitrate Nitrogen	5.5 mg/l
Phosphorous (Phosphate)	1.3 mg/l
Temperature	27 ^{o}C
PH	7.0
Dissolved Oxygen	7.0 mg/l

Scenario analysis

A 3-month period with no significant rainfall was chosen between 1st July and 30th September of years 1993, 1994 and 1995. This constituted a hot weather low-flow period as compared to other months. The periods were chosen based on the following four criteria:

1. Palmer Drought Severity Index
2. Monthly mean precipitation as observed at San Antonio International Airport.
3. Monthly mean temperatures as observed at San Antonio International Airport.
4. Monthly mean observed flows as observed at USGS gauging station number 08181480, which was used for hydrology calibration.

Appendix J gives an explanation as well as graphical representation of the above criteria. Six scenarios were evaluated. They are as follows:

1. Control (CTRL) – Simulated flow and DO without any external flow source. This is the “as is” scenario.

2. Scenario 1 (S1) – Flow augmented by adding a point source with 0.25 times base flow.

3. Scenario 2 (S2) – Flow augmented by adding point source with 0.5 times base flow.

4. Scenario 3 (S3) – Flow augmented by adding point source with 1 times base flow.

5. Scenario 4 (S4) - Flow augmented by adding point source with 2 times base flow.

6. Scenario 5 (S5) - Flow augmented by adding point source with 4 times base flow.

Daily mean DO concentrations were then calculated by averaging over the 24-hour period for each day, for 92 days. Plots of daily mean DO for each scenario during the 1993, 1994 and 1995 study periods are shown in figures 7, 8 and 9 respectively.

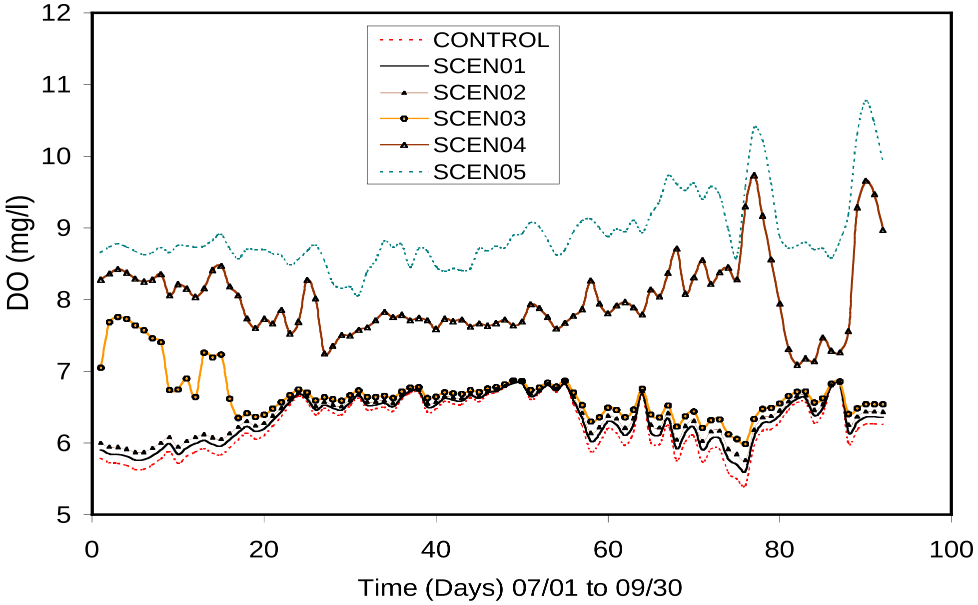

Figure 7. Daily mean DO during 1993 scenario analysis

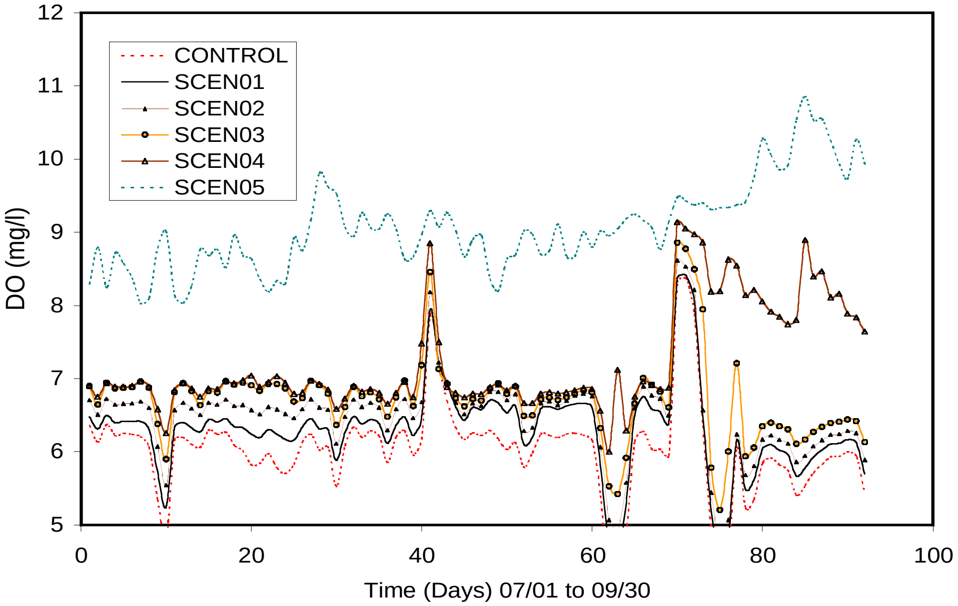

Figure 8. Daily mean DO during 1994 scenario analysis

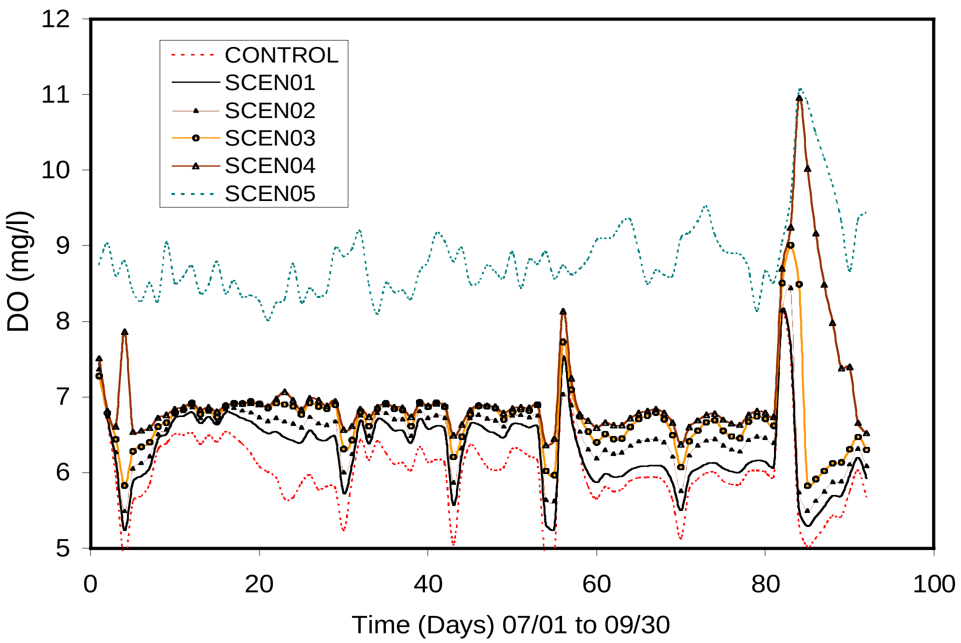

Figure 9. Daily mean DO during 1995 scenario analysis

To evaluate the scenarios, statistical analysis was performed using the Statistical Analysis System (SAS) software. The sample population consisted of 92 data points for each scenario. Each data point represented the daily mean DO concentration in mg/l over the chosen three-month low-flow period for 1993, 1994 and 1995. Following methods were used for comparison of the datasets and means:

1. Kruskal-Wallis Chi-Square Approximation Test – Pre-test for differences.
2. Student-Neuman-Keuls (SNK) Test
3. Tukey’s Studentized Range (HSD) Test

The output of statistical analysis is given in appendix K.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Statistical Analysis of Scenarios

Box plots of the six scenarios depicting the treatment type (quantity of flow augmentation) as the predictor variable (X) and daily mean DO (mg/l) as the response variable (Y) are shown in figures 10, 11 and 12 below.

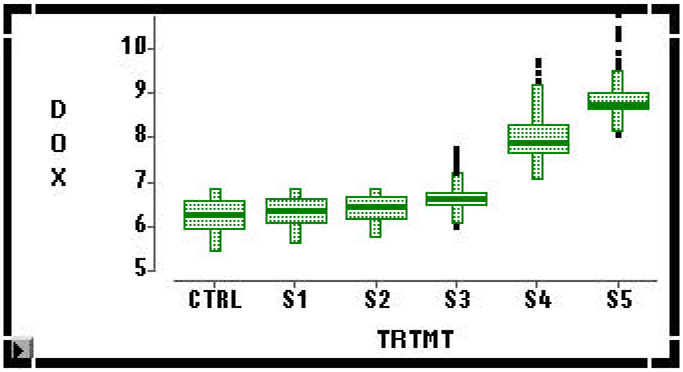

Figure 10. Box plot for 1993 scenario analysis

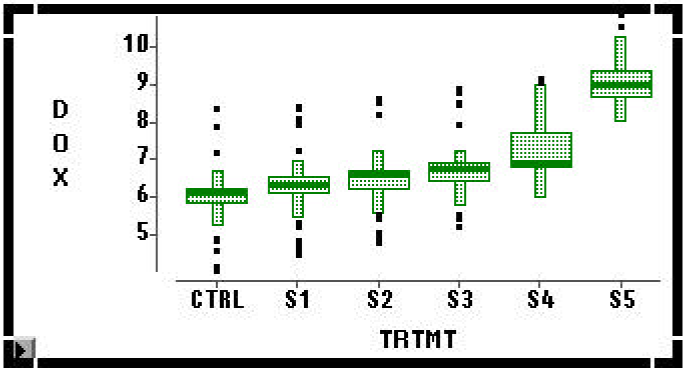

Figure 11. Box plot for 1994 scenario analysis

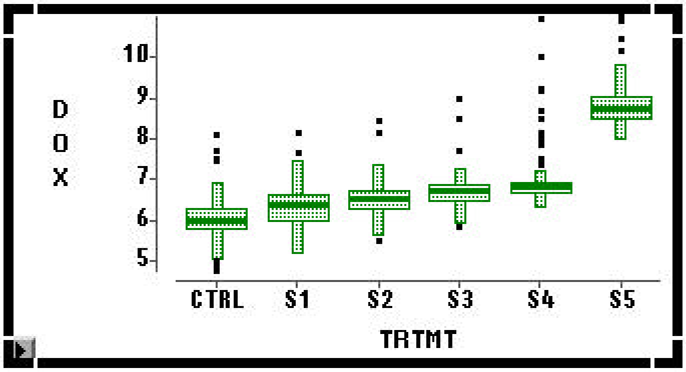

Figure 12. Box plot for 1995 scenario analysis

It can be incurred from the box plots that the data from the sample populations is not normally distributed. Most of the sample populations are skewed and some of them are heavily tailed. A visual comparison of the box plots shows that there is a considerable overlapping between the first four populations (CTRL, S1, S2 and S3). However, sample population S5 shows a significantly different mean than the rest. This suggests that the null hypothesis (H_0 = all means are equal) is not true. A statistical basis for arriving at this conclusion is the one-way analysis of variance (one-way ANOVA) test. However, the one-way ANOVA test assumes that the data is normally distributed. Since the sample populations are not normally distributed, an alternative test called the Kruskal-Wallis Test was used. The Kruskal-Wallis Test is good for data that is highly skewed. Moreover it is a non-parametric test, i.e. it makes no assumption about population distribution. It tests the following two hypotheses:

H_0 (Null hypothesis) = All k populations have the same distribution

H_1 = Data from some populations tend to be larger than data from others.

From the SAS output of Kruskal-Wallis test in Appendix L, it was observed that with a 95% confidence level (_ = 0.05), the p-value (i.e. probability > Chi-square) was less than _ for all three periods. Hence the null hypothesis was rejected and it was concluded that some means differ. To find which means differ, the Student-Newman-Keuls Test and the Tukey's Studentized Range Test were performed in SAS. A confidence level of 95% (_ = 0.05) was set for the tests. SAS output for the test is provided in Appendix L. Table 7 gives a summary of the statistical analysis.

Table 7. Summary of statistical analysis of augmentation scenarios

Scenario	Description	Rank	1993		1994		1995	
			SNK Grouping	**Tukey Grouping**	**SNK Grouping**	**Tukey Grouping**	**SNK Grouping**	**Tukey Grouping**
CONTROL	“As is”	6	E	D	F	E	F	E
			E	D				
S1	0.25 times base-flow (1.25 cfs[*])	5	E D	D	E	D	E	D
			D	D		D		D
S2	0.5 times base-flow (2.5cfs)	4	D	D	D	D	D	D
S3	1 times base-flow (5 cfs)	3	C	C	C	C	C	C
S4	2 times base-flow (10 cfs)	2	B	B	B	B	B	B
S5	4 times base-flow (20 cfs)	1	A	A	A	A	A	A

Note:

1. Average base flow for the study period during 1993, 1994, and 1995 was taken as 5 cfs.
2. Scenarios are ranked in descending order of mean daily DO for the sample populations.
3. Means with the same letter are not significantly different.

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[*] cubic feet per second

From the output the following observations were made:

Student-Newman-Keuls Test

1. The daily mean DO concentration for the sample population increases with increasing flows; i.e. S5 > S4 > S3 > S2 > S1 > CTRL.
2. 1993 scenario analysis showed no significant difference in mean DO for the Control, S1 and S2 scenarios. A significance difference in means is observed from scenario S3 onwards.
3. 1994 scenario analysis showed a significant difference in mean DO for all scenarios.
4. 1995 scenario analysis showed a significant difference in mean DO for all scenarios.

Tukey's Studentized Range Test

1. Daily mean DO concentration for the sample population increases with increasing flows; i.e. S5 > S4 > S3 > S2 > S1 > CTRL.
2. 1993 scenario analysis showed no significant difference in mean DO for the Control, S1 and S2 scenarios. A significance difference in means is observed from scenario S3 onwards.

3. 1994 scenario analysis showed no significant difference in mean DO for scenarios S1 and S2. All other scenario means were significantly different from each other.

4. 1995 scenario analysis showed no significant difference in mean DO for scenarios S1 and S2. All other scenario means were significantly different from each other.

Another important observation that was made from the box plots is that for 1994, scenario S1 and S2 as well as the control scenario had some data point that fell below the DO criteria of 5 mg/l. Similarly for 1995, some data point in the control scenario (CTRL) fell below 5mg/l where as some data point in scenario S1 were close to 5mg/l.

4.2 Interpretation of Results: Effects of Low-flow Augmentation

From the statistical analysis, the following conclusions can be made:

1. Increasing the flow in streams increases the mean daily DO concentration during low flow periods for the years 1993, 1994 and 1995

2. Scenarios S1 and S2 are not significantly different from each other and both show an increase in mean daily DO concentration as compared to the control scenario. However since some data points in S1 and S2 fall below DO criteria of 5 mg/l during at least one low-flow period (1994), they are not acceptable.

3. Scenario S3 shows a significantly different mean than scenarios S2 and S3 and also none of the data points in S3 fall below 5 mg/l. The same is true for S4 and S5. Hence it can be concluded that one can see a significant change (increase) in mean daily DO concentration from scenario S3 onwards.

4. Since the significance level of the tests was set to _ = 0.05, one can be 95% confident of the overall multiple comparison of means. This means that the confidence level for comparison of any two means in the ANOVA data set is greater than 95%. Hence, one can be more than 95% confident in saying that scenario S3 has a significantly greater mean DO than scenarios CTRL, S1 and S2 compared one at a time. Same holds true for comparing S4 and S5 with CTRL, S1, S2 and S3 respectively, one at a time.

One should note from the above discussion that scenario S3 defines a “threshold response”, meaning a significant change in the system is observed from scenario S3 onwards (with a certain confidence level). A watershed level modeling of DO is a highly complex process fraught with uncertainty in data, parameter estimation (because of lack of knowledge of various processes) and model performance. Hence, in order to be more certain of observing a positive change in system response, scenarios beyond the threshold response scenario should be considered strongly. Referring to figures 7, 8 and 9 in chapter III, one can visually interpret the response of a complex system. One can see that the system behaves linearly for scenarios S1, S2 and S3 and starts showing non-linear response from scenario S4 onwards. Scenario S5 shows a significantly different response for all three years whereas scenario S4 shows a significantly different response for the year 1994.

4.3 Feasibility of Scenario Implementation

The total capacity of Leon Creek Wastewater Treatment Plant is about 32mgd[2]. About 26mgd of this treated wastewater is earmarked for recycling purposes. The rest will be split up for downstream release and for delivery to Mitchell Lake. The recycling pipes are 42 inches in diameter and designed to deliver 26mgd of treated wastewater to various customers all year round. This translates to a flow of about 40.3 cfs. Hence, the flow augmentation scenarios of 5 cfs (S3), 10 cfs (S4) and 20 cfs (S5) for the three-month period can be implemented without any additional pumping or infrastructure costs to the City. As of now, no quantity of recycled water has been earmarked for in stream releases from the Leon Creek Water Recycling Center. Whether the City can allocate recycled water for flow augmentation depends on its commitments to other customers and is an issue that is beyond the scope of this study.

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[2] million gallons per day

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The hypothesis tested in this study was that increasing dry period base flow in streams by discharge from a wastewater treatment plant (with pre-defined water quality parameters) enhances water quality in terms of DO. This has been demonstrated to be the case. An increase in daily mean DO was observed for all treatment scenarios tested. With 95 % confidence level, a significant change was observed with scenario S3 (one times base flow), i.e. doubling the base flow during low-flow periods. This constitutes a risk-based design approach to remedy DO problems by low-flow augmentation. In other words, we can say with 95% confidence that a minimum flow augmentation of one times base flow can remedy DO problems during dry, low-flow periods. This amounts to a discharge of 5 cfs during each three-month period. As mentioned in the previous chapter, the various flow augmentation alternatives are well within the capacity of the plant.

As stated in chapter IV, scenario S3 defines the “threshold response” of a complex system fraught with uncertainty. Hence, to increase the chances of seeing a significant improvement in the system, scenarios S4 or S5 are highly recommended. As is evident, these alternatives are also within the capacity of the plant.

The basis of the above hypothesis is that the treatment plant discharge has a pre-defined water quality. The above hypothesis might not hold true for any wastewater treatment plant discharge. In fact, in all probability, the hypothesis will fail if there is increasing organic and nutrient burden (higher BOD, nitrates and phosphates) from the discharge. Studying the diurnal swings of DO cycle can assess the effects of such burden.

From a design consideration standpoint, carrying wastewater in pipelines to the point of flow-augmentation will completely strip it of its DO content. Therefore a passive entrainment aeration system is highly recommended at the point of discharge so that plenty of oxygen is available to aquatic organisms before the water enters the stream. This can be accomplished using gravity powered entrainment devices such as cascade- reaeration. Potential odor problems must be given consideration before deciding on a reaeartion process. However, given the quality of the water (Type I, the highest grade effluent), odor problems are not likely to occur.

Presently, the model is loosely calibrated for hydrology as well as DO. Besides, A very simplistic built-up and wash-off process was simulated for BOD and nutrient loading from land surfaces. This might not represent true conditions. As such, for now the model is good for predicting trends and cannot accurately simulate diurnal swings. Lack of historic data for DO is also a factor that limited model calibration. A detailed knowledge of nitrogen and phosphorus cycle on land surfaces, and in stream processes such as reaeration, algal respiration rate, sediment oxygen demand and algal growth among others is required for better model performance. Availability of representative precipitation data is also very crucial since the model is driven by precipitation.

The project demonstrated that the Non Point Source Model (NPSM), is capable of simulating watershed processes as well as in-stream processes and is good for a screening level analysis of scenarios and trends. However the model is extensively parameterized and requires a big learning curve for detailed studies. Thus comprehensive data requirements, overparametrization, lack of detailed knowledge and time constraints have limited the model performance. Moreover, the DO simulation process using NPSM has not been documented in detail in literature or elsewhere. As such, the model is fraught with bugs that are known only to a few experts. Some bugs were encountered during model use and they have been documented in Appendix K.

As stated earlier, a screening level analysis was performed to evaluate scenarios and observe trends. It is recommended that a more detailed analysis be carried out using a steady-state in stream water quality model such as QUAL2E. DO conditions can then be studied in detailed segment by segment there by giving a longitudinal resolution to water quality that is not possible using NPSM. This way, specific lengths of the creek that have low-flow DO problems can be identified and scenarios evaluated.

Finally, there is uncertainty involved in any modeling process. This uncertainty gets translated in model predictions. Therefore, it is critical for decision-makers to be cognizant of this uncertainty before making decisions based on model performance.