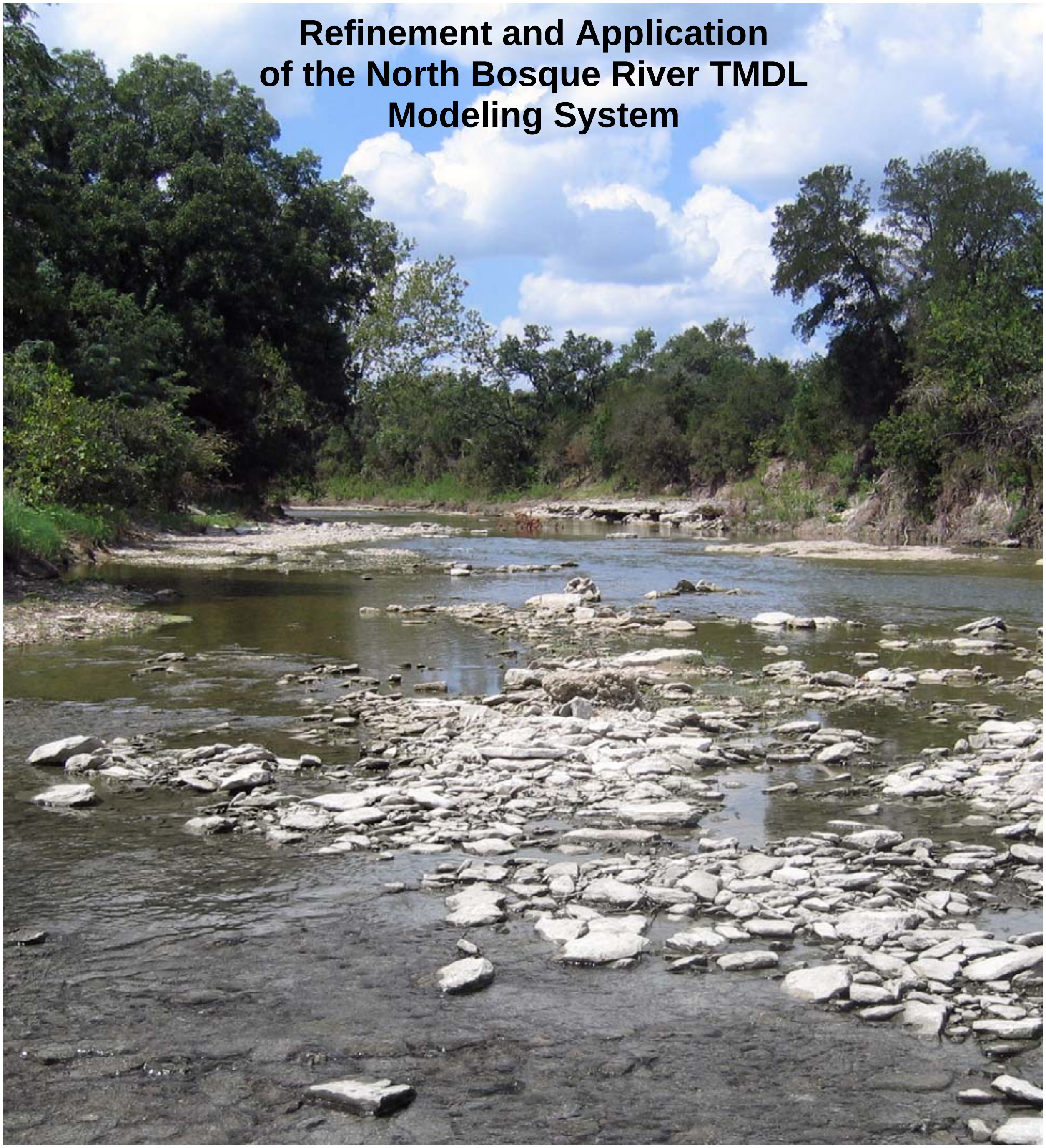
Refinement and Application of the North Bosque River TMDL Modeling System



Prepared by:

James B. Houser
Larry M. Hauck
Texas Institute for Applied Environmental Research
Tarleton State University
Stephenville, Texas

PR1001

March 2010

Refinement and Application of the North Bosque River TMDL Modeling System

Prepared for:

Texas Commission on Environmental Quality

TMDL Team

Prepared by:

James B. Houser
Larry M. Hauck
Texas Institute for Applied Environmental Research
Tarleton State University
Stephenville, Texas

PR1001

March 2010

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 Report Scope

Section 303(d) of the Clean Water Act (CWA) and U.S. Environmental Protection Agency (USEPA) Water Quality Planning and Management Regulations (40 Code of Federal Regulations [CFR] Part 130) require States to develop total maximum daily loads (TMDLs) for water bodies not meeting designated uses where water quality-based controls are in place. TMDLs establish the allowable loadings of pollutants or other quantifiable parameters for a water body based on the relationship between pollution sources and instream water quality conditions, so States can implement water quality-based controls to reduce pollution from both point and nonpoint sources and restore and maintain the quality of its water resources (USEPA, 1991).

The Bosque River is located in north central Texas, northwest of the City of Waco, and is a tributary of the Brazos River. The Bosque River is impounded at Waco, near its confluence with the Brazos River, to form Waco Lake (Segment 1225), which provides water for approximately 150,000 people. The North Bosque River (NBR) is the longest arm of the Bosque system, draining approximately 75 percent of the Waco Lake watershed, while the Middle and South Bosque Rivers and Hog Creek drain most of the remaining area (Figure 1-1).

The NBR is administratively divided between two designated water quality segments (see Figure 1-1):

- Segment 1226, North Bosque River – extends from a point 100 meters upstream of FM Road 185 in McLennan County to a point immediately upstream of the confluence of Indian Creek in Erath County
- Segment 1255, Upper North Bosque River – extends from a point immediately upstream of the confluence of Indian Creek in Erath County to the confluence of the North Fork and South Fork of the North Bosque River in Erath County

1.2 Background

In 1998 the NBR was included in the CWA § 303(d) List and assessed as impaired under narrative water quality standards related to nutrients and aquatic plant growth in the NBR (Segment 1226) and the Upper NBR (Segment 1255). Studies indicated that soluble phosphorus (P), which was analytically measured as soluble reactive P (or orthophosphate P (PO_4)), was a major form of P in the NBR and statistically better correlated to algal levels than total P (Kiesling et al., 2001), and that dairy waste application fields (WAFs) and municipal wastewater treatment plants (WWTPs) were the major controllable sources of P (McFarland and Hauck, 1999). The Texas Institute for Applied Environmental Research (TIAER) and its project team, which included Texas A&M System Blackland Research and Extension Center among others, made significant technical contributions to the Texas Commission on Environmental Quality

(TCEQ) effort to establish TMDL allocations for soluble reactive P in the NBR. The Soil Water Assessment Tool (SWAT) (Arnold et al., 1998) was applied to develop a TMDL for the NBR.

In September 2000, TCEQ released the TMDLs for the two NBR segments for public review. TMDLs for soluble reactive P were approved in 2001 by TCEQ and the USEPA for the NBR and the Upper NBR, Segments 1226 and 1255 respectively (TNRCC, 2001). The implementation plan was approved by both the TCEQ and Texas State Soil and Water Conservation Board in 2002 (TCEQ and TSSWCB, 2002). It was ascertained, however, that additional effort would be needed to address public concerns.

The development of the two TMDLs was based in part on applications of SWAT. While models are widely accepted for use in the development of TMDLs, public concerns regarding the modeling efforts for the NBR TMDLs included:

- Lack of spatial resolution in the definition of subbasins
- Exclusion of the 40 Public Law (PL)-566 flood retardation reservoirs in the watershed
- Exclusion of contributions associated with discharges from dairy lagoons and wastewater storage ponds not associated with routine dewatering

1.3 Report Purpose and Organization

The TCEQ contracted with TIAER to conduct the appropriate studies to (1) refine the SWAT model used for the TMDL simulation; (2) incorporate new data and/or knowledge regarding model-simulated activities or features; (3) validate the refined modeling system using measured streamflow and water quality data; and (4) use the refined modeling system to reanalyze the TMDL allocation.

The purpose of this report is to provide technical documentation of the model refinement process and the reanalysis of the TMDLs for soluble reactive P for the NBR and the Upper NBR. The report contains information on historical data; watershed properties; and verification and application of the refined SWAT model to provide reanalysis of the TMDL load allocation. TIAER was the technical lead entity for all studies and work provided in this report. The Center for Research in Water Resources (CRWR) at The University of Texas at Austin provided assistance in certain areas of model refinement.

Because of the extensive number of tables and graphics that are part of this report, tables and figures are provided at the end of each section in order to facilitate continuity of the text portion of the report. It is recognized that this arrangement to provide continuity of text does make access to tables and figures more difficult, and the authors apologize for that inconvenience. At the end of each section tables are provided first followed by figures.

SECTION 1

FIGURES

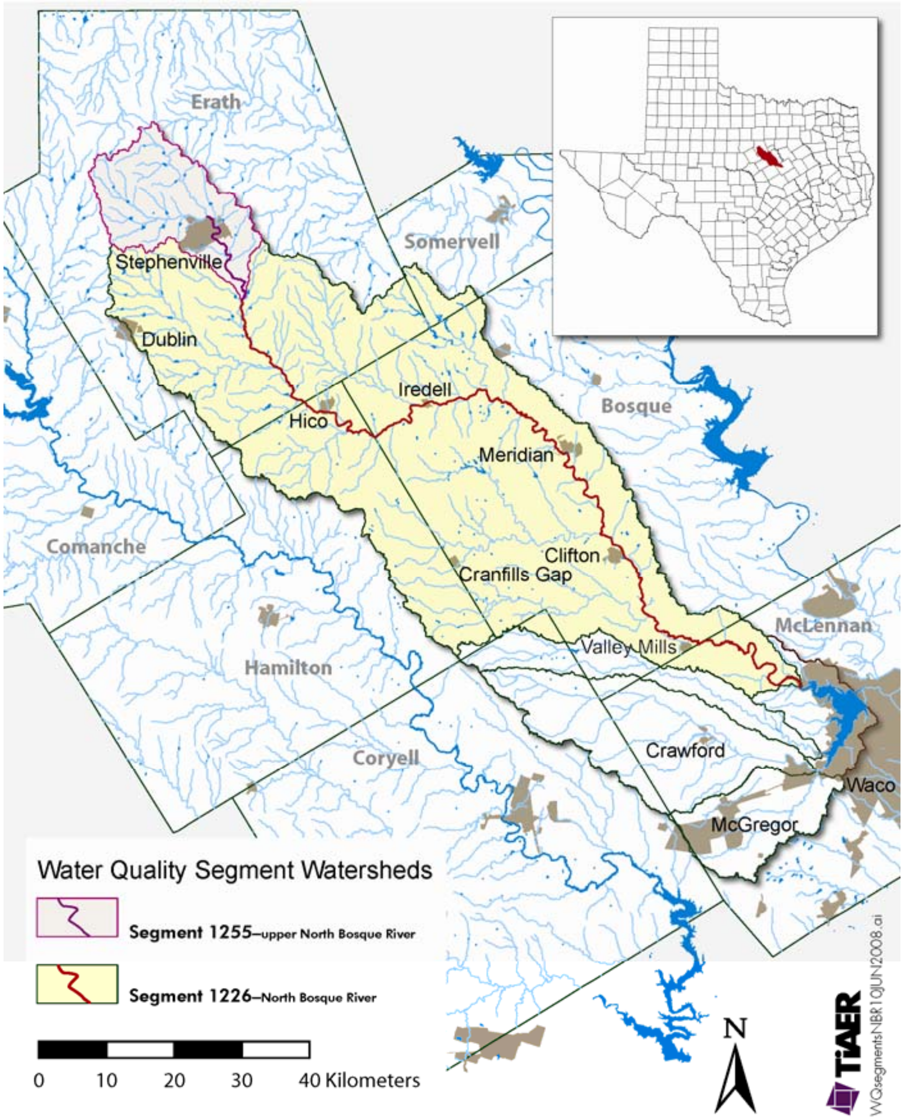


Figure 1-1 North Bosque River watershed showing classified segments 1226 and 1255

SECTION 2

MODEL AND DATA REFINEMENTS

2.1. List of Model and Data Refinements

The model used in the original TMDL effort was SWAT. The SWAT model is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. It evaluates management effects on water quality, sediment, and agricultural chemical yield in large basins. The major components of SWAT include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. SWAT divides a watershed into a number of subbasins. Hydrologic and biophysical processes are modeled within the subbasins through the use of hydrologic response units (HRUs). HRUs are lumped-parameter units based on unique combinations of soil and land use within a subbasin. SWAT is able to continuously simulate hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management on a daily time step (Arnold et al., 1998).

SWAT has an interface with ArcView known as AVSWAT. Based on user-defined inputs for subbasin delineation and HRU definition, AVSWAT automatically creates the files necessary to run SWAT using weather data and geographic information system (GIS) digital elevation model (DEM), soil, and land-use layers.

To address the concerns expressed in the public review of the TMDL, the same model (SWAT) was applied with refinements. The refinements required for the new TMDL effort were:

1) increased spatial resolution in the definition of subbasins;
2) inclusion of the 40 Public Law (PL)-566 flood retardation reservoirs in the NBR watershed;
3) contributions of discharges associated with dairy lagoons, wastewater storage ponds, and unauthorized discharges from WWTPs and their associated sewage collection systems;
4) improved instream water quality kinetics in SWAT to better simulate algae growth and nutrient dynamics that have a profound effect on average daily nutrient concentration during low flow; and
5) a new dynamic manure management component in SWAT to improve and enhance the capabilities to simulate the Natural Resources Conservation Service (NRCS) guidelines for manure management.

The refined model is hence forth referred to as SWAT-TCEQ.

2.2 Increased Spatial Resolution in the Definition of Subbasins

Spatial resolution of the NBR watershed was improved through a delineation process that defined additional subbasins within SWAT-TCEQ, particularly in the Upper NBR watershed where the majority of dairy operations are located (Figure 2-1). In addition, subbasin outlets were located to coincide with TCEQ and TIAER water quality monitoring stations and all PL-566 reservoir outlets.

2.3 Inclusion of PL-566 Flood Retardation Reservoirs

PL-566 flood retardation reservoirs were included in the new SWAT model of the watershed to improve hydrologic routing and water quality fate and transport. These flood retardation reservoirs are important hydraulic features of the Upper NBR watershed that need to be considered as part of the model refinement effort. Within the NBR watershed there are 40 flood retardation reservoirs found entirely in the headwaters of the NBR above Hico, Texas (Figure 2-2).

Two tasks were undertaken to provide information for the refinement of the hydrologic routing and water quality fate and transport components of these structures in SWAT-TCEQ. The first task involved collecting the existing design information and determining relationships of storage volume with water elevation for each reservoir to allow proper hydrologic routing. Design information to allow modeling of the hydraulic routing through each reservoir included spillway elevation, weir length, and other details (see Chapter 3 of TIAER (2006) for further details). Modifications were made to the SWAT-TCEQ code and model input reservoir files to accommodate the unique hydraulic information for each PL-566 reservoir.

The second task involved evaluation of inflow and outflow data from two PL-566 reservoirs to estimate nutrient and suspended sediment removal efficiencies. Monitoring of these two PL-566 reservoirs was initiated as a paired watershed study conducted by TIAER in the early 1990s (Hauck et al., 1994) that was continued as part of a larger basin-wide project funded by the USEPA through early 1997 (McFarland and Hauck, 1997). The two reservoirs evaluated are located within the watersheds of the South Fork and North Fork of the NBR north of Stephenville, Texas (see Figure 2-2) and represent a least impacted reservoir (UB8) and an impacted reservoir (UB3) with regard to agricultural nonpoint source pollution. Three full years of inflow and outflow data were available (1994-1996), which were analyzed to estimate sediment and nutrient removal efficiencies in both reservoirs (Table 2-1). More details on this analysis are provided in Chapter 3 of TIAER (2006). Removal efficiencies (RE) were calculated by:

$$RE = (LI_i - LO_i) / LI_i \qquad (1)$$

where LI_i is the annual loading into the reservoir for water quality constituent i and LO_i is the loading out of the reservoir for constituent i and LI and LO were estimated from measured data. The average nutrient and sediment removal efficiencies in Table 2-1 were built into the code of SWAT-TCEQ and applied to all 40 reservoirs. The application of average rates developed from interactions with the project advisory group at public meetings where it was concluded that the data for two reservoirs were insufficient to allow specification of different removal rates to individual reservoirs based on characteristics such as drainage area size, intensity of agricultural activities in the drainage area, and reservoir size. Further supporting the conclusion to use average removal rates was an analysis of the physical characteristics of 40 PL-566 reservoirs that determined reservoirs UB8 and UB3 were typical in size and drainage area.

2.4 Inclusion of Dairy Lagoons and Wastewater Storage Ponds Discharges and Unauthorized Municipal Discharges

In order to include discharges from dairy lagoons and wastewater storage ponds and discharges from municipal sanitary sewage collection systems and WWTPs, a computer code was written that operated on a daily time step and used the same input precipitation files as SWAT-TCEQ. This code was used to estimate these dairy and municipal discharges and to generate daily output files of these discharges that became SWAT-TCEQ input data to each subbasin that contained dairies and/or WWTPs. Since the code used the same precipitation files as SWAT-TCEQ, the timing of discharges was synchronized with the daily precipitation and weather files for SWAT-TCEQ and, hence, provided synchrony with simulations performed with SWAT-TCEQ.

2.4.1 Representation of Dairy Lagoons and Wastewater Storage Ponds

A water balance model was developed to simulate potential discharges or overflows from dairy wastewater storage ponds and waste treatment lagoons, hereafter referred to collectively as lagoons. The lagoon water balance model considered the physical characteristics (design volumes, contributing process wastewater, direct precipitation contribution to the lagoon surface, and runoff areas) associated with individual dairy operations using primarily information obtained from permit files. Inflows were simulated on a daily basis as runoff and direct contributions associated with precipitation and estimates of processing wastewater and livestock waste. Outflows were simulated through dewatering and evaporation. Because all lagoons must be lined to minimize seepage to groundwater, the lagoon model assumed that seepage is minimal and was ignored in the overall water balance. When inflow minus outflow exceeded the volume of the lagoon, a discharge was indicated, which became a direct input to the streamflow system simulated in SWAT-TCEQ. Specifics of the lagoon water balance model are provided in Chapter 6 of TIAER (2006).

Based on recommendations from an August 2005 public meeting of the project advisory group, winter dewatering was not restricted even when a winter crop was not present during the model validation period of 1993-1999. Members knowledgeable of the dairy industry at the August meeting indicated that during the time frame of the validation period, typical lagoon management operations would not have restricted winter dewatering when a winter crop was absent.

Because actual lagoon management for dewatering was unknown for any dairy operation, three general categories of operation were defined to trigger and terminate dewatering as follows:

A – Drawdown initiated when the lagoon volume reached halfway into the stormwater volume and terminated when the volume was just below the stormwater volume.

B – Drawdown initiated when the lagoon volume reached half the maximum operating level (below the stormwater volume) and terminated when the minimum operating level was reached (above the sludge and treatment volume).

C – Drawdown initiated when the lagoon volume reached the maximum operating level and terminated when half the maximum operating level was reached.

For reference, Figure 2-3 shows the various volumes for a lagoon used in association with management options for initiating and terminating dewatering.

On July 31, 2006 an additional project advisory group meeting was held in which feedback from the dairy industry was specifically solicited. It was recommended at this July 2006 meeting that dairy operations in the watershed be stratified by size (large (> 608 cows), medium (142 - 608 cows), and small (< 142 cows)), and that within these size categories management options be assigned the following percentages[1]:

- Small – 40 percent A, 30 percent B, and 30 percent C
- Medium – 30 percent A, 40 percent B, and 30 percent C
- Large – 10 percent A, 45 percent B, and 45 percent C

Based on input from the project advisory group, no minimum or cut-off discharge event volume was used and it was assumed that all lagoon discharge events reach the stream system regardless of size.

Lagoon discharge quality characteristics for nutrients and suspended solids were based on total nitrogen (TN) and total P (TP) concentrations from self-reporting data for lagoon effluent in the dairy TCEQ permit files and literature values for other pertinent constituents. There was some discussion at the August 23, 2005 advisory group meeting that concentrations for TN and TP for the lagoon liquid from the self-reporting data looked too low. The self-reported concentrations were lower than those reported by Mukhtar et al. (2004) in their study of lagoon nutrient content for dairies in the area (Table 2-2). The differences in the concentrations reported by Mukhtar et al. (2004) and the TCEQ self-reporting data most likely can be explained by differences in the how lagoon samples were collected. The Mukhtar et al. (2004) data represent integrated samples of the entire vertical profile of the lagoon, while the self-reporting data most likely represent samples collected only from near the lagoon surface. Hence, the self-reporting data would be more indicative of concentrations of a surface discharge due to a lagoon overflow than the data in Mukhtar et al. (2004). TIAER used the self-reporting data for determining the concentrations of effluent associated with discharges due to lagoon overflow. Assigning or estimating nutrient and total solids concentrations for each dairy lagoon discharge event are discussed in Chapter 6 of TIAER (2006).

To avoid double accounting of nutrients in lagoon discharges and in lagoon dewatering, the annual average loading of discharged nutrients for the simulated period was subtracted from the annual nutrient loading associated with the liquid phase for land application in SWAT-TCEQ.

---

[1] This matrix of management associated with dairy size was used for all the validation and TMDL allocation scenarios.

This approach meant that for any selected year the annual average loading of discharged nutrients subtracted from the annual nutrient loadings of liquids used in SWAT-TCEQ was either too much or too little, but totally balanced on an average across multiple years.

2.4.2 Representation of Unauthorized Municipal Discharges

As part of the computer code that determined dairy lagoon discharges, an algorithm was developed to provide for simulation of unauthorized municipal discharges from the sanitary sewage collection systems and the WWTPs in the watershed. TCEQ permit files were reviewed for information on unauthorized discharges and some direct data were collected by TIAER to characterize effluent from WWTPs. These data were gathered for use in estimating point source contributions as inputs into SWAT-TCEQ and to determine the occurrence of operational difficulties to provide a basis for quantifying unauthorized discharges and effluent quality outside of normal discharges. Based on these data, the algorithm was developed with a stochastic component based on daily rainfall where the probability of an unauthorized discharge was defined as 17.4 percent on a day with > 2 inches of rainfall, 8.7 percent for the day after a day with > 2 inches of rainfall, and 1.0 percent for all other days. The estimated average concentrations of nutrients used in the unauthorized discharges for municipalities are shown in Table 2-3. Chapter 4 of TIAER (2006) provides detailed explanation of how the frequency, volume, and the nutrient concentrations of discharges were determined.

2.5 Improved Instream Water Quality Kinetics (Fate and Transport)

Previous research had revealed that predictions from the current version of SWAT's instream kinetics were not matching results from proven analytical solutions, such as Streeter-Phelps equation, and proven steady-state models such as QUAL-2E (Houser and Hauck, 2004). Therefore, modifications were made to the algorithms for instream kinetics to improve SWAT-TCEQ's capabilities to simulate nutrient kinetics and instream nutrient concentrations.

The spatial resolution of the receiving-water stream channel in SWAT is the distance between points in the channel at which the subwatersheds flow into the channel, and is therefore determined by the number of subwatersheds used to represent the basin. Even with a large number of subwatersheds, such as employed in the present NBR SWAT-TCEQ model, the spatial resolution is at least two orders of magnitude coarser than that typically used for a stream water-quality model such as QUAL-2E or QUAL-TX. In SWAT, the water-quality concentrations resulting from loads in and transport of volume downstream out of the stream channel reach are computed on a volumetric basis. The exact equation for a solute subject to a single first-order reaction with coefficient K is:

$$c_t V_t - c_{t-\Delta t} V_{t-\Delta t} = \Delta t\, \overline{c_i Q_i} - \Delta t\, \overline{c_o Q_o} - \Delta t\, K\, \overline{cV} \qquad (2)$$

where c and V are the volume-mean solute concentration and water volume of the stream reach, both a function of time t, where (Q_i, c_i) and (Q_o, c_o) are the flow and concentration of water flowing into and out of the reach, respectively, also functions of time, and where the overbar denotes the time average from t-Δt to t, e.g.

$$\overline{cV} = \int_{t-\Delta t}^{t} cV dt$$

Various approximations are needed to render (2) in a form amenable to computation. These include $\overline{cX} = (\bar{c}) * (\overline{X})$ (where X denotes V or Q) and $c_o = c$. Because values of c, V and Q in SWAT are available only at discrete times, the time-integral terms in (2) must be approximated by combinations of values at time levels …, t-Δt , t , t+Δt ,… etc., and the solution to (2) stepped from values at time level t-Δt to time level t. This is the classic problem of time discretization in numerical modeling. Because both the spatial increment (i.e., the length of the stream reach) and the time increment (Δt = 1 day) in SWAT are very coarse, there is a danger of poor numerical behavior.

The SWAT formula is:

$$c_t = \left(\frac{c_{t-\Delta t} V_{t-\Delta t} + c_i Q_i \Delta t}{V_{t-\Delta t} + Q_i \Delta t} \right) (1 - K \Delta t) \tag{3}$$

which appears to have been derived from a conceptual view of the mixing in the reach at the beginning of the time interval (Neitsch et al., 2002). In this project, the numerical behavior of this and other candidate approximations were studied using an idealized stream channel model, with the same spatial discretization in a SWAT model, a QUAL-2E model, and Streeter-Phelps to provide an analytical solution (Houser, 2004). It was determined that the internal sink due to the first-order reaction is egregiously underestimated as the residence time in the stream reach increases, therefore the load transported into the next downstream segment is overestimated. By imposing an implicit-forward timestep on the fundamental equation (2), an alternative formulation was derived:

$$c_t = \frac{c_{t-\Delta t} V_{t-\Delta t} + c_i Q_i \Delta t + R V_t \Delta t}{V_{t-\Delta t} + Q_i \Delta t - K V_{t-\Delta t} \Delta t} \tag{4}$$

In this equation, the source/sink term was generalized to the form $Kc + R$, into which form all of the standard kinetics for BOD, DO, N species and P can be represented, where K is the total of first-order coefficients for all first-order reactions to which c is subject and R is the total of all zeroth-order reactions to which c is subject. This proved to closely approximate the QUAL-2E and Streeter-Phelps solutions, especially for low-flow conditions.

2.6 Dynamic Manure Management

A dynamic manure management component was added to SWAT-TCEQ in order to model NRCS guidelines for manure management in the TMDL load allocation scenarios.

The SWAT model used to develop the original TMDL had no dynamic mass balance accounting of manure, nor allowed for the temporal and spatial variability of manure application over the course of a simulation. The amount of manure applied was statically fixed by model input for each field before the simulation began. Therefore, SWAT-TCEQ was refined to give it the ability to do a mass balance accounting of manure in each subbasin based on the number of cows in the subbasin, the application rates of manure in the subbasin, manure received or transferred to other subbasins, and the amount of manure required to be hauled-out of or removed from the watershed. In addition, most animal feeding operations have manure in both solid and liquid forms that need to be land applied. The GIS land-use layer in the NBR differentiated between liquid and solid waste application fields. Therefore, SWAT-TCEQ split the manure source into a liquid and solid source and applied them separately.

Best management practices (BMPs) associated with manure application, that would be used in TMDL load allocation simulations, use some form of soil P indicator to determine the correct amount of fertilizer and/or manure to be applied to a dairy WAF (McFarland et al., 2000; NRCS, 2000). Therefore, the manure application rate to a WAF can be variable from year to year, and the maximum allowable application rate is a function of a soil P indicator. In order to more realistically simulate the potential impact of BMPs on watershed-level water quality, it was necessary to be able to model the effects of dynamic manure management based on soil P criterion at the field level. To simulate such requirements SWAT-TCEQ was enhanced with the capabilities to dynamically (within a simulation) change manure application rates by field based on annual soil test P at a user-defined depth, and to dynamically change the fields (or areas) receiving manure in response to changing application rates and available manure supplies.

Manure application as currently recommended by the Texas NRCS practice standard 590 utilizes a P index, which contains a spatial component of distance of a field to a receiving stream, in order to determine manure application rates. SWAT-TCEQ could not calculate P indexes for individual fields due to the fact that HRUs in SWAT are not identified spatially within the subbasin. Therefore, SWAT-TCEQ used an average P index in the reanalysis of TMDL allocation simulations.

To review, SWAT-TCEQ was enhanced by providing a dynamic manure management component that had: (1) the ability to do a mass balance accounting of manure in each subbasin based on the number of cows in the subbasin, the application rates of manure in the subbasin, manure received or transferred to other subbasins, and the amount of manure required to be hauled-out of or removed from the watershed; (2) the ability to move manure between subbasins as needed; (3) the ability to dynamically (within a simulation) change manure application rates by field based on annual soil test P at a user-defined depth; (4) the ability to dynamically change the fields (or areas) receiving manure in response to changing application rates and available manure supplies; and (5) the ability to differentiate between liquid and solid manure pools, and apply them separately.

2.7 Other Model and Data Improvements and Refinements

In addition to the above refinements, of which some were motivated by public concerns about the modeling process, other refinements and improvements were made in the model and data inputs, specifically, (1) an updated new land-use/land-cover layer to show current conditions in the NBR; (2) soil P processes in SWAT-TCEQ were updated to reflect more complete and more recent scientific understanding of landscape P processes; (3) agricultural sectors that contribute manure but were not part of the previous TMDL simulation (i.e., turkey operations and beef grazing) were added to the refined TMDL simulation; (4) measured stream cross-sectional areas of the NBR were incorporated into the model; and (5) the resolution of precipitation data was improved.

2.7.1 Updated Land Use and Land Cover

For model system validation to data predominately collected from 1993-1999, land use/land cover was based on Landsat Thematic Mapper imagery classification conducted by the NRCS, Temple State Office for TIAER in the late 1990s. This land-use data layer was developed from a 1992 overflight of Erath County and a 1996 overflight of Bosque, Coryell, Erath, Hamilton, McLennan, and Somervell counties. Extensive ground truthing was performed by TIAER from January through April 1998 to verify and update land use changes (Figure 2-4).

For TMDL scenarios under future conditions, a new land-use/land-cover layer was developed by the Spatial Science Laboratory (SSL) at Texas A&M University in College Station, Texas using selected LANDSAT-7 ETM satellite imagery from 2001, 2002 and 2003. The classes in the new land-use/land-cover layer were deciduous trees, evergreen trees, improved pasture, cropland, shrubland, rangeland, mine and quarries, urban, 1992 mines/rangeland /improved pasture[2], and water.

To compare with the older land-use/land-cover layer used in the original TMDL allocation scenarios and in validation model simulations for the NBR, and to prepare the new land-use layer as input for SWAT-TCEQ (Figure 2-5) which will be used to model the TMDL future allocation scenarios for the NBR, the following categories were reclassified:

- Deciduous trees and evergreen trees were combined into the class of trees.
- Shrubland, rangeland, mines and quarries and 1992Mines/Range/Pasture were combined as range.

A general comparison of the two land-use layers for the NBR watershed was conducted. The new land-use layer contained (rounded to the nearest thousand acres) about 79,000 less wood/rangeland acres, 27,000 less cropland acres, 99,000 more pasture acres, 3,000 more water acres and 7,000 more urban-land acres than the old land-use layer. There appeared to be a general shift of wood/rangeland and cropland to pasture from the older land use/land cover to the more recent land use/land cover (Table 2-4). Because of the difficulty typically experienced in satellite imagery in separating the continuum from rangeland to improved pastureland into the discrete categories of rangeland and improved pasture, it is impossible to conclude how much of the differences between the two land-use layers is real and how much is an artifact of the land-use characterization process. For this project, each land-use layer (older and newer) was considered to provide a reasonable characterization of land use/land cover for the periods they represent (i.e., 1996-1998 and 2001-2003).

---

[2] 1992 Mines/rangeland/improved pasture land use class indicates land area that was categorized as Mines/Quarries in the 1992 USGS National Land Cover Data but classified as a different land cover class based on image classification.

2.7.2 Improved Landscape Phosphorus Processes

Algorithms to improve the landscape P processes within SWAT were also included in SWAT-TCEQ. The program was modified to change the sorption and desorption processes based on chemical and physical soil properties (e.g., calcareous content) developed in Lewis and McGechan (2002). A new P algorithm created a new P soil partitioning coefficient (K_d). What was previously an entirely user-defined value was now described by the equation:

$$K_d = \text{phoskd}*(1.00 + (0.025 * \text{sol\_clay}))*100 \tag{5}$$

Where K_d is the P soil partitioning coefficient, "phoskd" is a user-defined variable adjustment factor with acceptable values between 0.6 to 1.4, and "sol_clay" is the percent of clay in the soil texture. K_d is the ratio of the soluble P concentration in the surface 10 mm of soil to the concentration of soluble P in surface runoff (Neitsch et al., 2002).

2.7.3 Added Agricultural Sectors

Manure contributions from other sources besides dairy were incorporated into the reanalysis modeling effort. Manure from beef cattle was simulated in the model by assuming that 90 percent of range and pasture were being grazed as was agreed upon at the special project advisory group meeting of July 31, 2006. The SWAT-TCEQ grazing function was used to simulate the manure contribution based on established animal carrying capacities for range and pasture (Table 2-5). In addition, according to the Dublin office of Texas State Soil & Water Conservation Board (TSSWCB), there were 12 poultry facilities within the lower portion of the NBR watershed that used land application of turkey manure during the validation period (1993-1999). The location of poultry operations was defined by the SWAT-TCEQ subbasin as input information for the modeling effort.

2.7.4 Improved Cross-sectional Area Representation in SWAT

The stream cross-section representation in the route files of SWAT created automatically by AVSWAT were adjusted to conform more closely with measured cross-sectional areas at locations along the NBR. Figure 2-6 shows an example of the difference between the adjusted cross-sectional areas compared to the cross-sectional areas created automatically by SWAT at BO095. Cross-sectional measurements were taken at 24 sites along the main stem and major tributaries of the NBR. Using these measurements new stream dimensions were extrapolated for every reach (subbasin) simulated by SWAT-TCEQ, and new route (RTE) files for each subbasin were created containing the new stream dimensions. The refinement of stream cross sections was undertaken for this project because of the direct relationship of cross sections to stream hydraulics and travel times, which influence instream transport and kinetics.

2.7.5 Improved Resolution of Precipitation Data

The primary inputs that determine streamflow in SWAT are precipitation data. Therefore, enhancing the accuracy and resolution of these data was an important step in assuring an accurate calibration of the model. Efforts were taken to refine and improve the resolution of the precipitation data input to SWAT-TCEQ. Two data sources were used to provide precipitation data. The first source was TIAER data collected within the NBR watershed between January 1993 and December 2004. The second source was National Climatic Data Center (NCDC) data for 1960 through 2004 obtained from an on-line archive maintained by the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) and the National Environmental Satellite, Data and Information Service (NESDIS) for stations near and within the NBR watershed. Interpolation methods were used to estimate missing values at existing weather stations, fill in temporal gaps prior to the monitoring period at a station, and to estimate precipitation data for locations without a nearby gauging station to fill in gaps in spatial coverage (see Figure 2-7). For more detail on the methodology and data used see Chapter 14 in TIAER (2006).

SECTION 2

TABLES

Table 2-1 Sediment and nutrient removal efficiencies for two PL- 566 flood retardation reservoirs based on measured data from 1994-1996

Constituent	UB3 Reservoir	UB8 Reservoir	Average
Organic-N	0.29	0.69	0.49
Ammonia (NH_3)	0.44	0.58	0.51
$NO_2 + NO_3$	0.70	0.67	0.69
Soluble-P	0.37	0.54	0.46
Organic-P	0.62	0.76	0.69
TSS	0.95	0.73	0.84

Table 2-2 Comparison of self-reporting data with effluent concentrations reported by Mukhtar et al. (2004). Values presented are averages plus or minus the standard deviation. Total N values from Mukhtar et al. (2004) are for total Kjeldahl nitrogen

Source	Total N (mg/L)	Number of Observations	Total P (mg/L)	Number of Observations
Self-reporting	260 ± 283	122	105 ± 147	127
Mukhtar et al. (2004)	1892 ± 828	12	470 ± 238	12

Table 2-3 Estimated average concentration used in unauthorized discharges for municipalities (concentration of nutrient forms represent estimated differences between influent and effluent concentrations)

Municipality	Mean Inorganic N (mg/L)	Mean Organic N (mg/L)	Mean Inorganic P (mg/L)	Mean Organic P (mg/L)
Hico	0.00	7.26	2.59	0.77
Iredell	0.00	7.23	2.09	1.84
Meridian	0.00	2.89	2.39	0.52
Clifton	0.00	8.38	1.50	0.44
Valley Mills	0.00	3.85	2.25	0.32
Stephenville	0.00	3.62	1.94	0.31

Table 2-4 Change by major category between 1996/1998 and 2001/2003 land use/land cover layers

Land Use/Land Cover Category	Percent Change in Category	Percent Change in Relation to Total Watershed Area[a]
Wood/Rangeland	-14.0	-10.1
Cropland	-35.5	-3.5
Improved Pasture	78.8	12.6
Water	261.2	0.4
Urban	60.1	0.9

[a] Percent change in relation to the total area does not add up to zero exactly because in the old land use there was an "other" category that corresponded to land uses which did not fit into any of the categories in the table and were not included in the table. The total area of the "other" category was about 760 ha or approximately 0.25 percent of the total watershed area. In the new land use all these land uses were identified as either shrubland, mines and quarries, and 1992Mines/Range/Pasture and were all combined with rangeland.

Table 2-5 Dry weight of biomass consumed and the dry weight of beef cow manure deposited daily. AU = animal unit.

Land Use	Daily Dry Weight of Biomass Consumed in kg/AU/d (lb/AU/d) [a]	Carrying Capacity in ha/AU (ac/AU)[a]	Daily Dry Weight of Biomass Consumed in kg/ha/d (lb/ac/d)	Dry Weight of Beef Cow Manure in kg/AU (lb/AU)[b]	Dry Weight of Beef Cow Manure Deposited Daily in kg/ha/d (lb/ac/d)
Pasture	11.8 (26.0)	2.0 (4.4)	5.83 (5.21)	8.50 (18.7)	4.20 (3.75)
Range	11.8 (26.0)	11.1 (24.5)	1.06 (0.95)	8.50 (18.7)	0.76 (0.68)

[a] Data from Mr. Kent Ferguson, regional rangeland management specialist for Zone 5 USDA-NRCS, Weatherford, Texas (January 19, 2006).
[b] ASAE Manure Production and Characteristics Standard (2005a).

SECTION 2

FIGURES

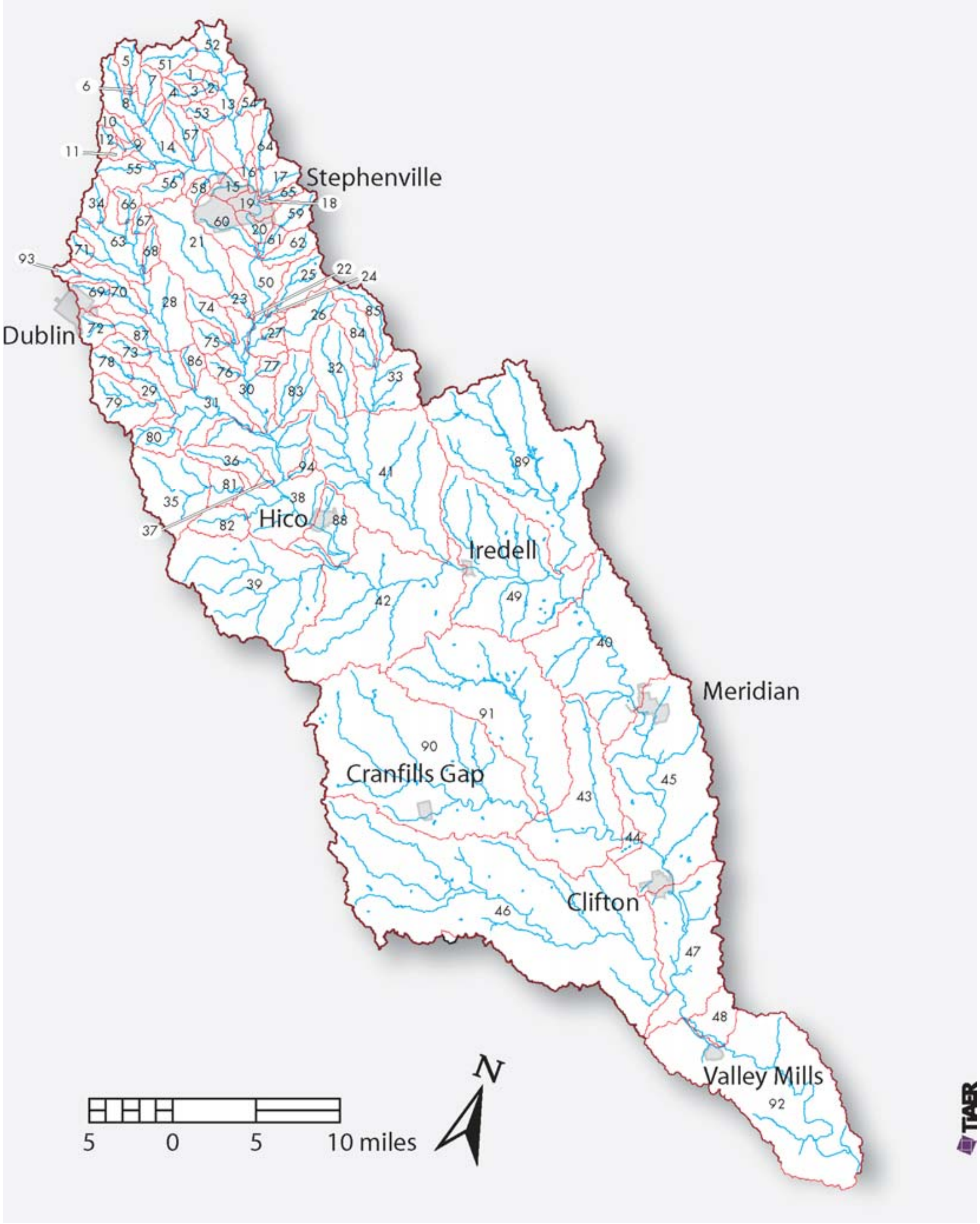


Figure 2-1 **Subbasin delineation of the North Bosque River watershed used in the SWAT modeling effort. Numbers are subbasin identification numbers used by the SWAT model**

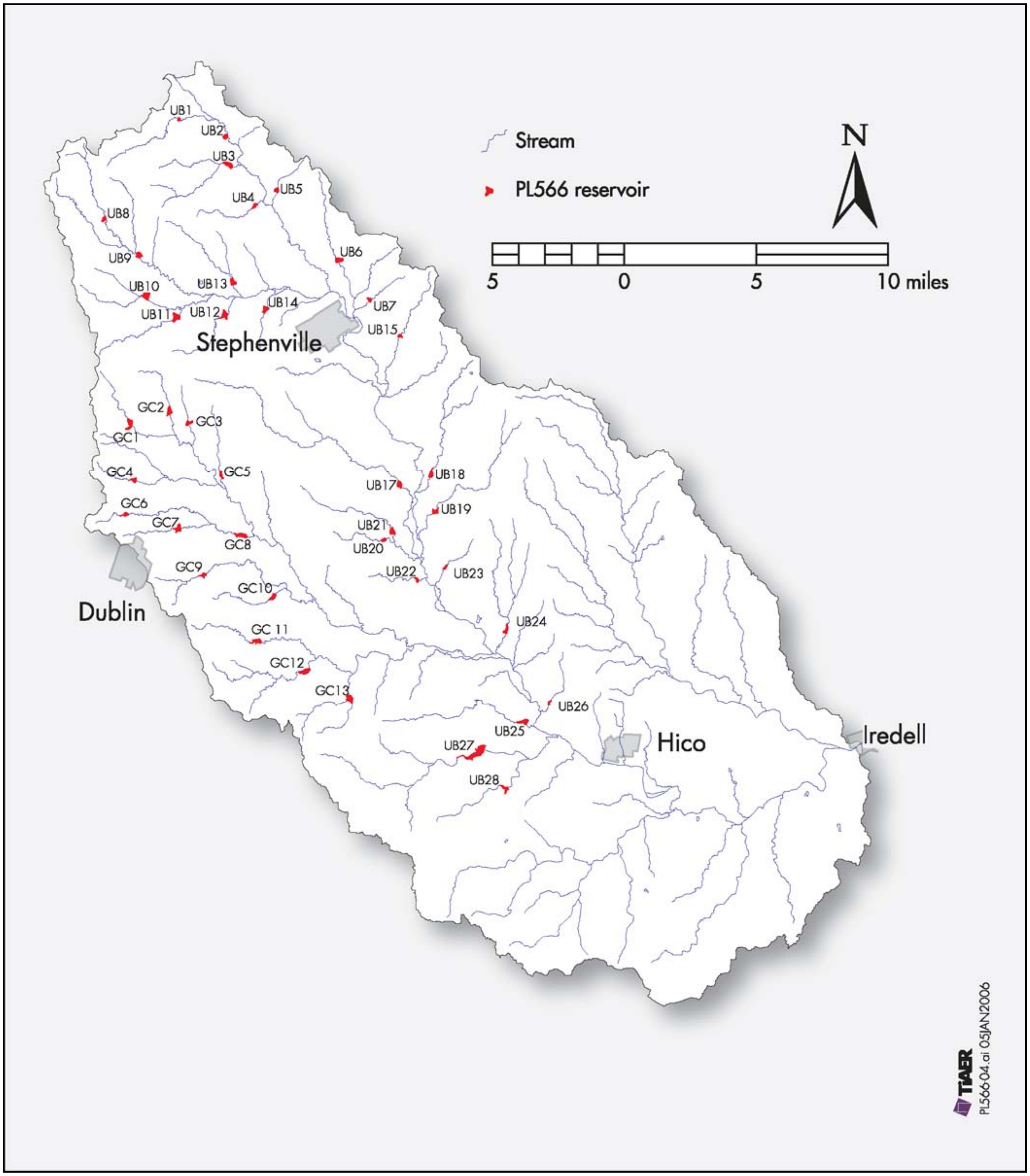


Figure 2-2 **Location of Public Law 566 reservoirs in the upper portion of the North Bosque River watershed. Labels represent NRCS identification codes**

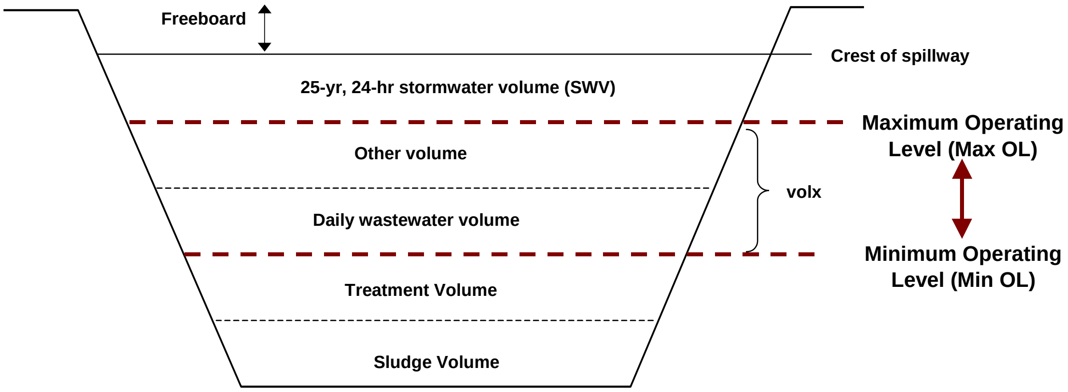


Figure 2-3 **General dairy lagoon design components**

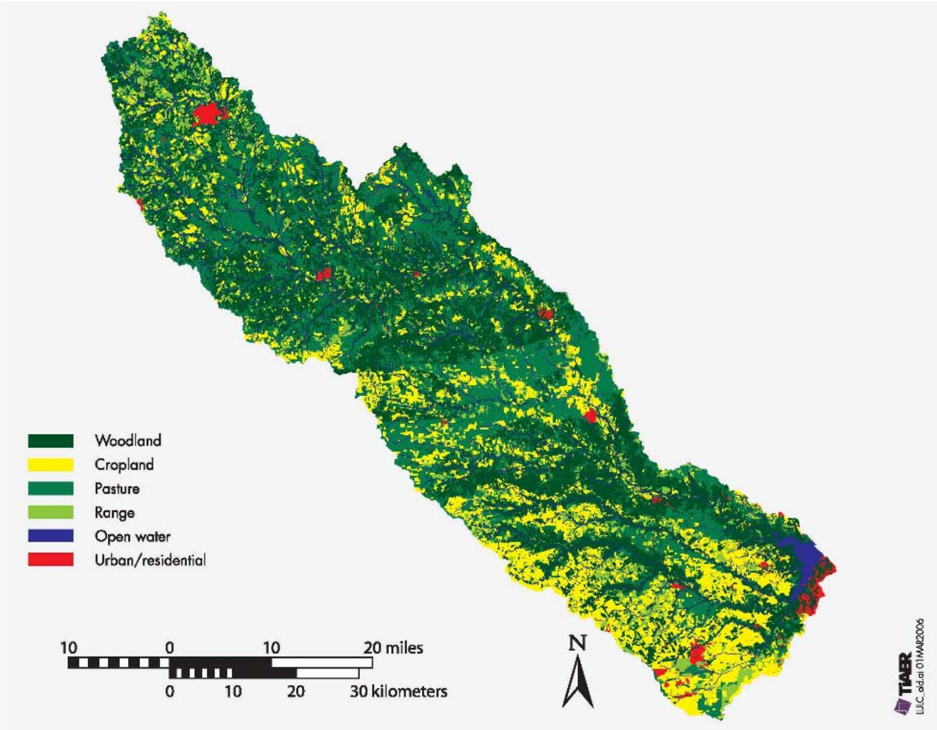


Figure 2-4 **Land use/land cover layer from 1996/98 for the Bosque River watershed for use in validation model simulations for the North Bosque River**

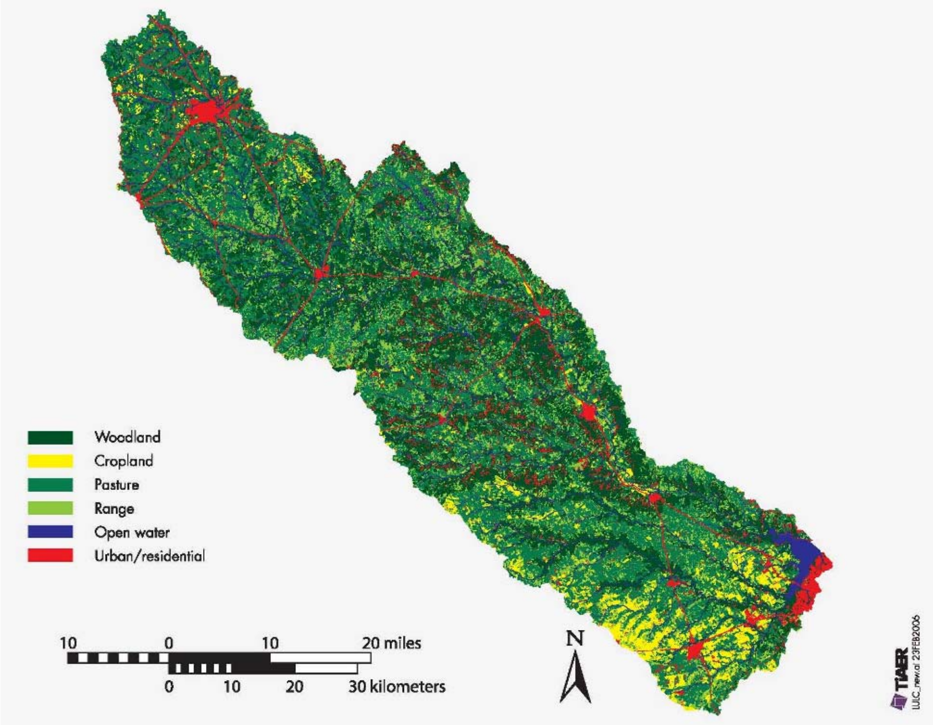


Figure 2-5 **Updated 2001/2003 land use/land cover for the Bosque River watershed used for modeling TMDL load allocation scenarios for the North Bosque River**

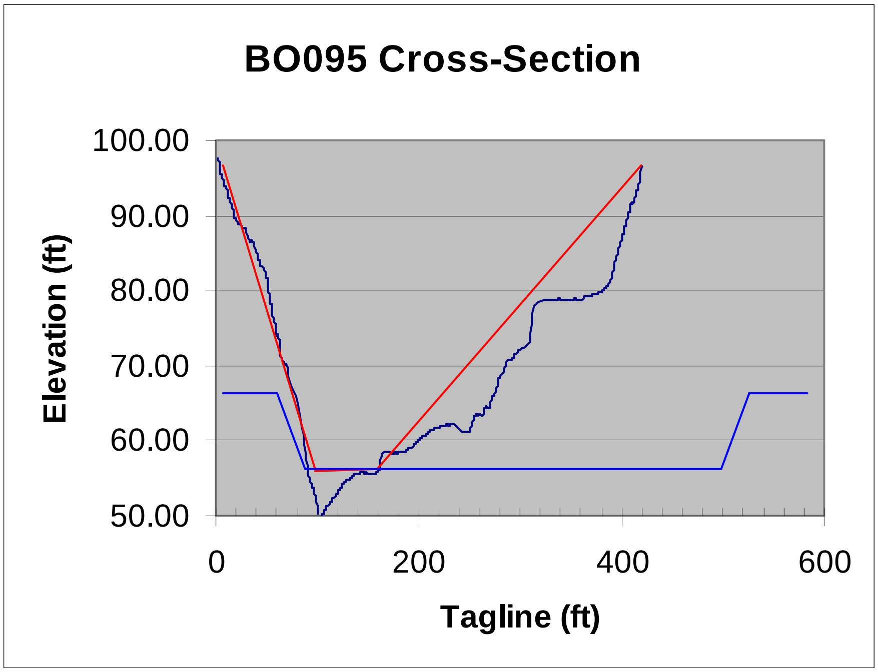


Figure 2-6 **Comparison of original SWAT stream dimensions (blue line), actual measured stream section (black line), and new SWAT input stream dimensions (red line) at BO095**

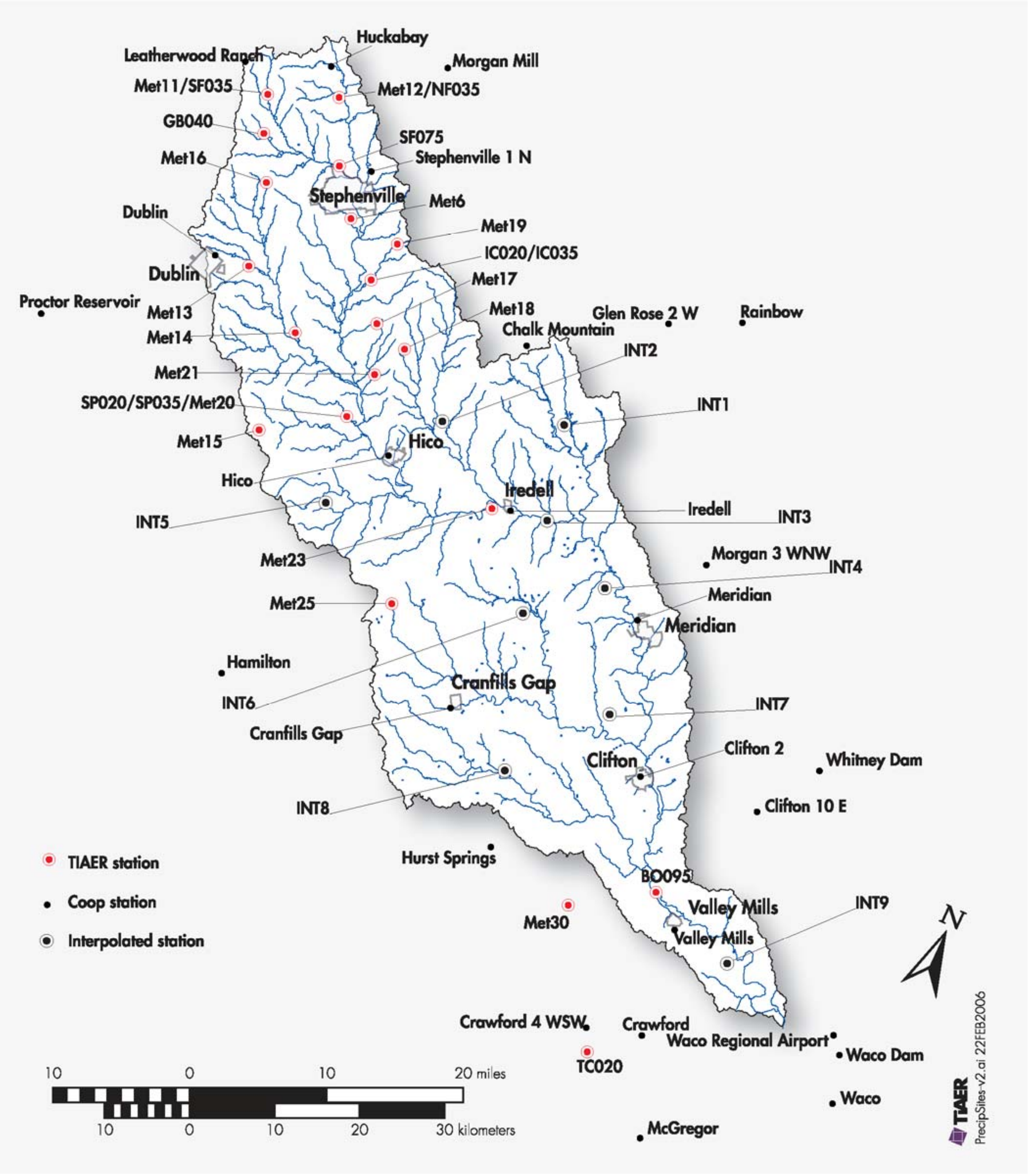


Figure 2-7 **Location of TIAER, NCDC Co-op, and interpolated rain gauge stations used to refine precipitation input data for SWAT-TCEQ**

SECTION 3

MODEL VALIDATION

3.1 Basics of Validation Process and Validation Monitoring Data

The validation process consists of model *calibration* and *verification*. During calibration model parameters are adjusted within allowable limits until model output for a given time period matches measured data within some predetermined measure of model performance. Verification refers to operating the model by holding adjustment parameters at the values determined during the calibration process, simulating a different time period, and comparing model output to measured values.

The first steps in the validation process are to evaluate measured data for appropriateness and utility in this validation process and then to determine which data and associated periods of time are to be used for calibration and which for verification. The methodology of the validation process for the SWAT-TCEQ model of the NBR watershed involved:

1) an initial hydrologic calibration to long-term data sets that are multiple years in length but only at limited locations on the NBR and as such provides only an aggregated response of the heterogeneous land uses comprising the watershed;
2) then a short-term and more intensive level of calibration to hydrologic and water quality data of only a few years in duration but at sites throughout the watershed including sites on relatively small streams and sometimes with dominating single land uses, and
3) concluded with verification to a few years of hydrologic and water quality data for sites throughout the watershed similar to those used in the short-term calibration.

Streamflow data from three USGS gauges on the North Bosque at Hico, Texas (08094800, collocated with TIAER site BO070), near Clifton (08095000, collocated with TIAER site BO090), and at Valley Mills (08085200, collocated with TIAER site BO100) were used in the long-term calibration (Figure 3-1). The 30-year period of daily streamflow from 1965-1994 was selected as the long-term hydrologic calibration period.

The short-term calibration and verification of both hydrology and water quality was performed predominately using data from stream monitoring sites throughout the NBR watershed. The primary sources of these data were streamflow and water quality data from 17 monitoring sites operated by TIAER supplemented with streamflow data from the same three USGS gauges used in the long-term calibration (Figure 3-1). The TIAER sites were located with drainage areas of a wide diversity of sizes and locations ranging from sites on the NBR with large drainage areas and sites on small drainage areas of which some had predominately certain land uses such as urban, intensive agricultural such as dairy WAFs, and low intensity agricultural such as forest/rangeland.

The short-term calibration and verification time periods were determined based on data availability and changing conditions in the watershed that could affect instream water quality conditions. The year 1993 was the first year in which TIAER began extensive monitoring in the NBR watershed. The sites TIAER monitored for streamflow and water quality varied over the years in response to changing projects and funding sources, though some core sites have been maintained to the present (2008). For the mid and late 1990s, conditions in the watershed were relatively stable regarding total number of dairy cows and other factors that could influence instream water quality conditions, such as manure management practices. Beginning about the year 2000, however, some notable changes began to take place. Dairy cow numbers after being relatively stable from 1994 through 1999 began to show a decreasing trend, the poultry operations in the southern part of the watershed began to take more of their litter to a compost facility located east of the watershed, and most importantly the TSSWCB Dairy Manure Export Support (DMES) project began November 2000. The now ceased DMES program provided over a period of several years financial assistance for the hauling of manure to local compost facilities. TCEQ operated a complementary program called the Composted Manure Incentive Project (CMIP), which subsidized the sale of compost outside of the watershed. Within the last two months of 2000 the amount of manure hauled to compost facilities under the DMES project equaled about 25 percent of the total manure anticipated to be produced in one year in the NBR watershed, and in 2001 the total amount hauled was some 30 to 40 percent greater than annual manure production for the watershed (Figure 3-2). Apparently, once dairy producers became aware of the DMES program, many producers stockpiled manure to take advantage of the program. The consequence of the DMES project along with declining dairy cow numbers and hauling of poultry litter is that beginning in 2000 factors within the watershed were occurring that could affect instream water quality in a very dynamic manner that could not be captured in the present model, which resulted in the decision that only monitoring data collected up through the end of 1999 should be used for model validation.

Based on the time constraint discussed above, the short-term calibration period was selected as 1993-1997 and the verification period was from 1998-1999. This particular division of the validation period into calibration and verification periods was due to the fact that there was a limited amount of streamflow and water quality data in the southern part of the watershed (sites BO090, NC060 and BO100) below Hico (site BO070) and these data did not begin to be collected until late 1995 and early 1996 (see Figure 3-3). The calibration period could not be extended past 1997 because a long period of dry weather that began in early 1998 would have created a verification period with little if any streamflow as shown by the graph of streamflow at Clifton (BO090) in Figure 3-4. The chosen calibration and verification periods were the best use of the TIAER measured streamflow and water quality data to both adequately describe the entire watershed and ensure that wet and dry periods were simulated in each of the calibration and verification periods.

3.2 Measured Streamflow and Water Quality Data

At TIAER sites, automated samplers collected water quality samples during rainfall-runoff events, a streamflow gauge was operated providing water level data at 5-minute intervals that was converted to streamflow through a site-specific rating curve, and routine (grab) water quality sampling was performed on either a monthly or once every two weeks (biweekly) basis. At all sites, ammonia-nitrogen (NH_3-N), nitrite-nitrogen plus nitrate-nitrogen (NO_2-N+NO_3-N), total Kjeldahl nitrogen (TKN), orthophosphate-phosphorus often referred to as soluble reactive P

(PO_4), total P (total P), and total suspended solids (TSS) were routinely evaluated for both the grab and storm samples. At main stem and major tributary sites, grab samples were also analyzed for chlorophyll-a (Chla) as a measure of suspended algae or phytoplankton. These shorter-term measured data were used to calculate daily and monthly flow values and daily and monthly concentrations and loadings of nutrient forms for N and P and total suspended solids for comparison with model output. First, daily flows and masses were calculated by combining flow and water quality data via a rectangular integration using a midpoint rule to associate concentration with streamflow for sequential and grab samples and these data were aggregated on monthly and annual bases to provide data for the model validation process. The following list provides the SWAT predicted water quality variables used in the validation process and how each variable was represented using the measured water quality data:

SWAT-TCEQ Variable	Representation in Water Quality Data
Total Sediment	TSS
Total P	Total P
Organic P	Total P – PO_4
Inorganic P	PO_4
Total N	TKN + (NO_2-N+NO_3-N)
Organic N	TKN – NH_3-N
NH_3-N	NH_3-N
NO_3-N	NO_2-N+NO_3-N

More specifics on data collection at the TIAER sites and computation of measured concentrations and loadings on monthly and annual bases are found in Chapter 15 of TIAER (2006).

3.3 Inputs and Assumptions for Model Validation

To provide for reasonable predictions of flow and water quality, the model input should reflect as much as possible the actual conditions in the NBR watershed. The data to characterize the watershed included various GIS layers, specifically, DEMs, land use/land cover, dairy WAFs, and soils; nutrient requirements for various crops; livestock (e.g., dairy cows and beef cattle) numbers; manure nutrient characteristics; manure application rates; soil test P concentrations in WAFs soils; among many other input data.

3.3.1 Digital Elevation Models

To determine subwatershed boundaries and slopes within subwatersheds, DEMs were obtained from the USGS (USGS, 1999). The most refined DEM data available for the NBR watershed are in the form of 7.5-minute DEMs (1:24,000 scale) based on 30- by 30-meter data spacing with the Universal Transverse Mercator (UTM) projection (Figure 3-5). The DEMs for the watershed were used in conjunction with AVSWAT to delineate subbasins for modeling the NBR following procedures outlined by DiLuzio et al. (2000).

3.3.2 Land Use/Land Cover

For model system validation, land use/land cover was based on Landsat Thematic Mapper imagery classification as previously explained in Section 2.7.1. On September 22, 2002 the land-use/land-cover layer was modified to fill in small gaps that were present along the edges when the land use/land cover was overlaid with the watershed boundary. A nearest-neighbor approach was used to fill in these gaps. The categories in this land use/land cover database are woodland, cropland, rangeland, improved pasture, water, and urban (Figure 2-4). In addition to model validation, this land use/land cover was used to model the reanalysis of the TMDL baseline and “existing” conditions scenario that are discussed in the next report section.

3.3.3 WAF Layer

To improve the characterization of dairies and enhance use of the GIS land-use/land-cover layer, dairy WAFs were included as a separate land-use category. In order to determine the land use associated with these fields, the location and size of dairy WAFs in the NBR watershed were overlaid with the general land-use/land-cover GIS layer (Figure 3-6). TIAER had constructed a GIS layer characterizing dairy WAF conditions as of May 2000 from information in dairy permits, permit applications, and waste management plans on record with the TCEQ and supplementary, aggregated information from TSSWCB Water Quality Management Plans for non-permitted facilities.

The land uses that were associated with these WAFs are alfalfa, Coastal bermudagrass, Coastal/wheat rotations, pasture, cropland, sorghum, sorghum/wheat rotations, sudan grass, sudan grass/wheat rotations, wheat, corn/wheat rotations, range, and peanut/wheat rotations. The GIS layer also included historical WAFs. Historical WAFs are those designated in 30 TAC 321.32 (21) as “an area of land located in a major sole-source impairment zone that at any time since January 1, 1995, has been owned or controlled by an operator or a concentrated animal feeding operation (CAFO) and on which agricultural waste or wastewater from a CAFO has been applied.” Historical WAFs were determined by which dairy operations were noted as operating in 1995 but out-of-business by 2000 based on TCEQ inspection and Department of Health Services milk marketing reports.

3.3.4 Soils Layer

TIAER obtained soil information for the watershed from the Soil Survey Geographic (SSURGO) database maintained by the NRCS (NRCS, 2003). Field mapping methods using national standards were used to construct these digital soil maps (Figure 3-7). SSURGO represents the most detailed level of soil mapping developed by the NRCS and duplicates information provided in county level soil surveys. Map scales vary by county but most counties are represented at a scale of 1:24,000.

3.3.5 Crop Nutrient Requirements

To determine the fertility recommendations that were in common use during the validation period (1993-1999), information developed by the Texas Agricultural Extension Service Soil

Laboratories in College Station and Lubbock was reviewed (Gass, 1987). Information from these labs was also summarized and reported by Sweeten et al. (1991). The summarized yield goals and nutrient recommendations presented by Sweeten et al. (1991) were used extensively in dairy permits between 1990 and 1998 in determining land area requirements for waste application. Other sources evaluated for fertility recommendations included the NRCS National Engineering Handbook on Agricultural Waste Management (SCS, 1992; NRCS, 1996). The fertility rates used as input to SWAT-TCEQ are shown in Table 3-1. For more detail on crops and crop nutrient requirements see Chapter 5 in TIAER (2006).

3.3.6 Dairy Cow Numbers

Total inspected dairy cow numbers associated with each SWAT-TCEQ subbasin were obtained from TCEQ inspection reports. Inspected cow numbers represent the total number of animals in confinement at the time of the inspection, including lactating cows, dry cows, heifers, and calves. Because specific cow numbers by animal type were not indicated in the inspection reports, a consensus was reached among dairy producers at the July, 31, 2006 advisory group meeting that for the modeling effort inspected numbers would be comprised of 64 percent lactating cows, 11 percent dry cows, 17.5 percent heifers, and 7.5 percent calves.

Individual dairy operations were located within SWAT-TCEQ subbasins to obtain inspected dairy cow numbers by subbasin. Inspected cow numbers for this project were available for fiscal years 1994-95, 1997-99, 1999-2000. For model validation, inspection numbers were averaged for 1994-95, 1997-1999, and 1999-2000. When possible, if inspected cow numbers were missing, they were estimated based on years with inspection numbers for the same facility. For nonpermitted facilities without inspection values, the allowed number of cows was assumed to be 249 or 200 depending on the circumstances of the operation.

Cow numbers were adjusted for the SWAT-TCEQ modeling effort by the percentage of the WAFs for each dairy within the watershed. Because some dairies were located on or at the watershed divide between adjacent watersheds, such as the Leon River, and have portions of their application fields in adjacent watersheds, actual cow numbers for each dairy were based on the percentage of total WAF area in the NBR watershed. Further refinement was performed to associate cow numbers based on the percent of each dairy’s WAF area within a specific subbasin. For example, if a facility had 50 percent of its WAFs in subbasin A and 50 percent in subbasin B, cow numbers for that dairy would be split evenly between subbasins A and B, as would be the manure associated with these cows. Unadjusted and adjusted inspected dairy cow numbers for the NBR watershed were 43,449 and 40,350 respectively, where the later number represented the cow number used in the simulations of the validation process.

3.3.7 Manure Characteristics

Dairy manure characteristics needed as input for the model include total solids (TS), N, and P by animal type (lactating, dry, heifer, or calf). For the SWAT-TCEQ simulations, TIAER based dairy manure characteristics on work by Nennich et al. (2005) that has been largely adopted as the standard by the American Society of Agricultural and Biological Engineers (ASABE). The most recent ASABE standard for determining manure production and nutrient characteristics presents a number of equations based on a variety of inputs, including concentration of P in diet, milk production, body weight, milk true protein, and days in milk (ASABE, 2005). In order to simulate the effect of changing the P concentration in the dairy cow's diet as part of the future modeling scenarios, it was necessary to use an equation that included the concentration of P in the diet (C_P) as a variable. For the diet of a lactating cow during the validation period, a Cp value of 0.0005 g P/g dry feed was assumed based on work by Jordan and Stokes (1998) and Stokes and Jordan (undated) for dairies in the NBR watershed. As a weighted average of the types of animals in confinement assuming 7.5 percent calves, 17.5 percent heifers, 11 percent dry, and 64 percent lactating cows the following total fresh manure values were obtained:

- TS = 5422 lb per cow per year (2462 kg/cow-yr)
- N = 271 lb per cow per year (123 kg/cow-yr)
- P = 48.2 lb per cow per year (22 kg/cow-yr)

To split the fresh manure into solid and liquid fractions, CDM (1998) and Osei et al. (1995) were reviewed. The CDM report provided estimates of solid and liquid fractions to determine the amount of solids that could be recovered on a typical Erath County open-lot dairy for the purpose of estimating volumes of solid material that would be available for composting.[3] Twenty-three percent of the TS in fresh manure were determined to go into the liquid fraction and the remainder to the solid fraction. The fresh dairy manure characteristics were then reduced by accepted losses associated with manure storage to determine characteristics of manure as would be applied to the land (Table 3-2). Losses for TS and nutrients were based on a compilation of research reported by Osei et al. (1995) and in the Livestock Waste Facilities Handbook by MidWest Plan Service (MWPS, 1985). N losses were considered to be on the higher end of their accepted range due to the warm, dry, and windy conditions of the NBR watershed. The nutrient losses created final nutrient values for solid and liquid applied dairy manure with N:P ratios of 3.2 and 2.9 respectively, which are similar to the median N:P ratio from dairy self-reported data. For more detail on manure characteristics see Chapter 5 of TIAER (2006).

3.3.8 Manure Application Rates

During the validation period it was assumed that manure was applied at the N agronomic rate on all WAFs, which was the maximum rate allowed within TCEQ permits (Gassman, 1997). Important assumptions embedded in determining the allowable N agronomic rate as taken from NRCS (1996) were: (1) only 50 and 80 percent of the N in the solid and liquid manure, respectively, is plant-available the year of application, and (2) 20 percent of the N that is either surface-applied solid or liquid manure will be lost due to ammonia volatilization while 10 percent volatilization losses are assumed for incorporated solid manure applications. These assumptions imply that only 64 percent of the N in the liquid manure, 45 percent of the N in the incorporated solid manure, and 40 percent of the N in the surface-applied solid manure would be readily available to the crop. Manure is surface-applied on Coastal bermudagrass and Coastal bermudagrass/winter wheat rotations, which are the dominant cropping systems that receive manure. Thus, the actual application rates of N in incorporated solid manure, liquid manure, and

---

[3] During the validation period, the vast majority of dairies in the NBR watershed were open lot, with the trend toward more free-stall operations occurring in the early 2000s.

surface-applied solid manure that are required to satisfy the N agronomic rates were 1.56, 2.2 and 2.5 times greater than the agronomic crop rates shown in Table 3-1.

3.3.9 Soil Test P in WAFs

To establish soil P concentrations for dairy WAFs a variety of soil P data sources were reviewed and compiled. The main data sources used where self-reporting records on file at the TCEQ Stephenville office as hard copies in individual permit files and data from a special study conducted by TCEQ in 2001 that involved collection and analysis of soil samples from many dairy WAFs in the NBR watershed.

Soluble soil P (SSP) is the state variable in the soil P component of SWAT most similar to soil test P (STP) measurements collected for agronomic and regulatory purposes. SSP, is defined in SWAT as soluble P extraction with anion exchange resin (Jones et al., 1984), which is theoretically less than STP, because STP measurements include a portion of the insoluble soil P that can be extracted by plants. The literature was thoroughly reviewed to determine relationships between various other soil P measurements and SSP. Understanding this difference between SSP and STP was important in the modeling effort for two reasons. First, SSP is rarely measured, so initializing this parameter in the model, especially for dairy WAFs, must be based on more commonly measured soil attributes, such as STP. Second specific TMDL load allocation scenarios were based on STP conditions. Therefore, an algorithm relating SSP from SWAT-TCEQ to Mehlich3-P soil test results was developed. See Chapter 7 of TIAER 2006 for a detailed explanation of the algorithm derivation.

A start-up date was determined for the model validation by finding an initiation date for the simulation which created an average simulated STP concentration in WAFs in the year 2001 comparable to the average measured STP in the TCEQ data, which was a Mehlich3 concentration of 200 ppm. Based on a simple trial-and-error process of trying various initiation dates and evaluating the STP concentration predicted for WAFs, a start-up date for the validation period was determined as January 1, 1988.

3.3.10 Point Sources

Municipal WWTPs are point sources that must be directly input into the SWAT-TCEQ model at the subbasin level. WWTPs are important, constant sources of nutrients, particularly at low river flow. During the model validation period, point source discharges occurred directly to the NBR from five municipal WWTPs, while the Hico WWTP discharged into a tributary of the North Bosque River (Table 3-3 and Figure 3-8).

For the modeling effort, data were compiled from discharge monitoring reports (DMRs) or self-reporting data required monthly from each WWTP and available through TCEQ and EPA databases and from monitoring data collected by TIAER and the Brazos River Authority (BRA) under project approved quality assurance project plans (e.g., BRA, 2003 and TIAER, 1993). Historical average daily discharge by month for all six WWTPs was obtained through data requests to the TCEQ main office in Austin and the regional offices in Arlington and Waco (see TIAER (2006) for more detail). Self-reporting data were requested back to 1990, if available, and go through September or October 2005. Of note, the Stephenville WWTP has two separate outfalls for discharge. The second outfall is located in the Stephenville City Park. For estimating point source loadings for SWAT-TCEQ, discharges from both outfalls were added together.

TIAER, with assistance from the BRA, routinely monitored the discharge from the Stephenville, Hico, Iredell, Meridian, Clifton, and Valley Mills WWTPs from December 1995 through May 2000. All samples were analyzed by TIAER's laboratory and the data maintained in TIAER's water quality databases. Samples were generally collected on a biweekly basis. Basic statistics (mean, median, standard deviation, maximum, minimum and number of observations) for nutrients and suspended solids from these routine samples indicate a wide range of concentrations associated with the plants (see Chapter 4 of TIAER (2006)).

The monthly self-reported discharge rates and the TIAER and BRA collected nutrient data were combined to create the WWTP point source files used during the validation period.

3.3.11 Dairy Lagoon Discharges and Unauthorized Municipal Discharges

Output from the lagoon discharge and unauthorized municipal WWTP discharge model explained in Sections 2.4.1 and 2.4.2 respectively were added to the WWTP point source files in order to create point source files for every subbasin in which a WWTP or a lagoon discharge was present. The nutrient content of the unauthorized discharges for each municipality are shown in Table 2-3. Chapter 4 of TIAER (2006) provides detailed explanation of how the frequency, volume, and the nutrient concentrations of unauthorized municipal discharges were determined.

3.4 Measures of Model Performance

3.4.1 Statistical Measures

The percent error (%E) of the means of daily-average predicted and measured streamflows over a specified time period[4] and the %E of the means of predicted and measured total sediment and nutrients loads over a specified time period, and the Nash-Sutcliffe model efficiency (*ENS*) (Nash and Sutcliffe, 1970) were used as the indicators for the calibration process when comparing the model output values to measured values. *ENS* was calculated as follows:

$$ENS = 1 - \frac{\sum_{i=1}^{n} (P_i - M_i)^2}{\sum_{i=1}^{n} (M_i - \overline{M})^2} \qquad (6)$$

---

[4] Depending on the nature of the simulation (e.g. long-term hydrological calibrations or short-term nutrient calibrations) the means of different time periods were used in the calculations of the performance measures. Each section dealing with the different calibrations and their measures of model performance explains which time-periods were used.

Where *ENS* equals the Nash-Sutcliffe model efficiency, M_i are measured values, P_i are predicted values, n is the number of predicted/measured values, and $\overline{M}$ is the average measured value. *ENS* can range from -∞ to 1. An efficiency of 1 (*ENS* = 1) indicates the pattern of model prediction perfectly matches the measured data. An efficiency of 0 (*ENS* = 0) indicates that the model predictions are as accurate as the mean of the measured data, whereas an efficiency less than zero ($-\infty < ENS < 0$) occurs when the mean measured value is a better predictor than the simulated value (Moriasi et al., 2007).

%E was calculated as follows:

$$\%E = 100*(\overline{X}_p - \overline{X}_m)/\overline{X}_m \qquad (7)$$

Where %E = percent error, $\overline{X}_p$ = mean predicted value for the calibration or verification period and $\overline{X}_m$ = mean measured value for the calibration or verification period. A value of %E = 0 indicates the predicted total amount of flow or loads equals the measured value.

3.4.2 Goals of Acceptable Model Performance

The guidelines of Moriasi et al. (2007) (Table 3-4) were considered in the development of performance goals for the long-term hydrologic calibration, short-term calibration, and short-term verification of this reassessment modeling effort. The performance goals were developed to allow evaluation of acceptability of model predictions and were based on numeric values for *ENS* and %E. These goals represent desired, but not required, levels of performance of SWAT-TCEQ predictions during model validation. During this validation effort it was not required that the model predictions meet the goals at every monitoring site where model results were compared to measured data, but it was further recognized that a failure of the model to meet these goals at a majority of sites would constitute unacceptable model validation.

For the long-term hydrologic calibration the objective was to achieve the goal in Moriasi et al. (2007) for a “good” performance rating for streamflow (*ENS* > 0.65; %E ≤ ± 15 percent; see Table 3-5 for performance goals for this study).

For the short-term hydrologic and nutrient calibration, the guidelines of Moriasi et al. (2007) were again consulted (Table 3-4). A dual level of model performance was established: one level for NBR main stem sites with large drainage areas and a reduced performance level for all other sites, which are referred to as secondary sites (Table 3-5). The goal of the calibration at the three primary sites (i.e., sites BO070, BO090, and BO100) was to have streamflow, sediment, *total* nutrients (total N and total P), and PO_4 achieve the “good” rating from Moriasi et al. (2007). For secondary sites and constituent parts of total nutrients besides PO_4 (i.e. organic N and P, NO_3 and NH_3) the “satisfactory” rating was considered as achieving the goal of acceptable model performance.

This dual level of acceptable model performance was developed in recognition of uncertainties in model input and measured data that resulted in an anticipation of better model performance for sites with larger drainage areas (primary sites) as compared to those sites with smaller drainage areas (secondary sites), and for total nutrients as opposed to their constituent parts.

Three important limitations of model input resulted in an anticipation of better model performance for large drainage areas. The three areas of input were: 1) the use of average management behavior to describe practices on the landscape (e.g., average harvest dates, average amounts of nutrient applications), since the individual behavior of producers was unknown; 2) assignment of dairy cow numbers (and associated quantities of manure) at a subbasin level based on distribution of WAFs (Section 3.3.6); and 3) specification of precipitation input based on locations of precipitation stations and interpolation stations (Section 2.7.5), since measured data were only known at stations and were extrapolated to other locations. The first consequence anticipated, and generally observed, was that as the drainage area above a monitoring site increased, the number of producers increased, which made it more likely that the average management used for model input represented the average of management occurring in the drainage area, and the more likely that deviations from average management balanced out. In a similar manner, as the drainage area above a monitoring station increased more model subbasins comprised the area above the site and it was anticipated that cumulative error in assignment of dairy cows to individual subbasins became less and “averaged out.” The third consequence was that as the drainage area increased, inaccuracies of individual precipitation stations to represent rainfall for locations was also averaged out by the size of the area and the presence of several precipitation stations.

Increased accuracy was expected for model predictions of total nutrients as opposed to their constituent parts due to the fact that traditionally the SWAT model has performed better predicting total nutrients, than their constituent parts (particularly NO_3) (Saleh et al., 2000, Saleh and Du, 2004). There are also unavoidable differences in how the model divides total nutrients into constituent parts as compared to how actual lab procedures define soluble, particulate, inorganic and organic components of total nutrients. These differences between model and laboratory separation of total nutrients into component parts create greater uncertainty with model predictions of the component parts than with the whole (or total), and an expectation of poorer model performance for these component parts (Harmel et al., 2006). The validation results presented in this report emphasize total nutrients with the exception of PO_4, which is the primary nutrient form of importance to the TMDLs. Despite the additional challenges of achieving the same level of validation for PO_4 as total P and total N, the same level of performance was set for PO_4 as the total nutrients (Table 3-5), because of its importance to the objectives of the project.

Ideally, model predictions at all secondary sites could achieve the performance measure goals quantified in Table 3-5 to indicate acceptable model performance. The reality is, however, that at sites with smaller drainage areas and particularly for the simulation of sediment and nutrients, which are strongly affected by land management, the above mentioned limitations of model input result in the potential for very large discrepancies between model predictions and measured data.[5] Nevertheless, it was the goal of the validation process to achieve predictions at as many secondary sites as possible that met the established statistical performance measures

---

[5] Conversely, precipitation could be specifically known if there was a rain gauge in the subwatershed, which often produced accurate streamflow predictions even in the smaller subwatersheds.

without detrimentally affecting the measures at primary main stem sites, which were of critical importance in the evaluation of the TMDL allocation scenarios.[6]

For the short-term verification period, the statistical measures of model performance were relaxed at the primary sites to the measures of the secondary sites (Table 3-5). The reason to reduce the acceptance standards from the "good" rating to the "satisfactory" rating in Moriasi et al. (2007) is two fold. First, as previously mentioned, the verification period was restricted to being only two years in duration and during that period the watershed experienced fairly intense drought conditions. Second, Moriasi et al. (2007) recommends stricter performance ratings for model calibration than verification, because parameter values are adjusted for conditions during the model calibration period, but not adjusted for verification.

A final note regarding the validation concerns urban areas. At the stream level, SWAT output is most readily produced at the most downstream point of each subbasin (i.e., the subbasin outlet) delineated (see Figure 2-1 for these subbasins). By intent, the subbasin-delineation process of the NBR watershed established the location of monitoring sites to be used in the validation process at subbasin outlets to facilitate comparisons of model predictions to measured data. Because of its very small drainage area, no subbasin outlet was established to correspond to the TIAER urban water quality monitoring site MB040, where streamflow and nutrients were measured from the Methodist Branch tributary that captures surface and storm drain runoff from the city of Stephenville (Figure 3-1). In order to get a sense of the urban calibration and to be sure it was within the correct order of magnitude, the surface runoff quantity and P content of that runoff from the HRUs that comprised the simulated urban area of Stephenville were compared to measured data at MB040.

3.5 Calibration

During calibration selected model input parameters were adjusted within allowable limits until model output for a given time period matched measured output within some predetermined measure of model performance. Repeated simulations of the calibration period were made with each simulation involving adjustments of the selected input parameters until model predictions at least met predetermined measures of model performance at key sites with measured data.

3.5.1 Time-of-Travel Calibration

Time-of-travel field studies were conducted to help provide information for hydraulic validation of SWAT-TCEQ. Time-of-travel studies were conducted on three reaches along the main stem of the NBR during low and moderate flow conditions (see Chapter 13 of TIAER (2006) for more details). The combination of accurately measured cross-sectional areas with calibration of the model to time-of-travel studies permitted a highly refined simulation of the NBR stream hydrology and hydraulics, especially during periods of low flow when instream kinetics play an important role in determining nutrient concentrations. Stream velocity determines the length of time that instream kinetics can act upon and transform nutrients.

---

[6] Some of the monitored subwatersheds were extremely small, such as NF009, and expectations of satisfactory calibrations particularly for sediment and nutrients were low for these very small subwatersheds.

To calibrate the model to stream velocity, measured stream velocities from the time-of-travel studies were used. In order to make a legitimate comparison between predicted and measured values of stream velocity, SWAT-TCEQ output used for comparison with the measured data was chosen by finding a day within the same relative time period of the time-of-travel study that had a predicted streamflow rate equal to the measured streamflow rate during the time-of-travel measurements. The parameter altered to affect predicted time-of-travel was Manning's n.

Changing Manning's n from the default value of 0.014 to a value of 0.150, the maximum value recommended in the SWAT User's Manual (Neitsch et al., 2002), improved the simulation of stream velocity compared to measured values, going from an average absolute percent error of 244 for simulations with a Manning's n of 0.014 (Figure 3-9) to an average absolute percent error of 60 for the simulation with a Manning's n of 0.150 (Figure 3-10).

A percent error of 60 was considered satisfactory due to the fact that the SWAT model is not truly designed to predict such parameters on as small a spatial scale as represented by the time-of-travel studies. The SWAT-TCEQ subbasin route file manipulated for calibration represented a much longer segment of river with a model assumed uniform channel configuration than the actual segment of river where the time-of-travel measurements were made. A Manning's n value of 0.150, which was admittedly at the extreme end of permitted Manning's n values, gave a much better prediction of stream velocity than the default value of 0.014. Combined with the fact that the model representation of stream cross-section dimensions had been improved based on actual measured cross-sectional areas, this was considered the best calibration of stream velocity that could be obtained. Attempting to calibrate the SWAT model to time-of-travel had, to our knowledge, never been attempted before.

3.5.2 Long-term Hydrologic Calibration

A long-term hydrologic calibration was performed for the 30-year period from 1965-1994 during which measured and predicted values for annual average streamflow were compared. There was no verification performed for the long-term hydrology, since the purpose of this exercise was to get the input parameters that control streamflow at roughly appropriate values prior to embarking on the more refined short-term calibration presented in section 3.5.3. Thus, the approach was to use the long-term streamflow to roughly calibrate the hydrology of the model, knowing that the short-term calibration process would refine this initial first phase of the hydrologic calibration. As the short-term calibration was conducted, the long-term calibration was continually re-checked to be sure changes made in the short-term calibration did not allow the long-term calibration to deteriorate below performance standards. The calibration results outlined in the following section (Section 3.5.2.1) represent the final long-term hydrological calibration results after the short-term calibration had been finalized.

Total streamflow is made up of base flow (e.g., groundwater contribution) and surface flow (direct rainfall runoff). Base flow tends to predominate during low flow and surface flow during high flow. Therefore, a program was used to extract base and surface flow from the measured and simulated data so that the calibration would ensure the accuracy of predicted base and surface flow. Base and surface flow predictions were not held to the statistical measures of acceptable model performance in Table 3-5, but were evaluated to ensure that total predicted streamflow was comprised of a similar ratio of base and surface flow as determined for the measured data.

3.5.2.1 Long-term Hydrologic Calibration Results

Streamflow data from three USGS gauges on the North Bosque at Hico, Texas (08094800, collocated with TIAER site BO070), near Clifton (08095000, collocated with TIAER site BO090), and at Valley Mills (08095200, collocated with TIAER site BO100) were used in the long-term calibration (Figure 3-1). The long-term hydrologic calibration had acceptable *ENS* values (> 0.65) and %E (≤ ± 15) at all three simulated sites based on the established model performance measures (Table 3-6 and Figures 3-11 through 3-13). In addition, the division of simulated streamflow into base and surface flow was very close to the measured values and accurately reflected the measured ratio of base to surface flow at all three simulated sites (Table 3-6 and Figures 3-14 through 3-16). Correct base and surface flow helps ensure that model simulations will add the correct component set of nutrients to the total streamflow.

3.5.2.2 Parameters Adjusted for Long-term Hydrologic Calibration

The model hydrologic output is calibrated to measured streamflow data by adjusting, within reasonable limits, key parameters that exist in a number of SWAT-TCEQ input files. The following outlines what those basic calibration adjustments were and in which files they occurred. SWAT-TCEQ uses a number of default values for parameters when no user decision is made about the parameter. All the parameters for which the default values were not used are shown in Table 3-7 which shows the file, the parameter, the recommended and/or default value and the actual value used for the calibration.

According to Neitsch et al. (2002) the first parameter to adjust during the hydrologic calibration is the NRCS curve number for moisture condition 2 (CN2). CN2 is the primary parameter that determines runoff from the HRU. The default CN2 for SWAT-TCEQ was determined by AVSWAT based on the soil hydrologic group and the land use contained in the soil and land-use GIS layers respectively. The CN2 number was assigned in the management (MGT) file for each HRU. Traditionally CN2 can be adjusted ± 10 percent during calibration. The lower the CN2 value the less runoff will occur (Neitsch et al., 2002). For most land uses the default CN2 values were used. However, for the following land uses the CN2 was adjusted:

- Coastal bermudagrass and Coastal/wheat rotation WAFs - CN2 reduced by 5 percent.
- Sorghum and sorghum/wheat rotation WAFs – CN2 increased 10 percent.
- Range with grazing and range WAF – CN2 reduced by 10 percent.

Other factors that affect the movement of water through soils such as soil bulk density, available water capacity (AWC) and saturated hydraulic conductivity were all determined by the SSURGO soil database when the soil (SOL) files were automatically created for each type of soil in the NBR watershed by the SWAT/GIS interface program AVSWAT.

Neitsch et al. (2002) recommends that AWC be the second parameter adjusted in hydrologic calibration. AWC is a measure of the water content of soil available to plants and tends to fall within the range of 0.0 to 0.35 mm H_2O/mm soil (Houser and Pitt, 2008). Increased organic matter in the soil is known to increase the quantity of AWC (Hudson 1994, Houser and Pitt, 2008). Neitsch et al. (2002) recommends that AWC be altered ± 0.04 mm H_2O/mm soil during calibration. Therefore, in the soils in the NBR watershed above Hico where dairy WAFs and grazed pasture predominated thereby adding more organic matter to the soil the AWC of soils were increased by 0.04 mm H_2O/mm soil, while below Hico soil AWC was decreased by 0.04 mm H_2O/mm soil. Raising AWC reduced the flow of water from the HRU since more water was being retained in the soil.

The following are other parameters that were altered from the default values and which affected the hydrologic output of the model. The altered parameters occur in various input files. One of the key input files for calibration is the basin (BSN) file. The BSN file is a "universal" file in the sense that a change in the parameters within this file change that parameter for the whole basin or watershed. In addition, within the BSN file there are choices about certain functions to be used in the modeling. The BSN file permits either Priestley-Taylor, Hargreaves, or Penman/Monteith potential evapotranspiration algorithms to be chosen to simulate evapotranspiration. Hargreaves was used in the calibration. Within the BSN file a function to model water flow in a cracked soil was selected. Two alternatives for modeling the routing of streamflow through a stream reach are offered: variable travel-time or Muskingum. Variable travel-time was used in the calibration. ESCO is the soil evaporation compensation factor (Table 3-7). As the value of ESCO is reduced, the model extracts more of the evaporative demand from lower levels of the soil (Neitsch et al., 2002). The value for ESCO in the previous TMDL modeling effort was 0.10 and that value was kept for this calibration. The surface runoff lag coefficient (SURLAG) controls the fraction of the total available water that will be allowed to enter the reach on any one day. Any decrease in SURLAG results in more runoff being prevented from reaching the main channel on the day it is generated. The delay in release of surface runoff will smooth the streamflow hydrograph simulated in the reach (Neitsch et al., 2002). SURLAG was increased to make the streamflow hydrograph less smooth. TRNSRCH represents the fraction of transmission losses from the main channel that enters the deep aquifer. The remainder of the transmission losses enters bank storage. TRNSRCH varies between 0.00 and 1.00. The default value for TRNSRCH is 0.0 (Neitsch et al., 2002). TRNSRCH was manipulated to 0.250 in the calibration primarily for its effect on base flow.

Additional parameters affecting the hydrology of the model were in the groundwater (GW) files. Every HRU has a unique GW file associated with it. Nevertheless, for the most part changes were made universally in all the GW files. Parameters in the GW files have the most impact on base flow, so these parameters were adjusted until simulated base flow matched well with the measured base flow. GW_DELAY is the lag between the time that water exits the soil profile and enters the shallow aquifer. There is no default value provided for SWAT (Neitsch et al., 2002). The calibration used a value of 31 days (Table 3-7). ALPHA_BF is a baseflow recession constant that was calculated by the program that separated total streamflow into base and surface flow. GW_REVAP controls the movement of water from the shallow aquifer to the root zone where it can be lost from the system through evapotranspiration (Neitsch et al., 2002). Increasing its value reduces groundwater flow. The calibration used 0.2 the highest recommended value. RCHRG_DP is the fraction of water from the root zone which recharges the deep aquifer, effectively removing water from potential streamflow (Neitsch et al., 2002). Above or north of Hico in the Upper NBR a value of 0.5 was used and below or south of Hico a value of 0.1 was used (Table 3-7).

Every subbasin has a RTE file which contains a number of parameters which affect the routing of water through the main channel of the subbasin. It was in the RTE file that the main stream channel's dimensions were entered based on the previously mentioned cross-sectional measurements. In addition, the Manning's n value (used in the calibration of time-of-travel in Section 3.5.1) was entered in the RTE file. CH_K2 is the hydraulic conductivity of the main channel, which is a measure of the amount of water lost from streamflow through the streambed over time (Neitsch et al., 2002). The calibration used a value of 0.0 mm/hr for the NBR and a value of 25.0 mm/hr for headwaters and tributaries to the NBR (Table 3-7).

3.5.3 Short-term Hydrologic, Sediment and Nutrient Calibration

The model was calibrated for streamflow, sediment, total P, PO_4, and total N. Organic P and the component parts of total N (nitrate (NO_3), ammonia (NH_3), and organic N) were visually reviewed for acceptability during the calibration process, but these output variables were not given the same level of focus as the output variables mentioned above to which the model was specifically calibrated. For nutrients, as indicated in Table 3-5, acceptability of model performance was determined for total N, total P, and PO_4. Algae simulation was used as a guide for the validation but the model was not directly calibrated to algae due to the lack of sophistication in the representation of aquatic vegetation in SWAT-TCEQ. SWAT-TCEQ simulates one form of phytoplankton (suspended algae), i.e., one set of constant kinetics to define suspended algae, and does not include representations of macrophytes and periphytic algae (periphyton). In reality, the streams and rivers of the NBR watershed contain many forms of aquatic plants, including multiple species of macrophytes, periphyton, and suspended algae and all these forms are operating on a seasonal basis in response to nutrient availability, water temperature, available sunlight, and streamflow. In Chapter 9 of TIAER (2006) the results of two years of quarterly sampling of macrophytes and periphyton are provided for seven main stem sites and four major tributary sites. These quarterly data suggested that most monitored sites experienced relatively low levels of periphyton, though a few stations had measured levels that indicated mesotropic conditions on average with eutrophic conditions experienced periodically at a couple of stations. In TIAER (2006) it was also concluded that such factors as scouring events and light limitations rather than instream nutrient concentrations were limiting periphyton biomass at most locations. Recognizing that the aquatic vegetation component in SWAT included only suspended algae and that periphyton as well as macrophytes would uptake soluble forms of N and P, the model input parameters controlling suspended algae biomass were purposefully set to over-predict measured Chla concentrations by a factor of roughly two. Therefore, the measured Chla data, as a measure of suspended algae, were only used to guide the calibration and as a refinement measure to adjust the PO_4 instream concentration as constrained by measured data, i.e., to keep measured and simulated algae output of the same magnitude.

3.5.3.1 Yield Results

Care was taken during the calibration that yields and biomass of crops were reasonable since they are a major sink of nutrients on the landscape and have a substantial influence on the amounts of nutrients that reach the stream. A calibration that creates unreasonable crop yields cannot be considered a good calibration, therefore yields were periodically checked during the calibration process to ensure that adjustments of input parameters were not resulting in unrealistic yields.

SWAT-TCEQ predicted values for yields from various crops during the short-term calibration indicated that growth rates and yields for crops were simulated reasonably, and no input adjustments were necessary for crop parameters to improve predictions of yields. The expected yields in the NBR watershed[7] for non-irrigated improved pasture Coastal bermudagrass are 5.6 – 22.3 ton/ha with a typical yield of 6.7 – 8.9 ton/ha. During the calibration period the average WAF Coastal bermudagrass simulated yield was 6.0 ton/ha. The maximum simulated yield was 13.4 tons/ha. In improved pasture (Coastal bermudagrass) that received only commercial fertilizer and no manure application, the average simulated yield was 6.0 ton/ha, with a maximum simulated yield of 9.2 ton/ha. These simulated values were within the acceptable expected range. The expected yield for sorghum hay is 2.2-5.6 ton/ha. The simulated average yield was 4.9, which was within the expected range. The expected yield for wheat is 2.2-5.6 tons/ha, and its simulated average yield was 4.1 tons/ha; again within the expected range.

3.5.3.2 Short-term Hydrologic, Sediment and Nutrient Calibration Results

Based on the established general performance measures (Table 3-5), the calibration of monthly streamflow was acceptable at all sites (primary and secondary) except sites SC020 which had unacceptable *ENS* and %E values and NC060 which had an unacceptable *ENS* value but an acceptable %E (Table 3-8). Site SC020 was a small microwatershed with very low flows. Low flows were difficult to measure and simulate which created compounding errors, and *ENS* values computed with low values were susceptible to being strongly influenced by one or two high values. In addition, the water quality monitoring site at SC020 was subject to high flows created by road runoff that was not simulated by the model, which could be one reason for the relative large negative %E, as well as the unacceptable *ENS* value. Site NC060 was on a major tributary to the NBR in the southern end of the NBR watershed where the coverage of precipitation stations was not as extensive as it was in the Upper NBR watershed. The more extensive coverage of precipitation gauges in the Upper NBR watershed may explain why the calibration to streamflow was considered acceptable in the Upper NBR even for the smaller low-flow microwatersheds. In addition, the period of measured data at site NC060 was only 2 years because the site was not installed until late 1995. The shorter the period being simulated, the more likely that a few aberrations from measured data will create low *ENS* values.

Sediment ratings were acceptable at the primary main stem sites and the smaller main stem watershed outlet represented by BO040, except for an unacceptable *ENS* value at site BO090,[8]

---

[7] Based on information received from County Extension Agents in Erath, Hamilton, Bosque, Somervell, Coryell, and McLennan Counties

[8] BO090 still qualifies as being "satisfactorily" calibrated based on the Moriasi et al. (2007) standards in Table 3-4.

but were often unsatisfactory at the smaller microwatersheds with low measured total sediment even though the %E was acceptable at all sites except NF090, SF020, and SP020, which were some of the smallest subbasins (Table 3-8). The unacceptable *ENS* values coupled with acceptable %E values for sediment illustrates that the general or average factors that result in stream sediment were satisfactorily predicted but the exact timing of those losses often associated with land management (such as tillage events) were less accurately predicted.[9]

The total P and total N calibration performance measure ratings for *ENS* and %E were acceptable at the three primary main stem sites. The *ENS* and %E ratings for TP at the other main stem and main tributary sites for smaller subwatersheds (BO040, SF075, and NF050) were acceptable (Table 3-9). It can be seen at secondary sites like NF020 and GC100 for TP and at numerous sites for TN, that even though there may have been unacceptable *ENS* ratings there were acceptable %E ratings, indicating that the amount of total nutrient losses from the landscape was being simulated correctly but that the exact timing of losses was not as accurately simulated, illustrating again the possibility of variability from average management practices that was more evident the smaller the area being evaluated.

Sites SC020 and NC060 had unacceptable *ENS* values for TP and TN as might be expected due to their unacceptable hydrologic and sediment calibrations. However, NC060 had acceptable %E values for both TP and TN (Table 3-9). The unacceptable *ENS* value (0.25) at NF020 may be partially due to the fact that actual confined cow numbers in its subbasin fluctuated greatly during the calibration period compared to the average cow number value used for the simulation (Table 3-10). Similarly, AL040, another site with an unacceptable *ENS* value for TP (Table 3-9), had a drainage area with very high fluctuation of actual cow numbers compared to the average used for simulation with an average absolute percent difference (%Diff) of 55 percent (Table 3-10). Sites NF009 and NF050, which have relatively small drainage areas but with a low fluctuation of actual cow numbers (Table 3-10), had acceptable *ENS* values (Table 3-9). Meanwhile, predictions at site SC020 showed a relatively low value for measured TP (88 kgs), similar to values from subbasins with little if any dairies like SF020 (20 kgs) and SP020 (42 kgs) (Table 3-9), and yet the cow number inputs for subbasin SC020 were high (Table 3-10). The predictions at site SC020 illustrate the potential that localized uncertainty regarding actual confined cow numbers and actual management practices could lead to poorer model performance in smaller subwatersheds as compared to larger watersheds where the probabilities are much higher that assigned confined cow numbers and the average management used for model input represent the prevailing conditions in the watershed.

Because the TMDLs for Segments 1226 and 1255 of the NBR were based on PO_4, it was the goal, as outlined in Section 3.4.2, that the PO_4 calibration predictions be rated as "good" based on the Moriasi et al. (2007) standards (Tables 3-4 and 3-5) at the primary main stem sites that correspond to the TMDL index stations for the large subwatersheds (sites BO070, BO090, and BO100). All three of the primary main stem sites had high *ENS* values and low %E for PO_4

---

[9] *ENS* is essentially a measure of how well predicted values match the pattern of measured values over time, while %E is a measure of how close the total predicted value is to the total measured value over a given amount of time. So the predicted amount of losses during a particular time period could be accurate giving a low %E but the predicted timing of those losses during the same time period may be inaccurate which would result in a low *ENS* value.

loads (Table 3-11), and the predicted PO_4 loads matched the measured loads well as shown in Figures 3-17 through 3-19. The match was particularly good at site BO070 (Figure 3-17) that had more measured data for comparison than did site BO090 or site BO100. The calibration for PO_4 loads was also acceptable at site BO040, another main stem site (which corresponds to the NBR below Stephenville index station). The outlets of the two major branches of the NBR the South Fork (SF075) and the North Fork (NF050) both had acceptable *ENS* and %E values (Table 3-11). Sites SF075 and the NF050 were located in the northern section of the Upper NBR watershed above BO040 where many of the dairies were located (and which collectively corresponded to the NBR above Stephenville index station). In general, the %E values for all monitoring sites for PO_4 were acceptable even if they had unacceptable *ENS* values, except for sites SC020 and AL040 which both had unacceptable *ENS* and %E values, probably due, in part, to the large fluctuation in actual cow numbers and uncertainty of actual cow numbers mentioned previously (Tables 3-10 and 3-11).

The model was also calibrated to PO_4 average *daily* load and concentration over the calibration period. The goal was to get as close to measured average daily concentration and load as possible at the main stem sites that correspond to the TMDL index stations. According to the established measures (Table 3-5), the prediction of average daily PO_4 concentrations and loads during the calibration period were rated as acceptable (Table 3-12).

The measured loads and concentrations at water quality monitoring stream sites to which the model was calibrated were a result of nutrient contributions from a variety of land uses and, in some instances, WWTPs that would be in the drainage area above each site. Since the TMDL allocation scenarios would be dynamically changing those land uses based on changing manure application rates and need to add new areas for manure application, it was important that the relative contribution of nutrients from different land-use types also be accurately represented. Table 3-13 shows that PO_4 from background areas, those subwatersheds that are predominately range and pasture without dairy WAFs, had an average %E of only -9.3 for the average kg/ha/yr from the three sites representing background areas (sites SP020, NC060, and SF020). The average %E of the mixed areas (SF075, AL040, and GC100), meaning subwatersheds that had some WAFs but not a preponderance of them, was -12.4. The intensive agricultural areas (NF090, NF020, NF050, SC020 and IC020), subwatersheds with a high density of WAFs, tended to under-predict with a %E of -22.6. However, that %E was impacted negatively by the poor prediction at NF020 compared to the measured data (Figure 3-20). Again this under prediction possibly represents the increased level of uncertainty within small drainage areas from prescribing average management operations. In general, however, the predicted loadings from drainage areas with different land types for the different forms of P followed the same pattern as the measured loadings with background areas having less loadings than the mixed areas and impacted areas contributing the highest loadings[10] (Table 3-13). The urban calibration at site MB040 shows a reasonable simulation of streamflow based on surface runoff from the urban HRUs (Figure 3-21). The primary model output variable of PO_4 was reasonably predicted with a %E of the average monthly load of around 4 percent (Figure 3-22).

---

[10] The one exception was organic P for which both measured and predicted loadings from the mixed areas were lower than the background areas (Table 3-13).

3.5.3.3 Adjusted Calibration Parameters for Short-term Calibration

The following sections outline the basic calibration adjustments for the short-term calibration and in which files they occurred. Hydrologic parameters that adjust streamflow were not altered in order to ensure that the long-term hydrologic calibration remained valid. All the parameters for which the default values were not used are shown in Table 3-7 which shows the parameter, the recommended and/or default value and the actual value used for the calibration.

3.5.3.3.1 Sediment Calibration

SWAT-TCEQ uses a number of default values for parameters when no user decision is made about the parameter. SPCON and SPEXP were the primary parameters used for calibrating the sediment loads in the reach. The higher the value of each, the higher the maximum amount of sediment that could be transported from a reach. The calibration used the highest suggested value for each. The other parameters that affected sediment loads in the reach were the channel erodibility factor (CH_EROD) and the channel cover factor (CH_COV). Both of these parameters are located in RTE files and therefore could be adjusted for each reach. CH_EROD could be set to a value between 0.0 and 1.0. A value of 0.0 indicates a non-erosive channel while a value of 1.0 indicates no resistance to erosion. CH_COV could be set to a value between 0.0 and 1.0. A value of 0.0 indicates that the channel is completely protected from degradation by vegetative cover while a value of 1.0 indicates there is no cover on the channel (Neitsch et al., 2002). These factors are difficult to quantify experimentally and are typically used as calibration factors to adjust sediment output.

CH_EROD and CH_COV were individually manipulated for each reach in the calibration to help match measured sediment to simulated sediment output. The values used for CH_EROD varied from 0.8 to 0.025 while the values for CH_COV varied between 0.9 and 0.05 (Table 3-7). CH_COV values tended to be lower in the northern part of the watershed where there was a fair amount of growth and cover on the stream banks and in the stream. Headwater streams tended to have a higher erodibility (CH_EROD) due to less exposed bedrock in the stream bed.

3.5.3.3.2 Nutrient Calibration for Landscape Processes

In the BSN file the concentration of N in rainfall is entered as parameter RCN. The calibration used an actual TIAER measured value (Table 3-7) based on the median concentration of N in 128 rainfall events from July 1, 1997 to June 30, 2002 as measured at the Texas AgriLife Research and Extension Center at Stephenville, Texas.

Some of the calibration parameter choices discussed in the remainder of this section increased soluble P in runoff and others decreased it. The reason for making adjustments that are seemingly at counter purposes is that there was initially too much soluble P runoff from range and pasture and not enough from dairy WAFs. The combination of parameters used in the calibration helped correct that imbalance.

The P uptake distribution parameter (P_UPDIS) controls the depth distribution of P uptake by roots of a crop. The importance of P_UPDIS lies in its control over the maximum amount of solution P removed from the upper soil layers. Because the top 10 mm of the soil profile interacts with surface runoff, P_UPDIS influences the amount of labile P available for transport in surface runoff. The model allows lower layers in the root zone to fully compensate for lack of solution P in the upper layers, so there will be no significant change in P stress with variation in the value used for P_UPDIS (Neitsch et al., 2002). The default value for P_UPDIS was 20, and by raising it to 70 more of the crop's P requirement was met by the upper layers of the soil profile reducing the amount of soluble P available for runoff, thereby reducing the amount of soluble P in runoff.

The N and P percolation coefficients (NPERCO and PPERCO) control the amount of NO_3 and solution P respectively removed from the surface layer in runoff relative to the amount removed via percolation. The value of NPERCO can range from 0.01 to 1.0. As NPERCO approaches 0.0, the concentration of nitrate in the runoff approaches 0.0. As NPERCO approaches 1.0, surface runoff has the same concentration of nitrate as the percolate (Neitsch et al., 2002). In the calibration NPERCO was set at its lowest value to reduce NO_3 runoff. The P percolation coefficient is the ratio of the solution P concentration in the surface 10 mm of soil to the concentration of P in percolate. The value of PPERCO could range from 10.0 to 17.5. The default value for PPERCO is 10.0 (Neitsch et al., 2002). The calibration used the highest value for PPERCO.

The P soil partitioning coefficient (K_d) is the ratio of the soluble P concentration in the surface 10 mm of soil to the concentration of soluble P in surface runoff (Neitsch et al., 2002). The new algorithm to determine K_d in SWAT-TCEQ (see section 2.7.2) used the original user-input parameter of SWAT (PHOSKD) to make slight adjustments to the calculated value of K_d. The calibration used a value of 0.8 (Table 3-7) which slightly reduced the calculated K_d value. By lowering K_d the concentration of soluble P in runoff was increased.

The P sorption coefficient (PSP) was altered from a default value of 0.40 to a value of 0.50 (Table 3-7). Increasing the PSP increases the amount of P in solution after fertilization and reduces the amount of P in runoff while increasing the amount of soil soluble P (Neitsch et al., 2002).

The denitrification exponential rate coefficient (CDN) allows the user to adjust the rate at which N is lost through denitrification (Neitsch et al., 2002). The calibration used the highest acceptable value in order to remove more N from the system and reduce the amount of total N in the stream (Table 3-7).

The organic N and P enrichment ratios (ERORGN and ERORGP respectively) are defined as the ratio of the concentration of organic N or P transported with the sediment to the concentration in the soil surface layer. SWAT-TCEQ calculates an enrichment ratio for each storm event or allows the user to define a particular enrichment ratio for organic N or P that is used for all storms during the simulation. To have the model calculate the enrichment ratio, the values for ERORGN and ERORGP are set to zero, which is the default option. User-defined enrichment ratios are set in the HRU input file (HRU). Each HRU has a unique HRU file (Neitsch et al., 2002). High enrichment ratios were set for non-forested land north of Hico (Table 3-7), since much of that land is WAF, improved pasture or highly grazed range land with soils that would be more enriched in organic matter (USDA, 1980). South of Hico the model was allowed to calculate the enrichment ratios.

In the MGT files there is a parameter representing the fraction of fertilizer applied to top 10 mm of soil (FRT_SURFACE). This parameter can be manipulated for individual land use types within their respective management files. The default value is 0.20 (Neitsch et al., 2002). In the calibration a FRT_SURFACE value of 0.50 was used for agricultural fields (AG) and coastal and range fields on which liquid manure was applied (LC and LR) (Table 3-7). On pasture fields (PAST) a FRT_SURFACE value of 0.8 was used since fertilizer was not incorporated, and on coastal and range fields receiving unincorporated solid manure (SC and SR) a FRT_SURFACE value of 0.95 was used (Table 3-7). In all other MGT files the default value was used for FRT_SURFACE. Increasing values of FRT_SURFACE serve to increase PO_4 runoff.

SWAT-TCEQ was modified so that the ground water concentration of soluble P was no longer user-assigned in the GW file (GWSOLP) as it was in the original SWAT model. In SWAT-TCEQ the concentration of soluble P in ground water was determined by an algorithm based on the concentration of soluble soil P.

3.5.3.3.3 Nutrient Calibration for Instream Processes

The data used by SWAT-TCEQ for instream water quality processes is contained in two files: the stream water quality input file (SWQ) for specific reaches and the general water quality input file (WWQ) for processes modeled uniformly over the entire watershed (Neitsch et al., 2002).

The WWQ file has parameters that control the growth of algae which affects the instream concentrations and loads of nutrients as nutrients are used and transformed by the growth, respiration, and settling of algae. Options for light averaging and the specific algal growth rate are chosen in the WWQ file. The algal growth rate in the calibration used the limiting nutrient option so that the local algal growth rate is limited by light and one of the nutrients (N or P).

Mostly default values for algal growth parameters were used in the calibration. Non-default values were often based on TIAER measured data from two years of algal assays conducted at three stations along the NBR (Chapter 10 of TIAER, 2006). The fractions of algal biomass that were N or P (AI1 and AI2 respectively), were manipulated within the accepted range in order to affect instream concentrations of N and P. AI2 was set to the highest acceptable value in order to reduce the concentration of soluble P in the stream (Table 3-7). The maximum specific algal growth rate at 20º C (MUMAX) was based on seasonal nutrient dose response bioassays conducted at three sites along the NBR from February 2004 through July 2005 (TIAER, 2006). The mean value for all sites was 1.51/day with a minimum of 1.00/day and a maximum of 2.49/day. However, as was previously mentioned in Section 3.4.4, SWAT-TCEQ only includes suspended algae, where in reality there are many forms of aquatic plants, including macrophytes, periphytic algae, and suspended algae. The measured growth rate data provided by TIAER was just for suspended algae. Therefore, it was assumed that the simulation of algae by SWAT-TCEQ should give higher concentrations and loads of algae than the measured data to compensate to some extent for the aquatic vegetation in the system that could not be directly simulated by the model. For that reason a higher value for MUMAX (4.0/day – see Table 3-7) than indicated by the TIAER bioassays was used. Nevertheless, the value for MUMAX was within the range of model documentation values of 0.20 to 8.0/day at 20ºC from Grenney and Krazewski (1981) and Baca and Arnett (1976). The algal respiration rate at 20º C (RHOQ) was set at its lowest acceptable limit in order to decrease the death rate of algae, thereby increasing the simulated concentration of algae. The values for the Michaelis-Menton half-saturation constant for N and P (K_N and K_P respectively) were based on TIAER algal bioassay data. The geometric mean for all sites was 0.022 mg N/l for K_N and 0.007 mg P/l for K_P (TIAER, 2006), which were the values used in the calibration (Table 3-7).

There are stream water quality input files (SWQ) for each subbasin and therefore, the values within these files could be different based on the individual reaches within the subbasins. Nevertheless, the same values were used universally for all of the SWQ files. The local algal settling rate in the reach at 20ºC (RS1) was given a value of 0.15 m/day in order to increase the concentration of algae in the stream compared to the default value of 1.00 m/day (Table 3-7). The benthic (sediment) source rate for dissolved P in the reach at 20ºC (RS2) was made a negative value based on the results of a studies conducted by TIAER (Chapter 11 of TIAER (2006)) to determine the equilibrium P concentration (EPC_o) for sediments at various locations within the NBR watershed. This study was conducted to ascertain the potential for movement of P either from ambient river water to sediment or vice versa under low to moderate flow conditions (TIAER, 2006). Sediment EPC_o defines the solution concentration or concentration of soluble P in the water column where there is no net adsorption or desorption of P to the sediment. When instream solution P concentration is above the value of EPC_o, the sediment acts as a sink for P, and when instream solution P concentration is below the EPC_o, the sediment acts as a source for P in the water column. The SWAT-TCEQ predicted soluble P instream concentrations on average were higher than the TIAER measured EPC_o values for the main stem water quality monitoring sites. Hence, the sediments would usually act as sinks, and negative values for the RS2 parameter are found in the literature (USEPA, 1985). The SWAT-TCEQ code was modified slightly so that as the simulated instream soluble P concentration approached the EPC_o value of a particular reach the negative aspect, or sink characteristic, created by the RS2 value was minimized. Once the simulated concentration fell below the EPC_o value the effect of the RS2 parameter was eliminated and the sediment no longer acted as a sink for P in the simulation.

The benthic source rate for ammonia (NH_3-N) in the reach at 20ºC (RS3) was set as low as possible in order to minimize the instream ammonia concentration and the overall instream total N concentration (Table 3-7). The rate coefficient for organic N settling in the reach at 20ºC (RS4) was set fairly low in order to minimize the loss of organic N concentration in the stream (Table 3-7). The organic P settling rate in the reach at 20ºC (RS5) was set at 0.010/day in order to reduce the amount of organic P settling but not eliminate it. Both RS4 and RS5 were parameters manipulated to help simulated organic N and P better match the measured values. The rate constant for hydrolysis of organic N to NH_4 in the reach at 20º C (BC3) according to the SWAT manual should be in the range of 0.2 to 0.4/day (Neitsch et al., 2002), however, values in the literature are as low as 0.001/day (USEPA, 1985). The parameter was set low in the calibration (0.020/day) (Table 3-7) in order to maintain the instream concentration of organic N. The rate constant for mineralization of organic P to dissolved P in the reach at 20º C (BC4) according to the SWAT manual should be in the range of 0.01 to 0.7/day (Neitsch et al., 2002), however, values in the literature are as low as 0.001/day (USEPA, 1985). The parameter was set low in the calibration (0.001/day) (Table 3-7) in order to maintain the instream concentration of organic P and minimize the instream concentration of soluble P in order to better match the measured values.

In general, the model was simulating too high a concentration and load of soluble P in the lower end of the NBR watershed compared to the measured values. Hence, within the calibration process, input parameters were adjusted within allowable limits to reduce the contribution of soluble P through instream process and maintain the concentration of organic P. Nevertheless, the calibrated model still tended to over-predict the instream concentrations of soluble P in the lower ends of the watershed South of Hico which should be kept in mind when assessing the ability to reach the targeted soluble P instream concentrations during the TMDL allocation scenario simulations.

3.6 Verification Results

As is often the case in validation efforts, the SWAT-TCEQ did not perform as well in the verification period compared to the calibration period. Acknowledging that most modeling efforts suffer from poorer validation results when compared to measured data, Moriasi et al. (2007) recommends stricter performance ratings for model calibration than verification. The difference is recommended according to Moriasi et al. (2007) because parameter values are adjusted for conditions during the model calibration period, but not adjusted for verification. The lower performance of the verification compared to the calibration was exacerbated by a shorter time period for the verification as well as an extended dry period, resulting in a long period of very low flow. Unfortunately, measured data in the southern portions of the watershed (i.e., sites BO090, BO100, and NC060) were not available until late 1995 and early 1996 and the changing conditions in the watershed, predominately as a result of the very large amounts of manure being hauled to compost facilities beginning in 2000, dictated the particular calibration and verification periods that were selected.

Data from a new site (BO020) were available for use in the verification. Site BO020 was located to represent the confluence of the South and North Forks of the NBR represented during the calibration period by SF075 and NF050 respectively (Figure 3-1). BO020 data was not used during the calibration because there was only one year of data available for it during that time period and SF075 and NF050 data could be used. BO020 replaced SF075 and NF050 during the verification period and represented the above Stephenville index station for that period. It should be noted that establishment, continuation, and discontinuation of monitoring sites was dictated by changing levels of funding and needs of studies being conducted under various TIAER research programs, as a result several of the monitoring sites for smaller watersheds were discontinued during the verification period**.**

At the mainstem sites BO070, BO090 and BO100 the *ENS* and %E values for streamflow and sediment during the verification period were all acceptable (Table 3-14). At site BO040 *ENS* values for streamflow and sediment were rated as acceptable (Table 3-14). At many of the microwatershed sites that exhibited very low flows, the %E was often rated as unacceptable, though the *ENS* values were usually rated as acceptable. So the model was simulating the pattern of flow well but was having difficulty accurately simulating the extremely low flows that occurred during the period. Sediment predictions were generally unacceptable at the very small subwatersheds which had extremely low amounts of measured sediment (NF009, NF020, and SP020) with the exception of SF020 which had acceptable *ENS* and %E values for sediment (Table 3-14). The predicted and measured sediment data resulting in an unacceptable *ENS* rating at site BO020 illustrate well the problems in the verification period caused by the short time period and the low flows (Figure 3-23). If the one extreme under prediction of sediment at site BO020 in January 1998 is removed the *ENS* value becomes 0.94.

The *ENS* and %E values for total P and total N were all rated acceptable at the three primary main stem sites during the verification period (Table 3-15). For total P, all the %E ratings were acceptable except at site SP020.

For the primary sites, the *ENS* values for PO_4 were rated as acceptable at sites BO070 and BO090 but not at site BO100, and only site BO070 had an acceptable %E value. %E was acceptable, however, at the more upstream main stem sites in the Upper NBR (sites BO020 and BO040) where the majority of dairies were located (Table 3-16). At site BO100 the compounding errors of inaccurate streamflow prediction (Figure 3-24), and low flows led to an unacceptable *ENS* rating and an over prediction of PO_4 due to the inaccurately high streamflow simulated between August 1998 and January 1999 (Figures 3-24 and 3-25).

For the verification period predictions of average daily concentrations of PO_4 were acceptable except at site B0100 where it was unacceptably over predicted (Table 3-17). Average daily loads were unacceptably over predicted at sites BO090 and BO100 reflecting the same problems that appeared in the monthly total load predictions (Tables 3-16 and 3-17), and indicative of the model's general tendency to over-predict PO_4 concentration in the lower portion of the NBR, the effect of which was exacerbated by the very low measured concentrations during the verification period. However, %E for *total* P average concentrations and loadings had acceptable rating at all sites along the NBR except for the average daily load at BO020 (Table 3-18). These accurate total P predictions indicated that the correct delivery of P nutrients was being simulated even during the extreme conditions of the verification period, but that perhaps under such low flow conditions the accurate division of P into its constituent parts and the nature of the relationship between modeled and measured nutrient constituents became even more uncertain.

3.7 Summary and Conclusion of Model Validation

The refinements to the NBR TMDL modeling effort based on public concerns regarding: 1) lack of spatial resolution in the definition of subbasins; 2) exclusion of the 40 PL-566 flood retardation reservoirs in the watershed; 3) and contributions of discharges associated with dairy lagoons and wastewater storage ponds, were all successfully incorporated into the SWAT-TCEQ model. In addition, improved simulation of instream water quality kinetics was realized, and a dynamic fertilizer management component was added to the refined SWAT model.

The SWAT-TCEQ model was successfully calibrated for long-term annual average daily streamflow based on acceptable performance values for *ENS* and %E, and exhibited a correct ratio of base to surface flow compared to measured data. Based on acceptable measures of model performance at most stations and most predicted constituents, SWAT-TCEQ was successfully calibrated for streamflow, sediment, and total nutrients, as well as PO_4, at the three primary main stem sites on the NBR. The SWAT-TCEQ model also calibrated successfully to average daily PO_4 loads and concentrations at sites which correspond to the index stations for the TMDL allocation scenarios using the acceptance rating in Table 3-5. SWAT-TCEQ also adequately simulated the relative contribution of nutrients from different land-use types which is important since the TMDL allocation scenarios will be dynamically changing those land uses based on changing manure application rates and the need to add new areas for manure application. SWAT-TCEQ also performed acceptably for streamflow, sediment and total nutrients at the key three main stem sites (BO070, BO090, and BO100) during the verification period. At some sites during the verification period unacceptable performance for PO_4 occurred. The poor performance for PO_4 at some of the primary main stem sites during the verification period was due in part to the occurrence of very low flows during a significant portion of the verification period. However, the %E for average daily PO_4 concentration during the verification period was acceptable at all the main stem sites except BO100 (Table 3-17).

Because large differences in hydrologic conditions were suspected as a partial explanation for poorer model performance during the verification period than during the calibration period, a 40-year period (1960-1999) of average annual streamflow was analyzed for the USGS gauge on the NBR at Clifton. The Clifton gauge location was selected as representative of conditions for most of the watershed, and the 40-year period was considered as representing a sufficient period to include a reasonable range of hydrologic conditions. Rank and percent of the time the annual flow is exceeded (percent exceedance) was determined for each individual year (Table 3-19). What becomes apparent from this simple analysis is that the calibration period (1993-1997) was represented by two very high flow years (1995 and 1997). Of the other three years in the calibration period, 1996 had the least flow, yet it was only exceeded in less than 60 percent of years during the 40-year period. In stark contrast, the streamflow in 1999, the second year of the verification period, was exceeded in almost 93 percent of the years. The 1998 flow and percent exceedance indicates a high flow year, but a more detailed view of the hydrograph for that year (Figure 3-4) indicates that the highest flows that year occurred in the first four months with a very high flow period in March. Hence, low flow conditions were experienced for about 20 of the 24 months during the verification period. It seems reasonable to conclude that large differences in the hydrologic conditions between the calibration period (high and normal flow) and verification period (low flow) resulted in the model not being calibrated to represent low flow years as well as high and normal flow years.

It was concluded that the refined SWAT-TCEQ model was successfully validated for the NBR watershed and appropriate for applications to investigate and reassess allocations and targets from the TMDL, with the awareness that it had a general tendency to over-predict PO_4 concentrations at very low flows in the lower part of the NBR and under-predict concentrations and loads in the upper part of the NBR.

3.8 Sensitivity Analysis

A list of pertinent parameters for sensitivity analysis was developed from the literature and comments by participants at the various public advisory group meetings. As a way of determining which parameters to consider in the model sensitivity analysis the article by van

Griensven et al. (2006) was used as a guide. This article reviews many parameters that are adjusted in calibrating SWAT and ranks them for sensitivity based on simulations done in the NBR watershed. The parameters and conditions chosen for sensitivity analysis based on public meeting comments, Van Griensven et al. (2006), and direct experiences from the calibration process of this project were grouped as those requested in the public meeting and additional analysis:

Sensitivity analyses based on comments from public meetings:

- With and without activation of instream water quality subroutine
- With and without P sequestered in lagoons
- Different lagoon management
- With and without PL-566 reservoirs
- PL-566 reservoirs with different removal efficiencies.

Additional sensitivity analyses:

- Manure application rate (± 25 percent).
- CN2: Curve number (± 10 percent of actual CN).
- CH_K2: Hydraulic conductivity of stream channel (± 50 percent)
- GW_REVAP: Groundwater re-evaporation coefficient (± 50 percent)
- P_PERCO: P soil percolation coefficient (± 10 percent)

The magnitude of the prescribed percent variation of each input parameter listed under additional sensitivity analyses was based on subjective evaluation of the uncertainty associated with each parameter as determined by TIAER staff directly involved in the model validation process.

The parameters and conditions included in the sensitivity analysis were evaluated at the five index stations for the TMDL on the NBR: above Stephenville, below Stephenville, above Meridian, at Clifton, and at Valley Mills (Figure 3-26). The sensitivity analysis was performed by varying only one parameter or condition at a time and holding all other input at values determined during model calibration. The model output variable against which sensitivity was evaluated was the average monthly loading of PO_4 over the calibration period of 1993 – 1997. Sensitivity was defined as percent change to the monthly average PO_4 loadings:

$$\text{Percent difference} = [(AALi - AALm) / AALi] \cdot 100 \qquad (7)$$

where AALi is the initial average monthly loading of PO_4 at an index station with the calibration input and AALm is the average monthly loading of PO_4 at an index station for a perturbation of the parameter or condition in the sensitivity analysis. The model was operated in the same manner as for calibration wherein each simulation was initiated on January 1, 1988 and the output from 1993-1997 at each index station location were used to determine sensitivity.

The model without instream kinetics exhibited a higher PO_4 load at all of the index stations except for the NBR below Stephenville (3-20). Since PO_4 is both created (conversion of organic P to PO_4) and removed (streambed sediment uptake, algal growth and settling) by instream kinetics, it was not self-evident how turning off instream kinetics would affect the instream load of PO_4. However, no algae grew when the water quality component was not used and there was no streambed sediment uptake, so the lack of algae growth and streambed sediment uptake serving as a sink of PO_4 seemed to be the over-riding factors affecting the sensitivity of the simulation.

As explained in Section 2.3 the average of measured nutrient removal rates from the two reservoirs UB8 (least impacted) and UB3 (more impacted) were used for all reservoirs in the watershed. Members of the project advisory group wanted to examine that assumption by running the simulation with all the reservoirs using the lower measured nutrient removal rates of UB8 and conversely with all the reservoirs using the higher measured nutrient removal rates of UB3. There was less than a 10 percent change in PO_4 loadings created by those changes at all the index stations except for the NBR above Stephenville where the low removal reservoirs created an 11 percent change (Table 3-20). The effect of those changes became very minimal at the southern most index stations (Clifton and Valley Mills) (Table 3-20). However, if no PL-566 reservoirs were simulated, the increase in PO_4 loads was substantial, being as high as 41 percent greater for the NBR above Stephenville and more than 10 percent greater in the most downstream end of the watershed (Table 3-20).

There were also discussions with the project advisory group about the best way to include in the model P that settled in dairy lagoons and that would periodically be cleaned out (removed) from the lagoon. It was decided with the advisory group that this P would eventually be applied to WAFs during periodic lagoon cleanouts; therefore, it was applied every year of the simulation. To see what the effect on loadings would be if this P was left in the lagoons or alternatively the lagoon solids and associated P removed from the watershed during lagoon cleanout, a simulation was constructed that did not apply lagoon solids. The effect on overall PO_4 load was less than 3 percent at all index stations and about 1 percent at the most downstream stations (Table 3-20).

There was also an interest within the project advisory group about how the assumed management within the dairy lagoon discharge model would affect loads predicted in the NBR. For the model validation a matrix of lagoon management explained in Section 2-4 was used. Various different combinations of lagoon management were simulated based on the A, B and C management options explained in Section 2.4. Three different simulations were run with every lagoon managed as either management option A, B or C respectively. The model predictions at the five index stations were found to be insensitive to differences in lagoon management. Part of the reason for this insensitivity was that the different management options did not create great differences in lagoon discharge occurrence and the amount of nutrients contributed by the lagoon discharges were very minor compared to the total load of nutrients in the watershed (see TIAER(2006) for more detail).

The remaining sensitivity analyses looked at certain input parameters to determine which assumptions were critical in the calibration of the model. For the most part the analysis revealed that the model was most sensitive to parameters that affected hydrology. The hydraulic conductivity of headwater and tributary stream channels affected by the variable CH_K2 were critical components in the successful calibration of the model, and the model was highly sensitive to changes in the CH_K2 parameter (Table 3-20). It was more sensitive to increases in CH_K2 because channels that had a value of 0.0 were increased, but when the CH_K2 value was decreased those values were not reduced below 0.0. The model was also highly sensitive to curve number changes (Table 3-20) which affected runoff volumes, but the model was much less sensitive to GW_REVAP which affected ground water volumes (Table 3-20).

The model was not very sensitive to parameters that just affected nutrients like P_PERCO (Table 3-20). Of the non-hydrologic parameters which we examined, PO_4 nutrient loads were most affected by changing manure application rates (Table 3-20).

SECTION 3

TABLES

Table 3-1 Fertility recommendations for modeling of crops grown in the North Bosque River watershed during the validation period

Crop	Nutrient Recommendations N (lb/ac/yr)	P_2O_5 (lb/ac/yr)
Coastal bermudagrass	300	100
Winter wheat	160	60
Sorghum or sudan	160	60
Bermudagrass overseeded with winter wheat[a]	460	160
Sorghum or sudan double-cropped with winter wheat	320	120
Alfalfa	20	100
Corn	200	85
Range	40	46
Peanut	20	55

a In actual practice the nutrient recommendations for bermudagrass overseeded with winter wheat are not strictly additive due to the competitive nature of the two crops. However, SWAT currently cannot simulate two crops at once, but simulates the bermudagrass and winter wheat as two separate crops (one without the other).

Table 3-2 Total dry solids and nutrients per cow per year delivered to the field via the liquid and solid dairy manure fractions from a weighted average of cows in confinement

Nutrient	Solid (lb/cow/yr)	Liquid (lb/cow/yr)	Total (lb/cow/yr)
TS	4175	1247	5422[a]
TKN	129.4	18.0	147.4
NH_4	10.8	12.9	23.7
NO_3	0.30	0.20	0.50
TP	40.6	7.6	48.2

[a] In reality, there are probably TS losses. However, TS is used here to account for the fractionation of manure into liquid and solid pools and for creation of the fertilization file. It does not impact the final delivery of nutrients to the field.

Table 3-3 Municipal wastewater treatment plants within the NBR watershed and the average discharges used during the validation period in cubic meters per day (m^3/d) and million gallons per day (MGD) and permitted discharge

Municipality	Average Discharge (m^3/d)[a]	Average Discharge (MGD)[a]	Permitted Discharge (MGD)	Discharge Location
Stephenville	7,339	1.94	3.0	North Bosque River
Hico	325.5	0.086	0.20	Jacks Hollow Branch of the North Bosque River
Iredell	90.84	0.024	0.05	North Bosque River
Meridian	594.2	0.157	0.45	North Bosque River
Clifton	1,147	0.303	0.65	North Bosque River
Valley Mills	325.5	0.086	0.36	North Bosque River

[a] Actual discharges used during the validation period varied from month to month based on self-reported discharges, the values for discharges reported in the table represent the average discharges during the validation period which were later used in the 1990s TMDL allocation simulations.

Table 3-4 General performance ratings for recommended statistics from Moriasi et al. (2007)

Ratings	*ENS* Value	% E Streamflow	 Sediment	 N,P
Very Good	0.75 < NSE ≤ 1.00	%E ≤ ±10	%E ≤ ±15	%E ≤ ±25
Good	0.65 < NSE ≤ 0.75	±10 ≤ %E < ±15	±15 ≤ %E < ±30	±25 ≤ %E < ±40
Satisfactory	0.50 < NSE ≤ 0.65	±15 ≤ %E < ±25	±30 ≤ %E < ±55	±40 ≤ %E < ±70
Unsatisfactory	NSE ≤ 0.50	%E ≥ ±25	%E ≥ ±55	%E ≥ ±70

Table 3-5 Statistical measures used in the validation process to define a rating of acceptable SWAT-TCEQ performance

	Streamflow		Sediment		Total Nutrients		PO_4	
Location[1]	***ENS***	**%E**	***ENS***	**%E**	***ENS***	**%E**	***ENS***	**%E**
Long-term calibration								
USGS Gauges	> 0.65	< ±15	–	–	–	–	–	–
Short-term calibration								
Primary Sites	> 0.65	< ±15	> 0.65	< ±30	> 0.65	< ±40	> 0.65	< ±40
Secondary Sites	> 0.5	< ±25	> 0.5	< ±55	> 0.5	< ±70	> 0.5	< ±70
Short-term verification								
Primary Sites	> 0.5	< ±25	> 0.5	< ±55	> 0.5	< ±70	> 0.5	< ±70
Secondary Sites	> 0.5	< ±25	> 0.5	< ±55	> 0.5	< ±70	> 0.5	< ±70

[1] Primary sites = BO070, BO090, BO100; secondary sites = all other sites (NF009, NF020, NF050, SF020, SF075, BO040, IC020, AL040, SC020, GC100, SP020, & NC060)

Table 3-6 Measured vs. predicted yearly average daily total, base and surface streamflow during a 30-year (normal) period from 1965-1994

			Streamflow (m^3/s)					
	Total Streamflow		Total		Base		Surface	
Site	*ENS*	% E	Meas	Pred	Meas	Pred	Meas	Pred
BO070	0.76	-12.7	1.7	1.5	0.49	0.50	1.2	1.0
BO090	0.74	0.20	6.2	6.2	1.8	2.0	4.4	4.2
BO100	0.71	4.7	7.5	7.9	2.4	2.8	5.0	5.1

Table 3-7 Parameters adjusted for calibration

Input File	Parameter	SWAT recommended range/default	Value used in calibration
Basin (.BSN)	ESCO: soil evaporation compensation factor [unitless]	0.01 to 1.0 Default 0.95	0.10
Basin (.BSN)	EPCO: plant water uptake compensation factor [unitless]	0.01 to 1.0 Default 1.0	0.10
Basin (.BSN)	SURLAG : Surface runoff lag time [days]	NL Default 4.0	10.0
Basin (.BSN)	SPCON : Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing [unitless]	0.0001 to 0.01	0.010
Basin (.BSN)	SPEXP : Exponent parameter for calculating sediment reentrained in channel sediment routing [unitless]	1.0 to 2.0	2.0
Basin (.BSN)	RCN: nitrogen in rainfall [ppm]	NL Default 1.0	0.71
Basin (.BSN)	P_UPDIS : Phosphorus uptake distribution parameter [unitless]	NL Default 20	70
Basin (.BSN)	NPERCO : Nitrogen percolation coefficient [unitless]	0.01 to 1.0	0.01
Basin (.BSN)	PPERCO : Phosphorus percolation coefficient [unitless]	10.0 to 17.5 Default 10.0	17.5
Basin (.BSN)	PHOSKD : Phosphorus soil partitioning coefficient [unitless]	0.6 to 1.4	0.8
Basin (.BSN)	PSP : Phosphorus sorption coefficient [unitless]	NL Default 0.40	0.5
Basin (.BSN)	TRNSRCH: reach transmission loss partitioning to deep aquifer [unitless]	0.0 to 1.0	0.25
Basin (.BSN)	CDN: denitrification exponential rate coefficient [unitless]	0.0 to 3.0	3.0
HRU general input file (HRU)	ERORGN : Organic N enrichment ratio [unitless]	NL Def. calculated	24 N of Hico Def. S of Hico
HRU general input file (HRU)	ERORGP : Organic P enrichment ratio [unitless]	NL Def. calculated	14 N of Hico Def. S of Hico
Management file (MGT)	FRT_SURFACE: Fraction of fertilizer is applied to top 10mm of soil [unitless]	0.0 to 1.0 Default 0.20	AG LC LR 0.5 PAST 0.8 SC and SR 0.95
Groundwater (.GW)	GW_DELAY : Groundwater delay [days]	NL	31
Groundwater (.GW)	ALPHA_BF : Baseflow alpha factor [days]	NL	0.048
Groundwater (.GW)	GW_REVAP : Groundwater "revap" coefficient [unitless]	0.02 to 0.20	0.2
Groundwater (.GW)	RCHRG_DP : Deep aquifer percolation fraction [unitless]	0.0 to 1.0	0.1 S of Hico 0.5 N of Hico

Route (.RTE)	CH_K2 : Effective hydraulic conductivity [mm/hr]	0.0 to > 127	0 main branch 25 tributaries
Route (.RTE)	CH_EROD: Channel erodibility factor [unitless]	0.0 to 1.0	0.025 – 0.80
Route (.RTE)	CH_COV : Channel cover factor [unitless]	0.0 to 1.0	0.05 – 0.9
General Water Quality (WWQ)	AI1 : Fraction of algal biomass that is nitrogen [mg N/mg alg]	0.07 to 0.09 Default 0.08	0.072
General Water Quality (WWQ)	AI2 : Fraction of algal biomass that is phosphorus [mg P/mg alg]	0.01 to 0.02 Default 0.015	0.02
General Water Quality (WWQ)	MUMAX : Maximum specific algal growth rate at 20º C [day^{-1}]	1.0 to 3.0 Default 2.0	4.0
General Water Quality (WWQ)	RHOQ : Algal respiration rate at 20º C [day^{-1}]	0.05 to 0.50 Default 0.30	0.05
General Water Quality (WWQ)	K_N : Michaelis-Menton half-saturation constant for nitrogen [mg N/l]	0.01 to 0.30 Default 0.02	0.022
General Water Quality (WWQ)	K_P : Michaelis-Menton half-saturation constant for phosphorus [mg P/l]	0.001 to 0.05 Default 0.025	0.007
Stream Water Quality (SWQ)	RS1: Local algal settling rate in the reach at 20ºC [m/day]	0.15 to 1.82 Default 1.0	0.15
Stream Water Quality (SWQ)	RS2: Benthic (sediment) source rate for dissolved phosphorus in the reach at 20ºC [mg dissolved P/[m^2·day]]	NL Default 0.05	-40.0 [a]
Stream Water Quality (SWQ)	RS3: Benthic source rate for NH_4-N in the reach at 20ºC [mg NH_4-N/[m^2·day]]	NL Default 0.5	1.E-9
Stream Water Quality (SWQ)	RS4: Rate coefficient for organic N settling in the reach at 20ºC [day^{-1}]	0.001 to 0.10 Default 0.05	0.018
Stream Water Quality (SWQ)	RS5: Organic phosphorus settling rate in the reach at 20ºC [day^{-1}]	0.001 to 0.10 Default 0.05	0.010
Stream Water Quality (SWQ)	BC3: Rate constant for hydrolysis of organic N to NH_4-N in the reach at 20º C [day^{-1}]	0.2 to 0.4 Default 0.21	0.02
Stream Water Quality (SWQ)	BC4: Rate constant for mineralization of organic P to dissolved P in the reach at 20º C [day^{-1}]	0.01 to 0.7 Default 0.35	0.001

[a] Parameter RS2 was made a negative value based on the results of a studies conducted by TIAER (Chapter 11 of TIAER (2006)) to determine the equilibrium P concentration (EPC_o) for sediments at various locations within the NBR watershed. For further details see Section 3.3.5.4.3

[b] Values in the literature for BC4 are as low as 0.001 (USEPA, 1985)

Table 3-8 Monthly average streamflow and total sediment during calibration period (1993-1997): *ENS*, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5), measured and predicted value.

Site	Streamflow						Sediment					
	ENS	**pm**	**%E**	**pm**	**Meas (m^3/s)**	**Pred (m^3/s)**	***ENS***	**pm**	**%E**	**pm**	**Meas (tons)**	**Pred (tons)**
NF009	0.76	A	-3	A	0.024	0.024	0.03	U	-71	U	94	27
NF020	0.72	A	-13	A	0.038	0.033	0.34	U	-36	A	105	68
NF050	0.80	A	4	A	0.27	0.29	0.41	U	-37	A	445	280
SF020	0.63	A	-12	A	0.035	0.031	0.03	U	-82	U	30	5
SF075	0.59	A	11	A	0.29	0.32	0.15	U	-50	A	254	127
BO040	0.85	A	-5	A	0.97	0.93	0.67	A	-13	A	825	715
IC020	0.64	A	10	A	0.055	0.061	0.35	U	-54	A	81	37
AL040	0.67	A	-19	A	0.15	0.13	-0.28	U	-36	A	25	16
SC020	0.30	U	-29	U	0.11	0.077	0.57	A	-40	A	43	26
GC100	0.73	A	-19	A	1.21	0.98	0.84	A	-24	A	868	661
SP020	0.72	A	-6	A	0.087	0.082	-0.02	U	88	U	24	45
BO070	0.86	**A**	-9	**A**	3.45	3.16	0.88	**A**	8	**A**	3,917	4,237
BO090	0.70	**A**	-3	**A**	10.7	10.4	0.56	**U**	-2	**A**	21,480	21,075
NC060	0.36	U	-20	A	2.94	2.34	0.54	A	54	A	3,658	5,622
BO100	0.66	**A**	-12	**A**	14.43	12.68	0.74	**A**	2	**A**	30,724	31,227

Table 3-9 Monthly average total P and total N during calibration period (1993-1997): *ENS*, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5), measured and predicted value

Site	Total P						Total N					
	ENS	**pm**	**%E**	**pm**	**Meas (kgs)**	**Pred (kgs)**	***ENS***	**pm**	**%E**	**pm**	**Meas (kgs)**	**Pred (kgs)**
NF009	0.69	A	-37	A	59	37	0.58	A	-47	A	237	126
NF020	0.25	U	-30	A	258	182	0.25	U	-19	A	693	563
NF050	0.60	A	-32	A	642	439	0.14	U	-15	A	2,395	2,034
SF020	0.58	A	-36	A	20	13	0.54	A	-4	A	131	126
SF075	0.51	A	9	A	585	637	0.54	A	1	A	2,443	2,464
BO040	0.73	A	-22	A	2,677	2,091	0.62	A	-36	A	11,515	7,385
IC020	0.76	A	-22	A	165	128	0.13	U	-16	A	686	576
AL040	0.16	U	-76	U	239	58	0.53	A	-39	A	812	493
SC020	-9.2	U	205	U	88	269	-5.9	U	151	U	439	1,104
GC100	0.47	U	51	A	1,226	1,858	0.68	A	-3	A	8,171	7,902
SP020	0.76	A	11	A	42	46	0.69	A	36	A	244	332
BO070	0.71	**A**	-7	**A**	5,241	4,891	0.78	**A**	-7	**A**	22,822	21,212
BO090	0.66	**A**	12	**A**	12,999	14,591	0.67	**A**	12	**A**	64,217	72,242
NC060	0.36	U	64	A	1,793	2,939	0.02	U	-48	A	10,931	5,643
BO100	0.70	**A**	8	**A**	21,431	23,133	0.72	**A**	14	**A**	107,389	122,701

Table 3-10 Subbasin confined cow number variability for the periods of 1994-95, 1997-99 and 1999-2000

	Cow number				**% Difference**			**Abs.**
	Years				**Avg**			**Avg. %**
Subbasin	**94-95**	**97-99**	**99-00**	**Avg.**	**94-95**	**97-99**	**99-00**	**Diff.**
NF009	78	84	100	87	-11	-4	+14	10
NF020	342	429	659	477	-28	-10	+38	26
NF050	996	906	1040	981	+2	-8	+6	5
AL040	165	219	23	136	+22	+61	-83	55
SC020	1013	1133	1121	1089	-7	+4	+3	5

Table 3-11 Monthly average PO_4 load during calibration period (1993-1997): *ENS*, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5), measured and predicted values.

	PO_4					
Site	***ENS***	**pm**	**%E**	**pm**	**Meas (kgs)**	**Pred (kgs)**
NF009	0.57	A	-27	A	25	18
NF020	0.27	U	-55	A	148	67
NF050	0.64	A	-13	A	308	268
SF020	0.15	U	-14	A	4	3
SF075	0.62	A	10	A	296	326
BO040	0.67	A	-18	A	1,648	1,359
IC020	0.70	A	-22	A	81	64
AL040	0.10	U	-81	U	151	29
SC020	-6.4	U	237	U	42	143
GC100	0.60	A	57	A	494	775
SP020	0.69	A	13	A	18	20
BO070	0.77	**A**	6	**A**	2,164	2,293
BO090	0.73	**A**	17	**A**	3,663	4,297
NC060	0.26	U	-31	A	383	265
BO100	0.66	**A**	3	**A**	5,815	5,998

Table 3-12 **Average daily PO_4 concentration and load during calibration period (1993-1997): measured and predicted values, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5)**

Site	PO_4 (mg/l) Meas	PO_4 (mg/l) Pred	%E	pm	PO_4 (kgs) Meas	PO_4 (kgs) Pred	%E	pm
NF050	0.335	0.168	-50	A	12.7	8.6	-32	A
SF075	0.247	0.272	10	A	10.1	11.6	14	A
BO040	1.17	0.767	-35	A	55.5	45.4	-18	A
BO070	0.214	0.225	5	A	79.0	80.6	2	A
BO090	0.046	0.051	11	A	134.2	158.9	18	A
BO100	0.044	0.052	18	A	167.5	172.6	3	A

Table 3-13 **Measured and predicted loading and the average loadings (AVG) in kg/ha/yr during the calibration period at water quality monitoring stations representing different type of predominant land uses and stream types, background (yellow), intensive agriculture (pink), and mixed (beige) and the %E of the average predicted data compared to the measured data for each land use type.**

		PO_4		OrgP		TP	
	Site	measured (kg/ha/yr)	pred (kg/ha/yr)	measured (kg/ha/yr)	pred (kg/ha/yr)	measured (kg/ha/yr)	pred (kg/ha/yr)
	SP020	**0.13**	**0.15**	**0.19**	**0.20**	**0.32**	**0.36**
	NC060	**0.13**	**0.09**	**0.48**	**0.91**	**0.61**	**1.00**
	SF020	**0.06**	**0.05**	**0.22**	**0.13**	**0.28**	**0.18**
	NF009	**0.57**	**0.41**	**0.80**	**0.45**	**1.37**	**0.86**
	NF020	**2.21**	**0.99**	**1.64**	**1.72**	**3.85**	**2.71**
	NF050	**0.44**	**0.38**	**0.42**	**0.29**	**0.86**	**0.67**
	SC020	**0.27**	**0.90**	**0.29**	**0.79**	**0.56**	**1.70**
	IC020	**0.56**	**0.44**	**0.58**	**0.45**	**1.14**	**0.88**
	SF075	**0.29**	**0.32**	**0.30**	**0.31**	**0.59**	**0.63**
	AL040	**0.33**	**0.06**	**0.19**	**0.06**	**0.53**	**0.13**
	GC100	**0.24**	**0.37**	**0.35**	**0.52**	**0.58**	**0.89**
AVG	background	0.11	0.10	0.30	0.41	0.40	0.51
	impacted	0.81	0.63	0.75	0.74	1.55	1.37
	mixed	0.29	0.25	0.28	0.30	0.57	0.55
	% E	background	-9.3		40.1		26.9
		Impacted	-22.6		-0.7		-12.1
		Mixed	-12.4		6.2		-3.2

Table 3-14 Monthly average streamflow and total sediment during verification period (1998-1999), *ENS*, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5), measured and predicted value

	Streamflow						**Sediment**					
Site	***ENS***	**pm**	**%E**	**pm**	**Meas (m^3/s)**	**Pred (m^3/s)**	***ENS***	**pm**	**%E**	**pm**	**Meas (tons)**	**Pred (tons)**
NF009	0.11	U	-66	U	0.020	0.0068	-13.70	U	176	U	4	11
NF020	0.71	A	-44	U	0.018	0.0097	-0.55	U	62	U	17	27
SF020	0.95	A	32	U	0.0092	0.012	0.63	A	-49	A	4	2
BO020	0.77	A	-19	A	0.27	0.21	0.45	U	-48	A	416	218
BO040	0.78	A	-26	U	0.46	0.34	0.83	A	-24	A	295	226
GC100	0.80	A	-5	A	0.36	0.34	0.91	A	-26	A	281	208
SP020	0.64	A	-30	U	0.076	0.053	-6.53	U	1888	U	3	57
BO070	0.89	**A**	16	**A**	1.11	1.29	0.83	**A**	-17	**A**	1,902	1,586
BO090	0.75	**A**	6	**A**	4.76	5.04	0.76	**A**	-13	**A**	11,122	9,664
NC060	0.08	U	30	U	1.06	1.38	0.25	U	157	U	1,093	2,814
BO100	0.70	**A**	12	**A**	6.06	6.77	0.53	**A**	-43	**A**	19,349	11,091

Table 3-15 Monthly average total P and total N during verification period (1998-1999), *ENS*, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5), measured and predicted value

	Total P						**Total N**					
Site	***ENS***	**pm**	**%E**	**pm**	**Meas (kgs)**	**Pred (kgs)**	***ENS***	**pm**	**%E**	**pm**	**Meas (kgs)**	**Pred (kgs)**
NF009	-2.7	U	-27	A	17	12	-1.0	U	-56	A	93	41
NF020	0.50	U	-66	A	101	34	0.62	A	-59	A	263	108
SF020	0.86	A	24	A	4	5	-0.1	U	94	U	28	54
BO020	0.42	U	-57	A	779	332	0.11	U	-68	A	3,014	973
BO040	0.56	A	-42	A	1,590	925	0.66	A	-31	A	4,957	3,412
GC100	0.45	U	19	A	518	616	0.65	A	21	A	2,633	3,194
SP020	-1.4	U	97	U	18	35	-0.4	U	205	U	98	299
BO070	0.53	**A**	2	**A**	2,116	2,152	0.59	**A**	-15	**A**	12,558	10,691
BO090	0.72	**A**	-9	**A**	8,293	7,538	0.71	**A**	-2	**A**	40,751	39,931
NC060	0.31	U	-54	A	3,487	1,606	-0.1	U	150	U	4,517	11,309
BO100	0.75	**A**	-1	**A**	9,225	9,175	0.74	**A**	10	**A**	47,690	52,341

Table 3-16 Monthly average PO_4 load for verification period (1998-1999), *ENS*, %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5), measured and predicted loads

	PO_4					
Site	***ENS***	**pm**	**%E**	**pm**	**Meas (kgs)**	**Pred (kgs)**
NF009	-2.1	U	-17	A	7	6
NF020	0.35	U	-76	U	62	15
SF020	0.87	A	42	A	1	1
BO020	0.75	A	-28	A	236	170
BO040	0.40	U	-37	A	1,005	637
GC100	0.59	A	-4	A	255	246
SP020	-2.3	U	189	U	5	14
BO070	0.61	**A**	43	**A**	650	929
BO090	0.51	**A**	104	**U**	923	1,880
NC060	-4.2	U	248	U	45	155
BO100	0.34	**U**	118	**U**	946	2,063

Table 3-17 Average daily PO_4 concentration and load during verification period (1998-1999), %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5)

	PO_4 (mg/l)				**PO_4 (kgs)**			
Site	**Meas**	**Pred**	**%E**	**pm**	**Meas**	**Pred**	**%E**	**pm**
BO020	0.200	0.140	-30	A	11.6	5.8	-50	A
BO040	1.618	1.231	-24	A	33.3	20.9	-37	A
BO070	0.230	0.155	-32	A	22.6	30.5	35	A
BO090	0.019	0.028	49	A	30.1	61.8	105	U
BO100	0.019	0.036	87	U	30.9	67.0	117	U

Table 3-18 Average daily TP concentration and load during verification period (1998-1999), %E, performance measure (pm) (A – acceptable, U – unacceptable based on Table 3-5)

	TP (mg/l)				**TP (kgs)**			
Site	**Meas**	**Pred**	**%E**	**pm**	**Meas**	**Pred**	**%E**	**pm**
BO020	0.425	0.337	-21	A	44.1	11.1	-75	U
BO040	2.050	1.488	-27	A	52.4	30.4	-42	A
BO070	0.363	0.361	-0.6	A	87.0	70.8	-19	A
BO090	0.137	0.212	55	A	271	248	-8.5	A
BO100	0.132	0.219	66	A	301	302	0.3	A

Table 3-19 Annual daily-average discharge in the NBR at Clifton from 1960-1999[a] (Calibration years in red font and verification years in blue font)

Year	Annual Avg. Flow (cfs)	Rank	Percent Exceedance
1960	166.2	22	53.7%
1961	410.2	6	14.6%
1962	80.4	28	68.3%
1963	35.8	34	82.9%
1964	132.1	25	61.0%
1965	295.1	12	29.3%
1966	161.5	23	56.1%
1967	26.2	36	87.8%
1968	563.0	4	9.8%
1969	202.9	17	41.5%
1970	266.6	13	31.7%
1971	218.2	15	36.6%
1972	79.9	29	70.7%
1973	197.7	18	43.9%
1974	74.1	30	73.2%
1975	169.6	21	51.2%
1976	70.3	31	75.6%
1977	393.4	7	17.1%
1978	13.6	40	97.6%
1979	190.5	20	48.8%
1980	30.5	35	85.4%
1981	70.2	32	78.0%
1982	117.6	26	63.4%
1983	13.8	39	95.1%
1984	23.7	37	90.2%
1985	57.1	33	80.5%
1986	209.5	16	39.0%
1987	264.5	14	34.1%
1988	85.7	27	65.9%
1989	364.5	9	22.0%
1990	374.4	8	19.5%
1991	823.8	1	2.4%
1992	664.0	3	7.3%
1993	191.0	19	46.3%
1994	325.0	11	26.8%
1995	517.5	5	12.2%
1996	149.4	24	58.5%
1997	704.8	2	4.9%
1998	325.3	10	24.4%
1999	20.9	38	92.7%

[a] Surface Water data for USA: USGS Surface-Water Annual Statistics
URL: http://waterdata.usgs.gov/nwis/annual?

Table 3-20 Percent difference of simulated average of monthly total PO_4 loads between the calibration simulation with instream water quality kinetics and perturbation of sensitivity parameter/condition

Sensitivity Parameter or Condition	Above Stephen-ville (%)	Below Stephen-ville (%)	Above Meridian (%)	At Clifton (%)	At Valley Mills (%)
Without instream kinetics	9.8	-4.6	17	28	31
PL-566 low removal	11	5.7	6.0	2.6	1.5
PL-566 high removal	-9.2	- 9.8	-3.8	-2.1	-2.5
No reservoirs	41	30	34	16	14
With lagoon P left in lagoon	-1.9	- 2.8	0.1	-1.6	-1.2
Lagoons all mgt A option	0	0	0	0	0
Lagoons all mgt B option	0	0	0	0	0
Lagoons all mgt C option	0	0	0	0	0
150% CH_K2	-15	-12	-27	-34	-35
50 % CH_K2	3.7	9.7	8.2	14	13
110% CN2	29	21	32	36	37
90% CN2	-35	-22	-31	-34	-35
150% GW_REVAP	-0.06	-0.18	-0.60	-0.64	-0.71
50 % GW_REVAP	-0.58	0.20	1.3	1.4	1.5
110% P_PERCO	1.8	0.9	1.4	1.5	1.5
90% P_PERCO	-2.2	-1.0	-1.7	-1.8	-1.8
125% Manure Applic. Rate	0.4	1.4	4.5	4.5	4.3
75% Manure Applic. Rate	-9.9	-4.1	-4.6	-3.8	-3.4

SECTION 3

FIGURES

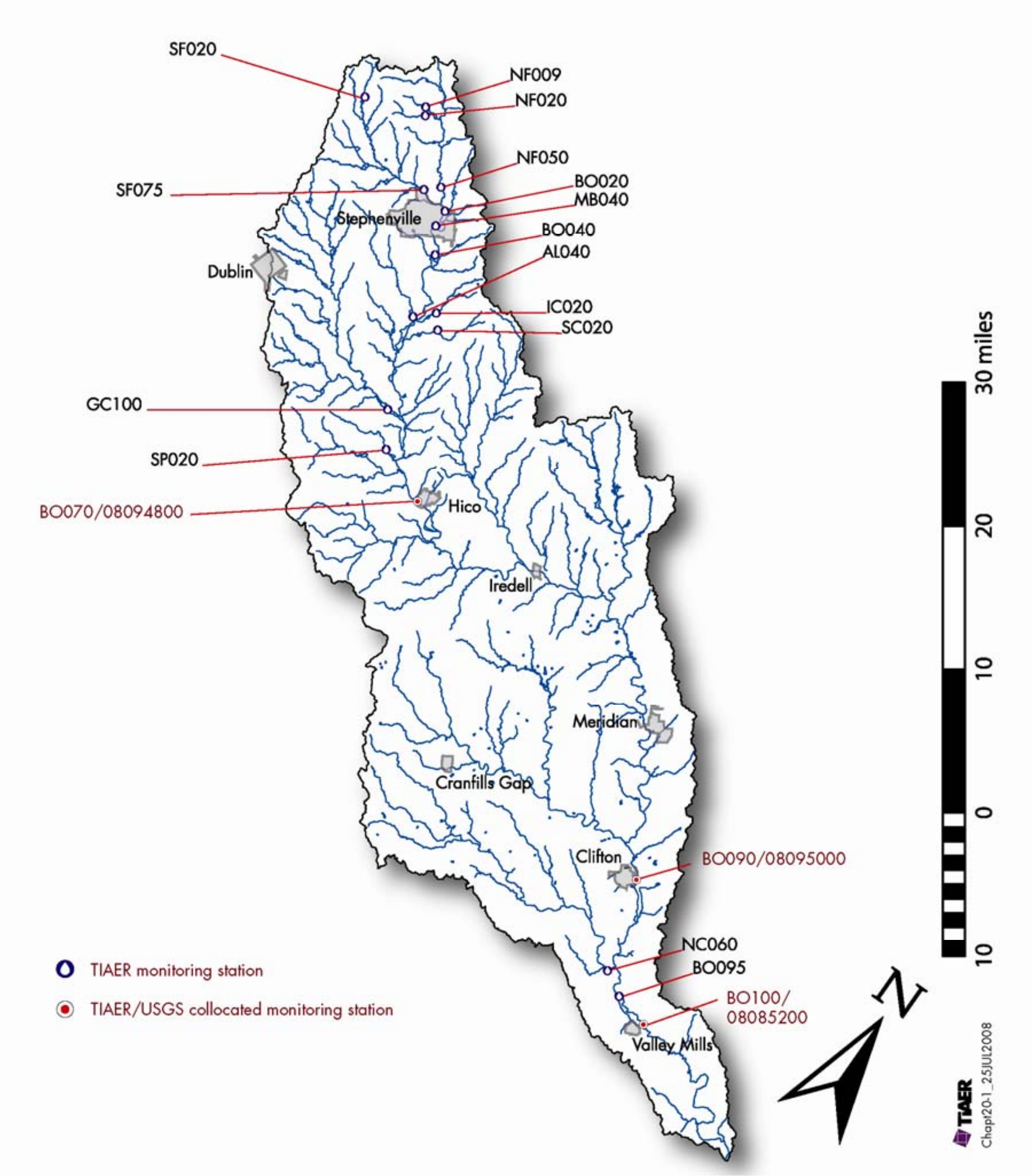


Figure 3-1 **North Bosque River watershed showing USGS streamflow gauges and TIAER flow and water quality stations used in model validation**

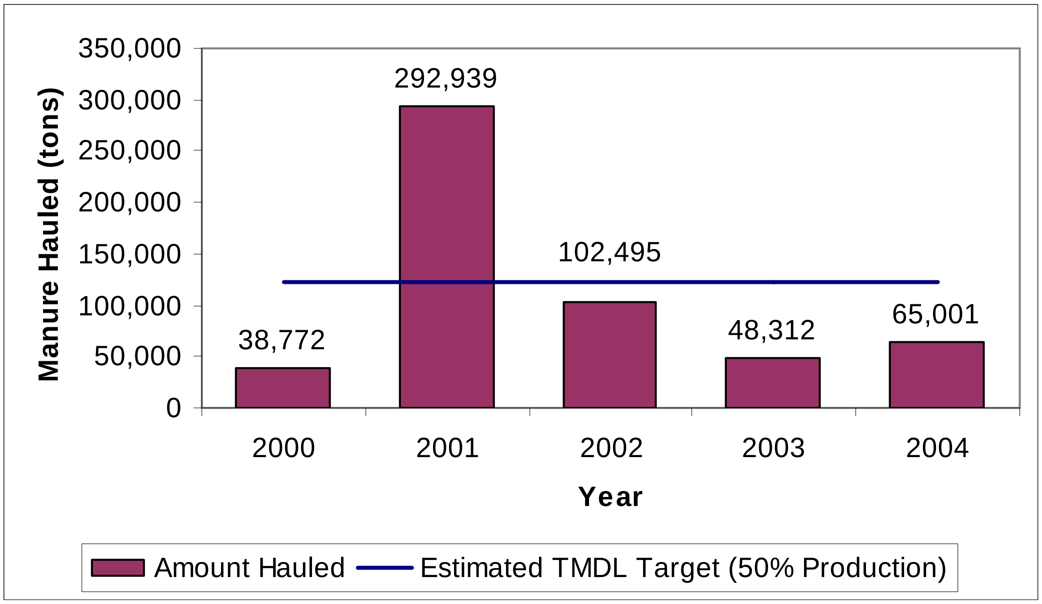


Figure 3-2 Manure hauled to composting facilities in the NBR watershed

Figure 3-3 Periods of data collection for the TIAER streamflow and water quality monitoring sites used for the calibration and verification of the SWAT-TCEQ model [11]

---

[11] Data from BO020 was not used in the calibration because there was only one year of data for BO020 during the calibration period and the sites of SF075 and NF050 for which there was more than three years of data characterized essentially the same drainage area.

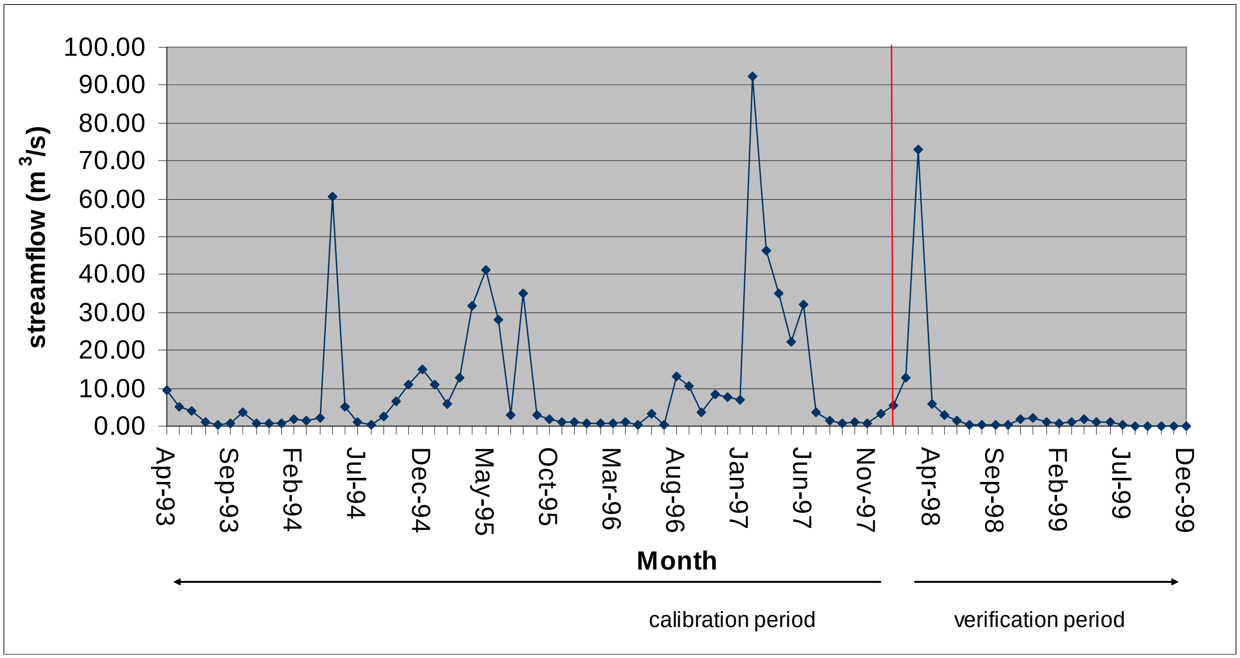


Figure 3-4 **Monthly average streamflow at Clifton (BO090) showing the date of demarcation between the calibration and verification periods (red line)**

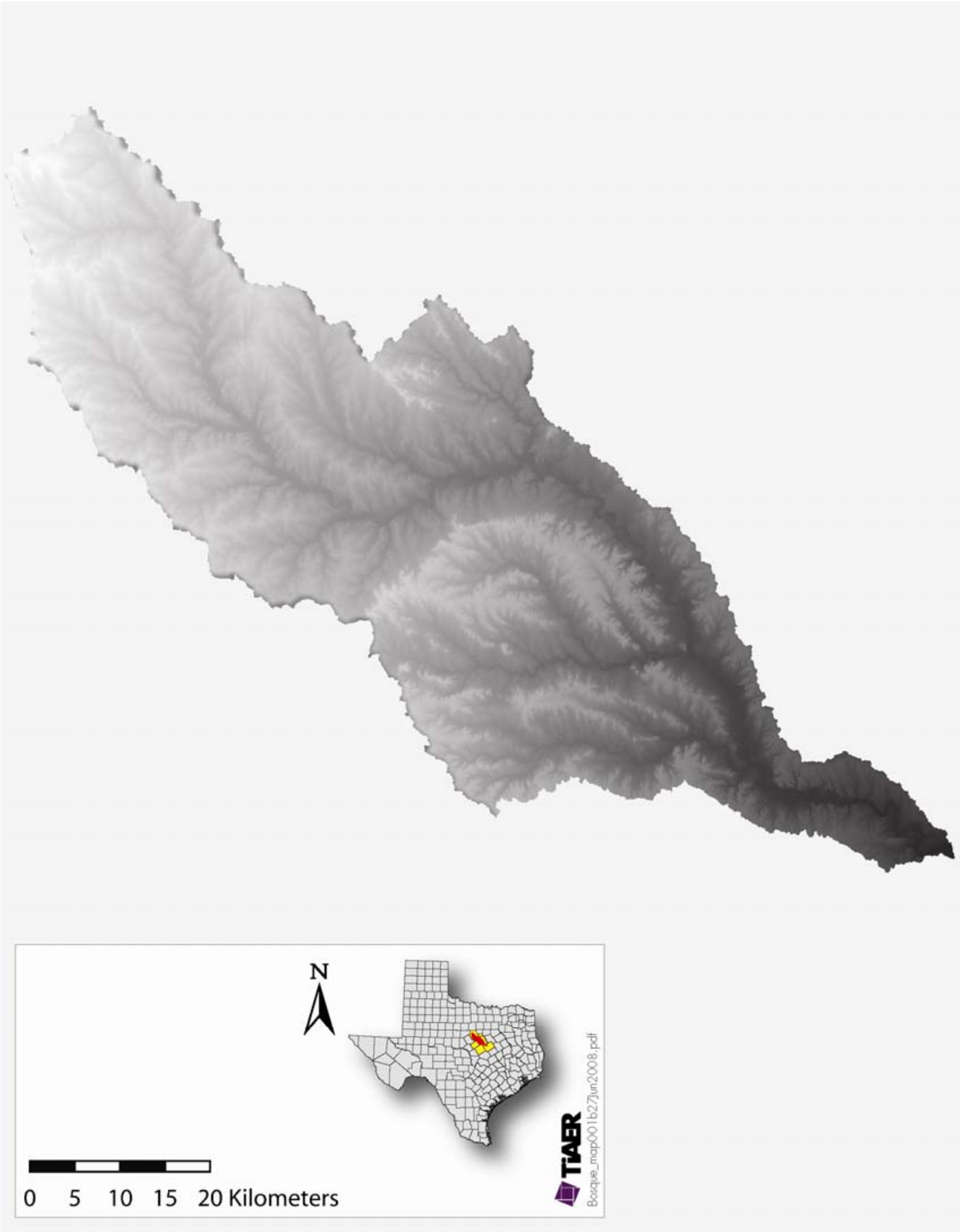


Figure 3-5 7.5-minute Digital Elevation Model (DEM) (1:24,000 scale) based on 30- by 30-meter data spacing with the Universal Transverse Mercator (UTM) projection, with outline of Bosque River watershed

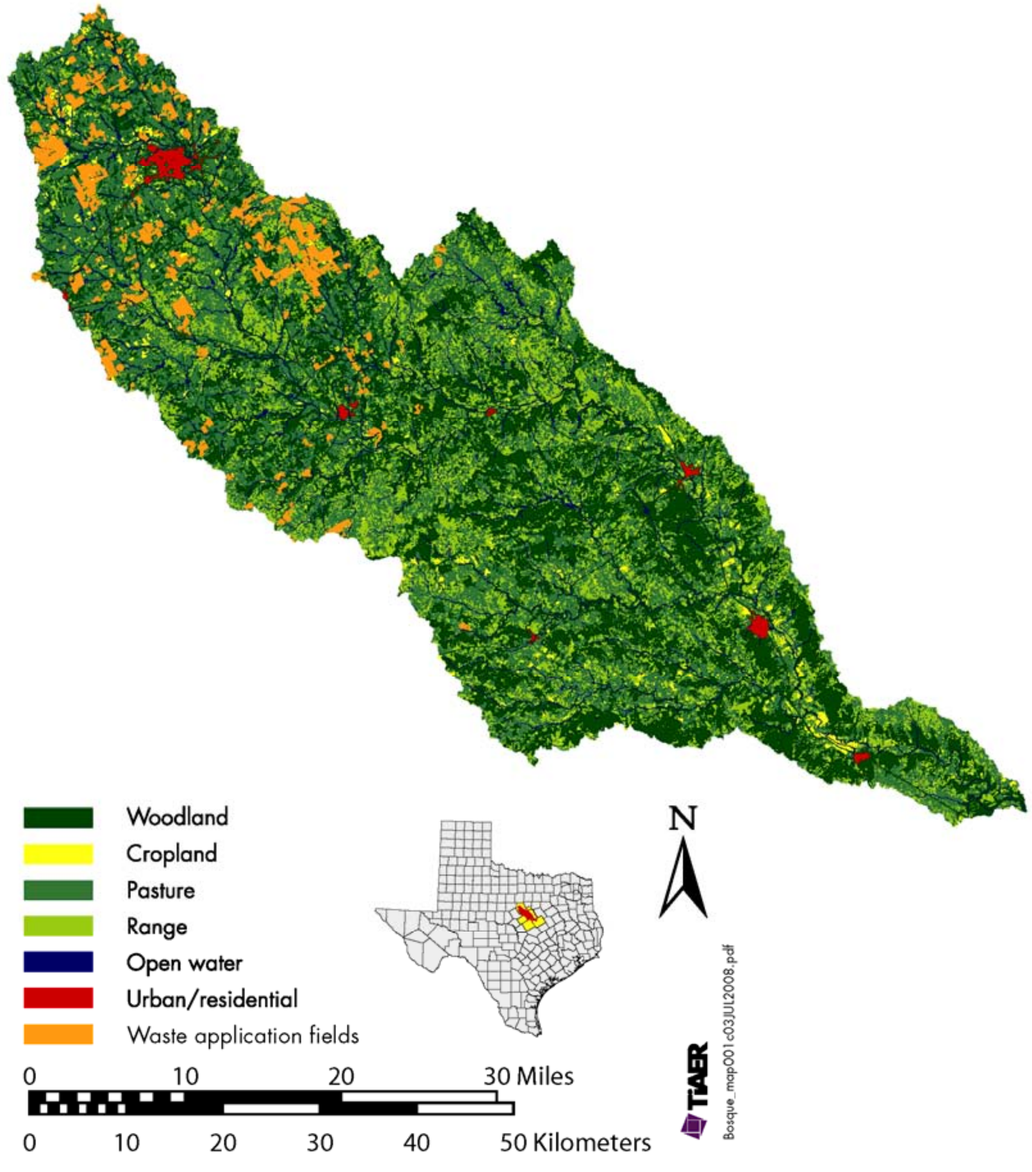


Figure 3-6 **Land use/land cover layer from 1996/98 with dairy waste application fields for the North Bosque River watershed for use in validation model simulations for the North Bosque River**

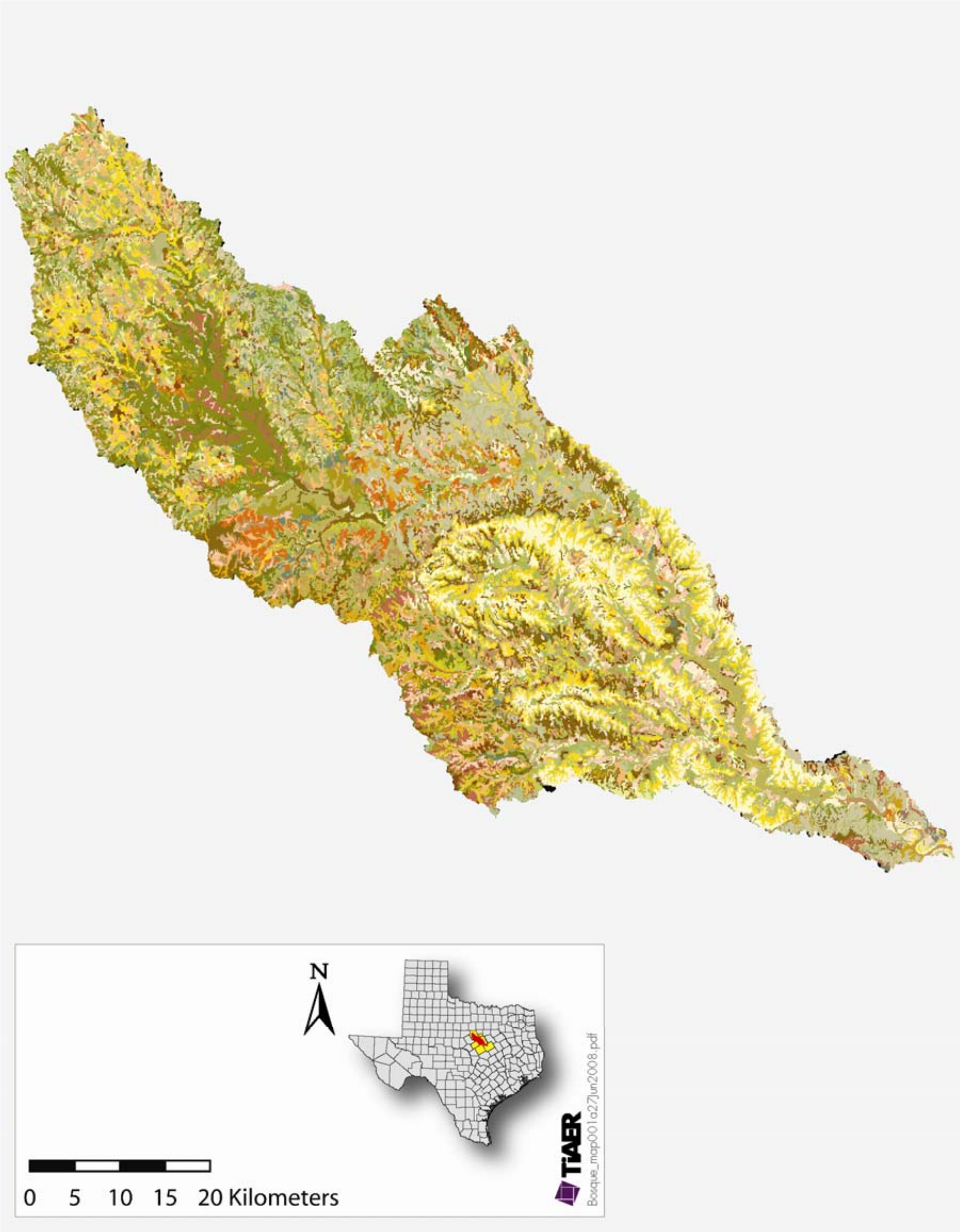


Figure 3-7 SSURGO soil layer for the North Bosque River watershed

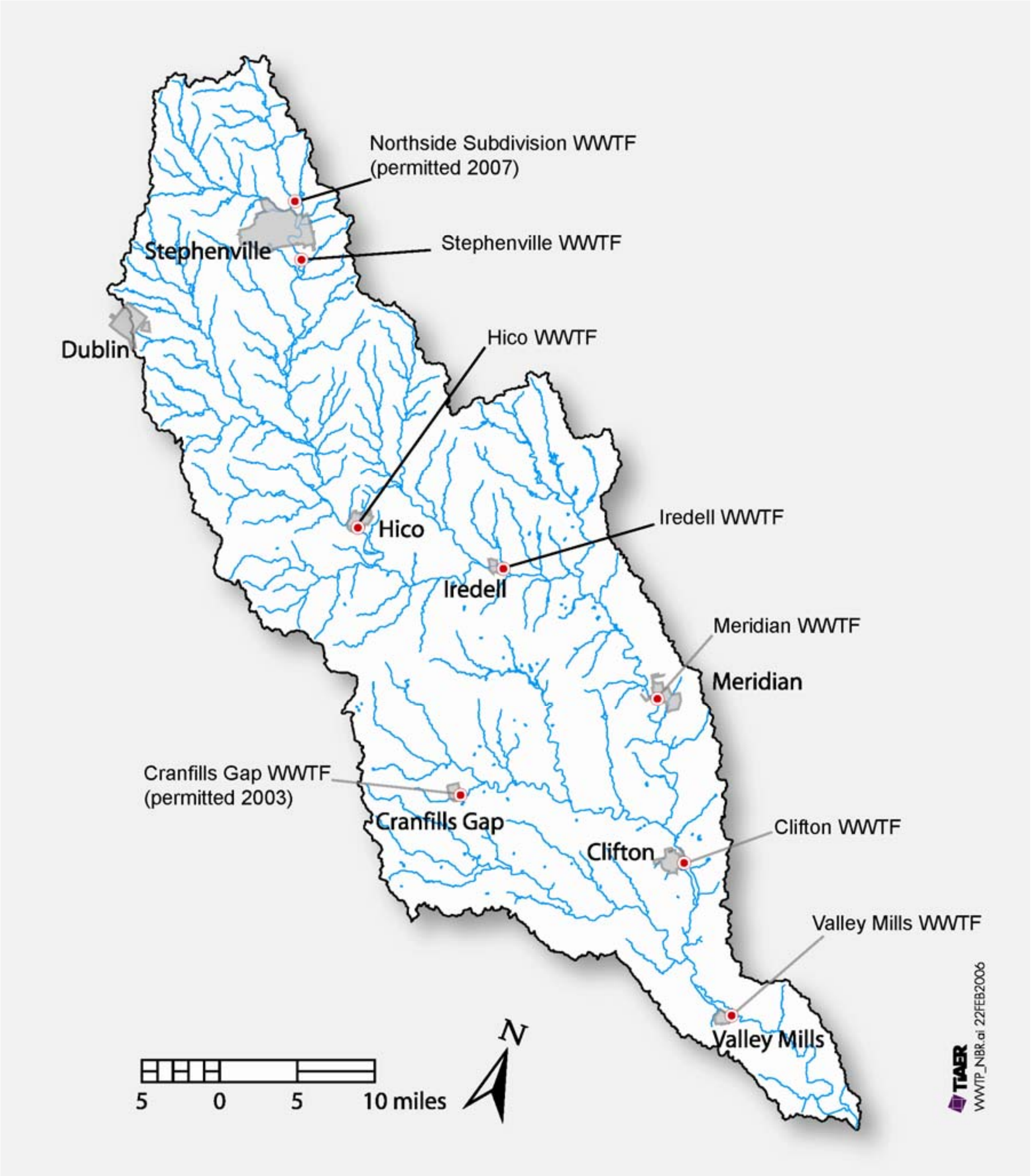


Figure 3-8 **Location of wastewater treatment plant discharges within the North Bosque River watershed labeled with TIAER site identifications**

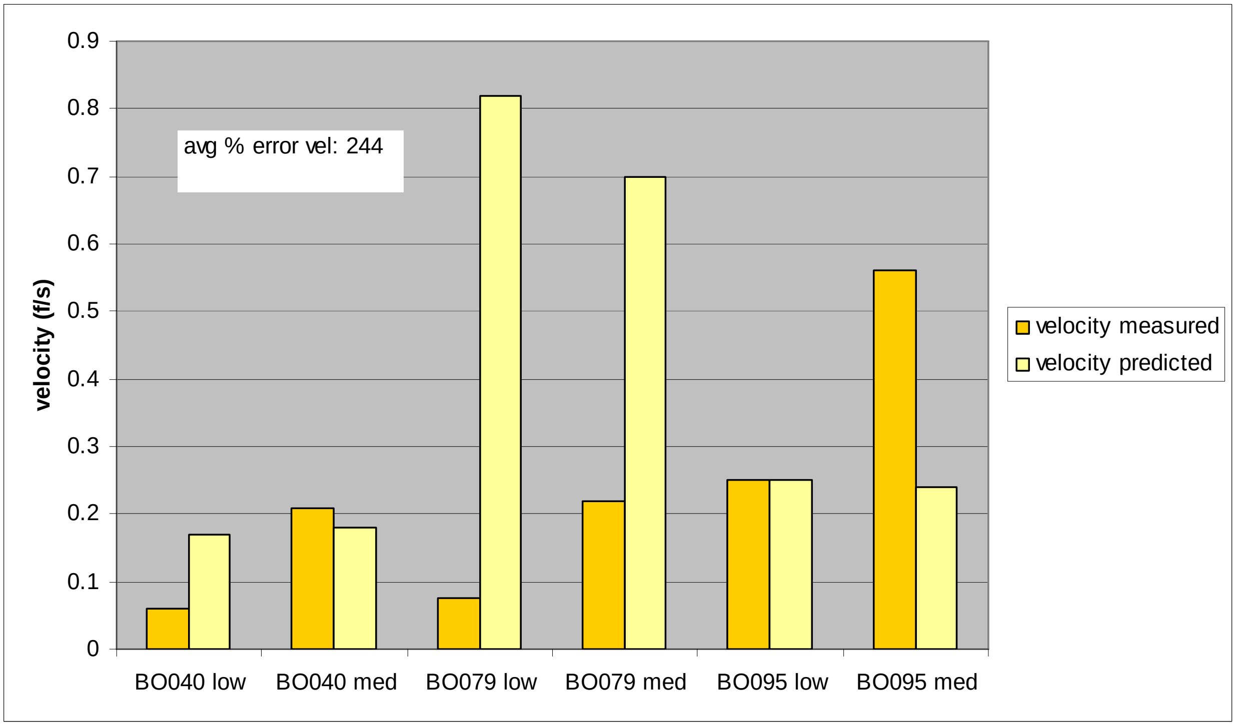


Figure 3-9 Predicted (with a Manning's n of 0.014) and measured flow velocity at three sites along the NBR (sites BO040, BO079 and BO095) during a period of low and moderate flow at each site

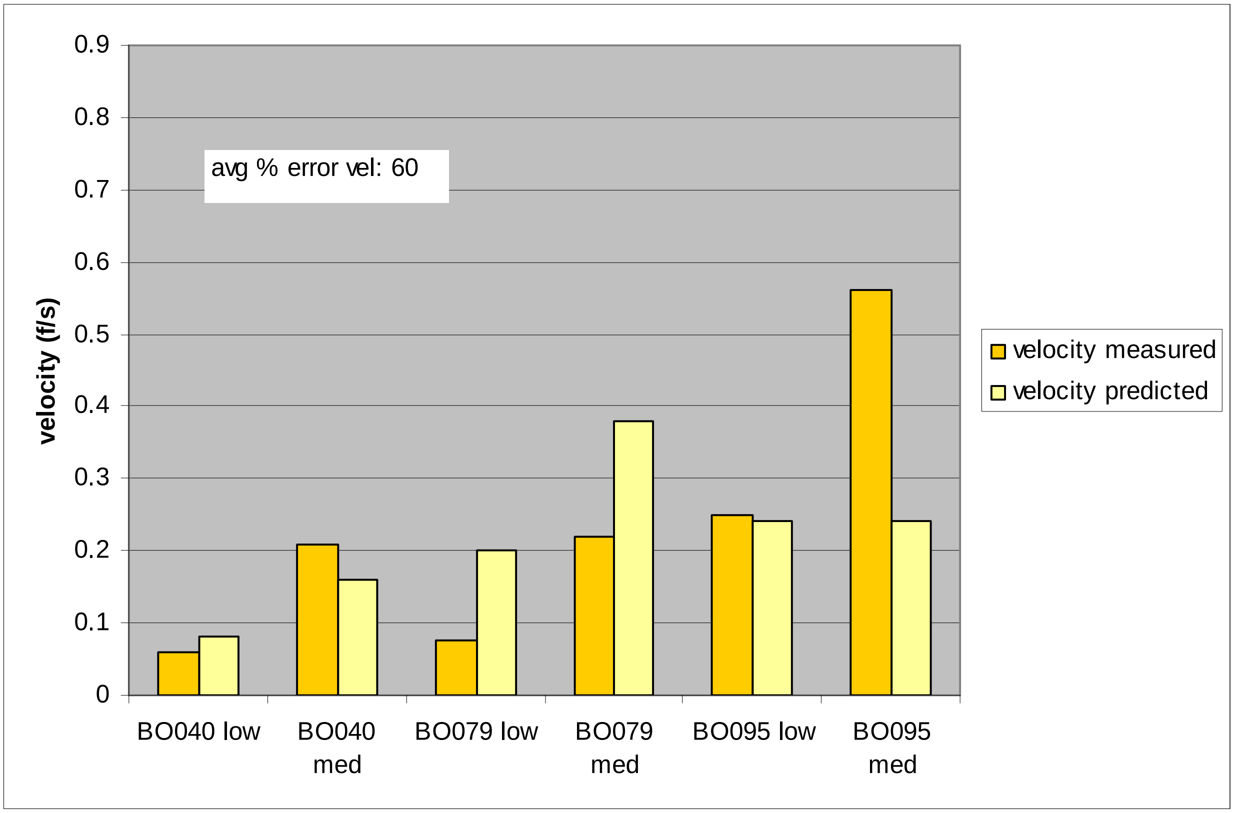


Figure 3-10 Predicted (with a Manning's n of 0.150) and measured flow velocity at three sites along the NBR (site BO040, BO079 and BO095) during a period of low and moderate flow at each site

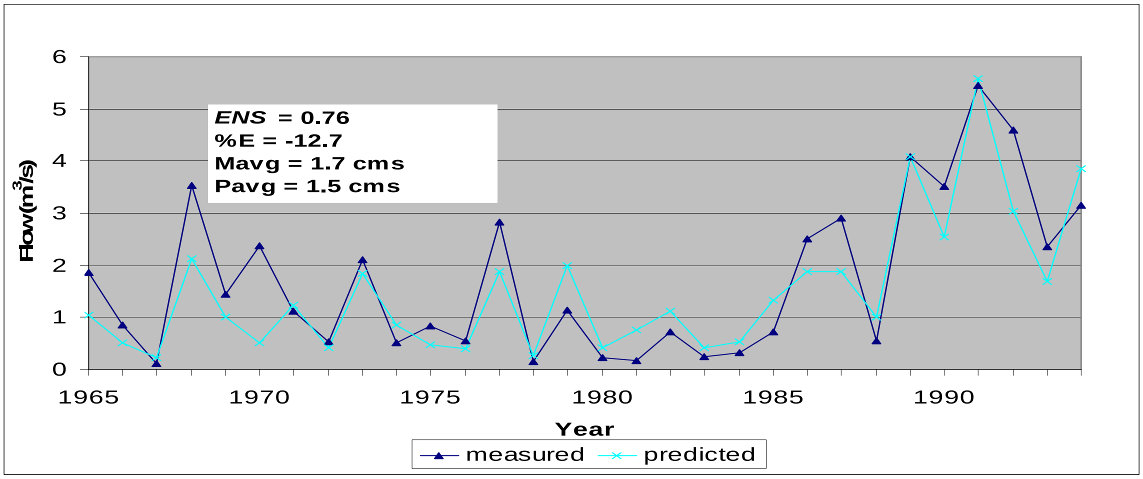


Figure 3-11 **Measured and predicted yearly average daily streamflow for the NBR at Hico (1965-1994)**

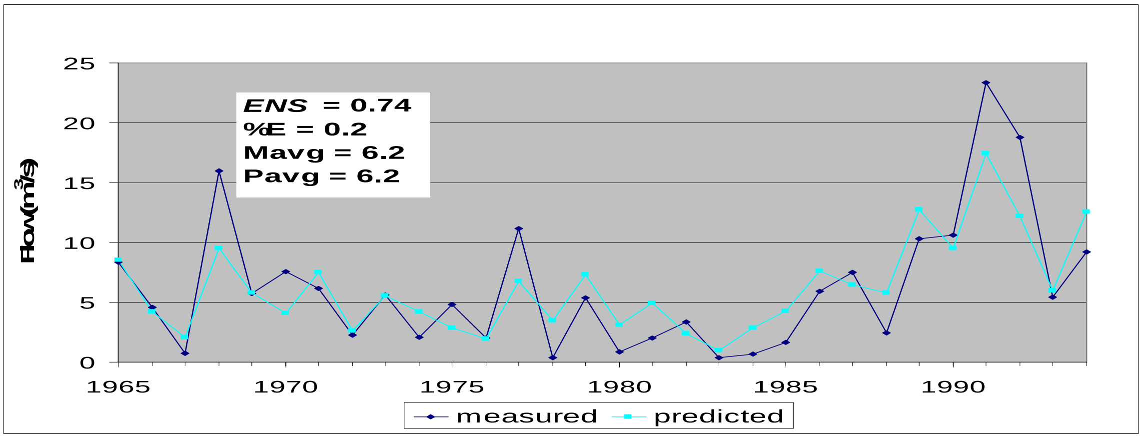


Figure 3-12 **Measured and predicted yearly average daily streamflow for the NBR at Clifton (1965-1994)**

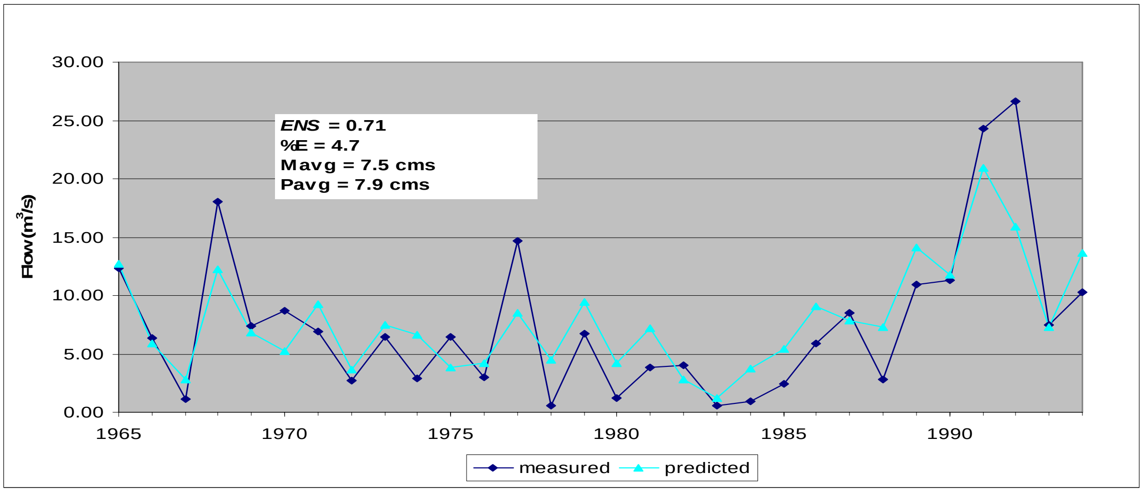


Figure 3-13 **Measured and predicted yearly average daily streamflow for the NBR at Valley Mills (1965-1994)**

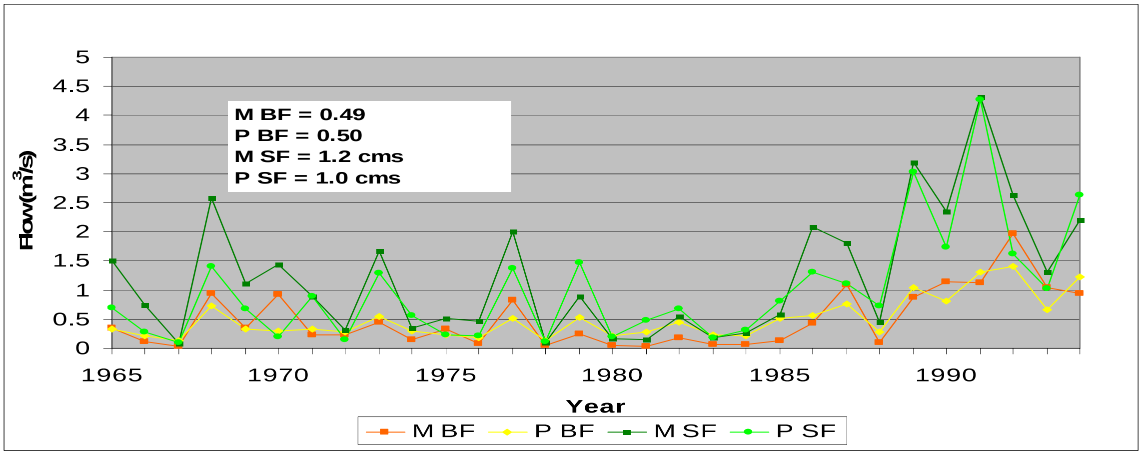


Figure 3-14 **Measured and predicted yearly average daily base and surface flow for the NBR at Hico (1965-1994)**

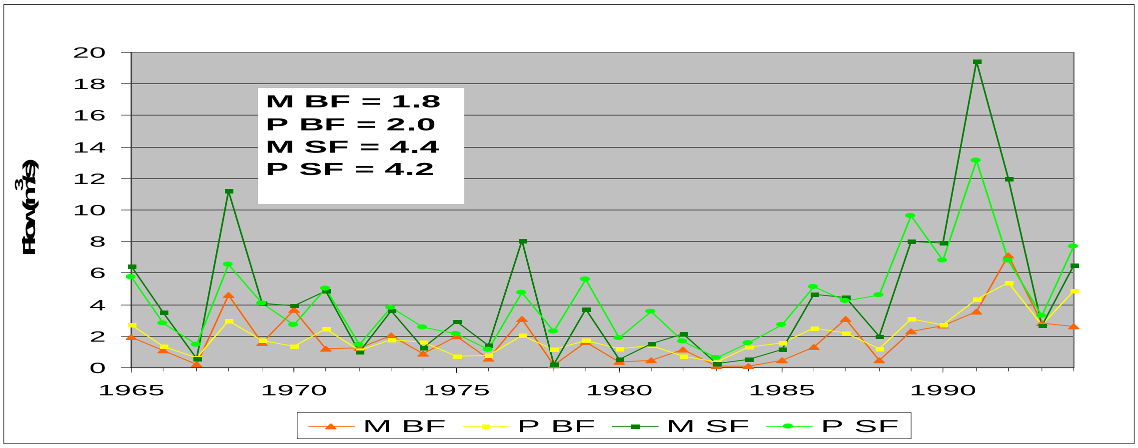


Figure 3-15 **Measured and predicted yearly average daily base and surface flow for the NBR at Clifton (1965-1994)**

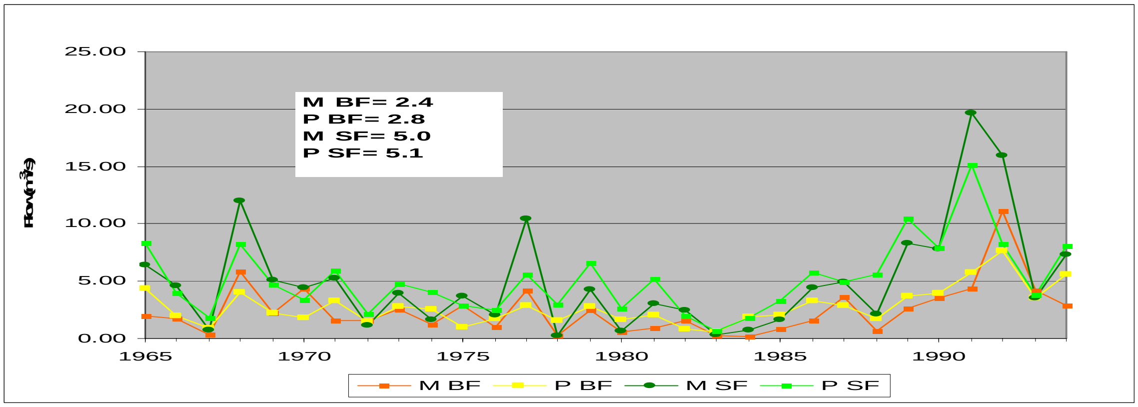


Figure 3-16 **Measured and predicted yearly average daily base and surface flow for the NBR at Valley Mills (1965-1994)**

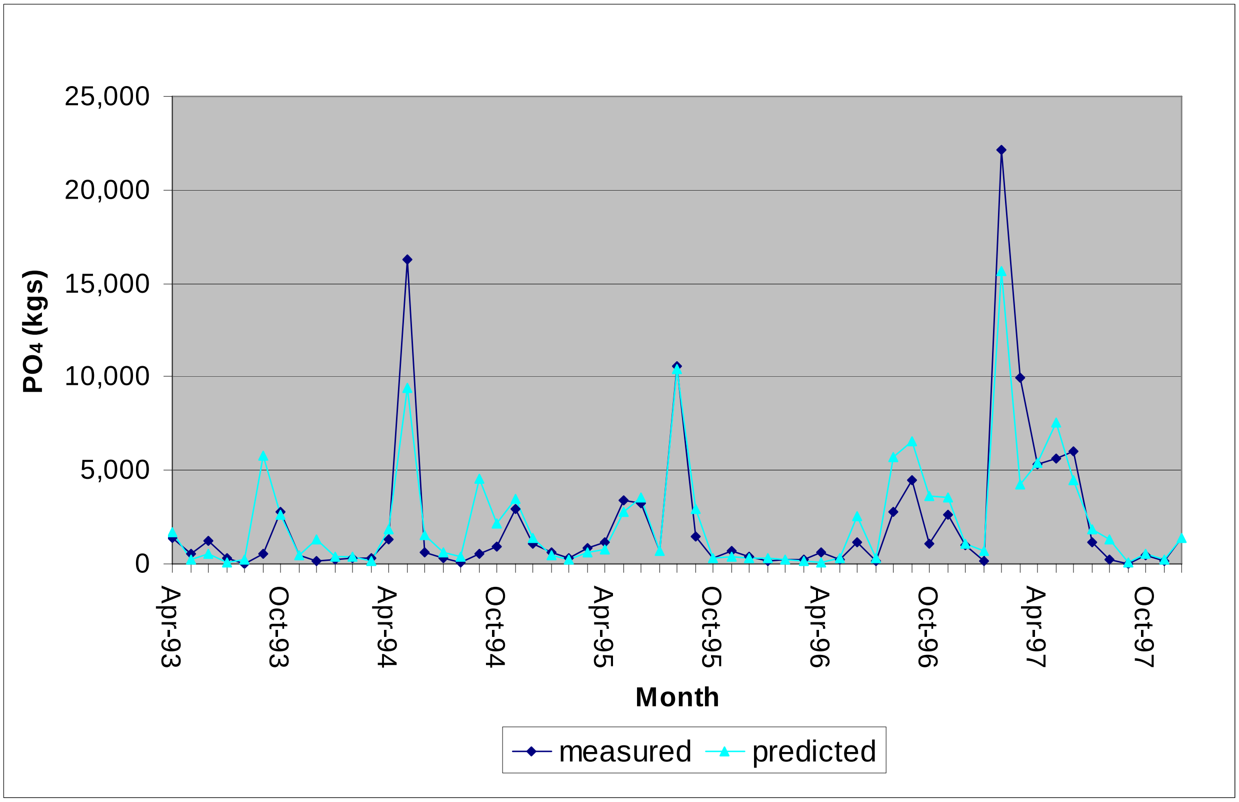


Figure 3-17 **Measured and predicted monthly PO_4 load for the NBR at Hico (BO070) during the calibration period (1993-1997)**

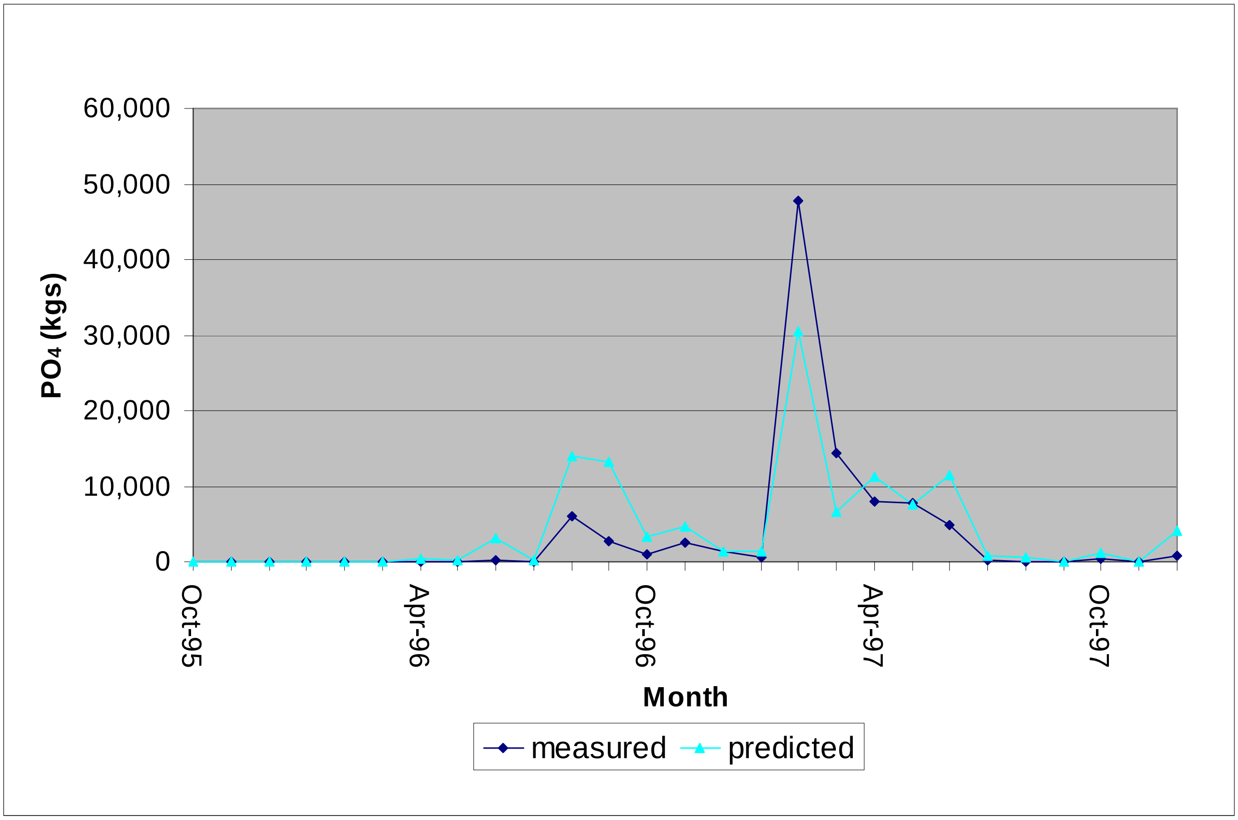


Figure 3-18 **Measured and predicted monthly PO_4 load for the NBR at Clifton (BO090) during the calibration period (1993-1997)**

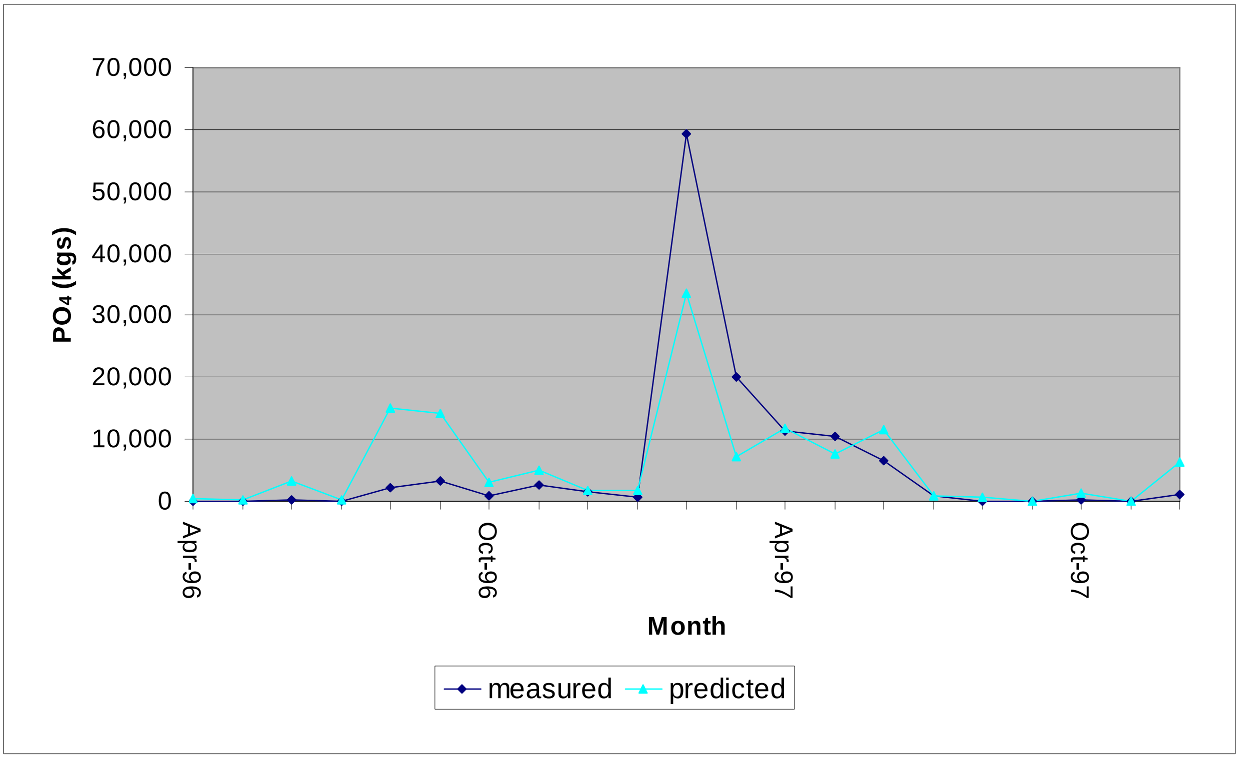


Figure 3-19 Measured and predicted monthly PO_4 load for the NBR at Valley Mills (BO100) during the calibration period (1993-1997)

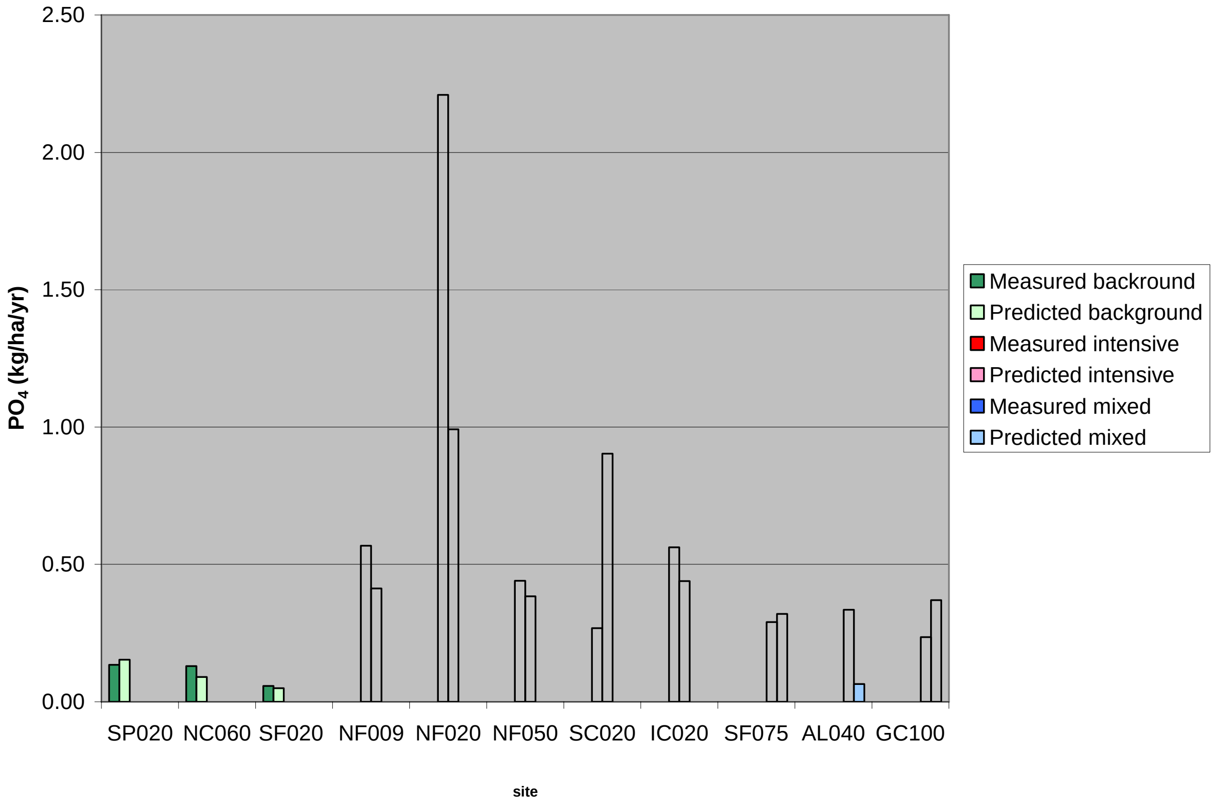


Figure 3-20 Measured and predicted loadings of PO_4 in kg/ha/yr during the calibration period at water quality monitoring stations with drainage areas representing different predominant land uses: background or low intensity (green), intensive agriculture(red), and mixed (blue)

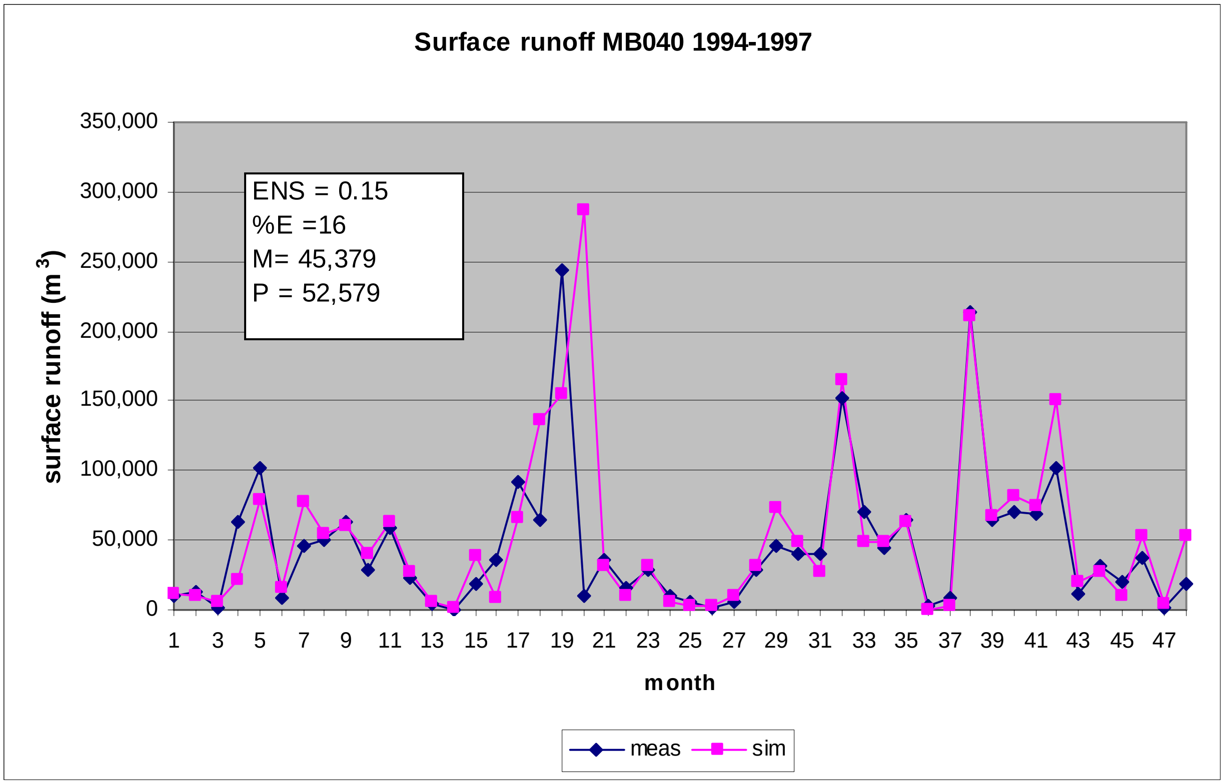


Figure 3-21 **Measured and predicted (based on HRU output) total monthly surface runoff at site MB040 during the calibration period**

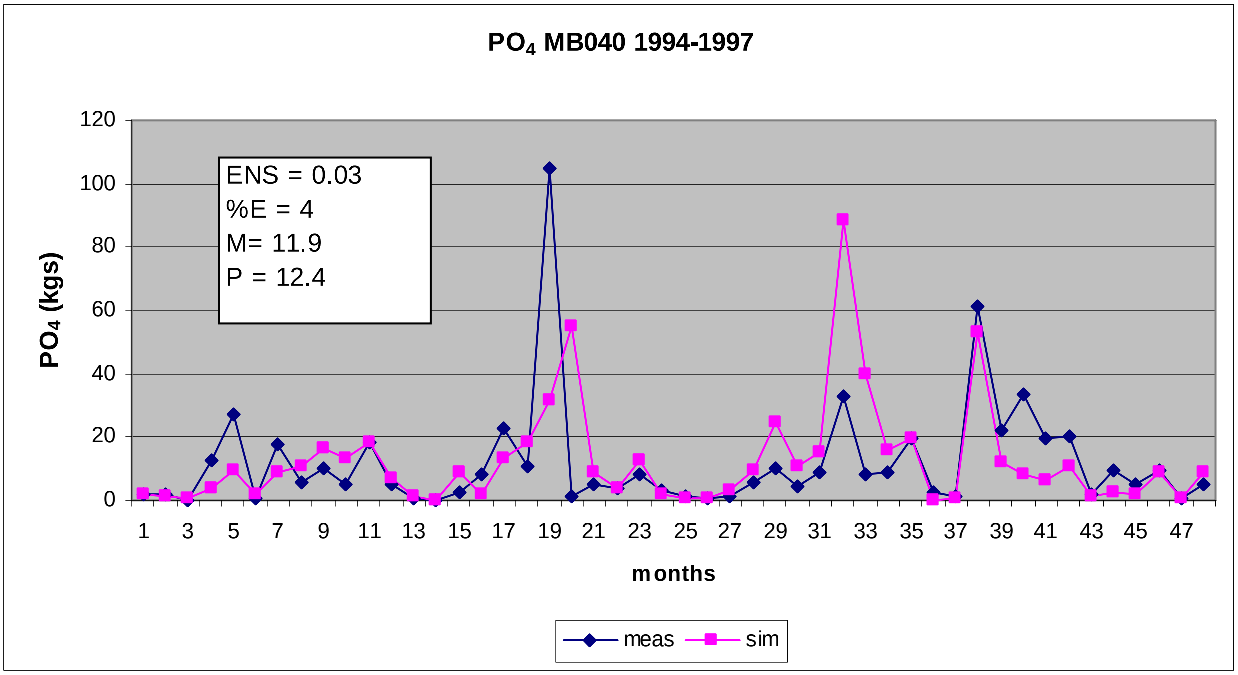


Figure 3-22 **Measured and predicted (based on HRU output) average monthly load of PO_4 at site MB040 during the calibration period**

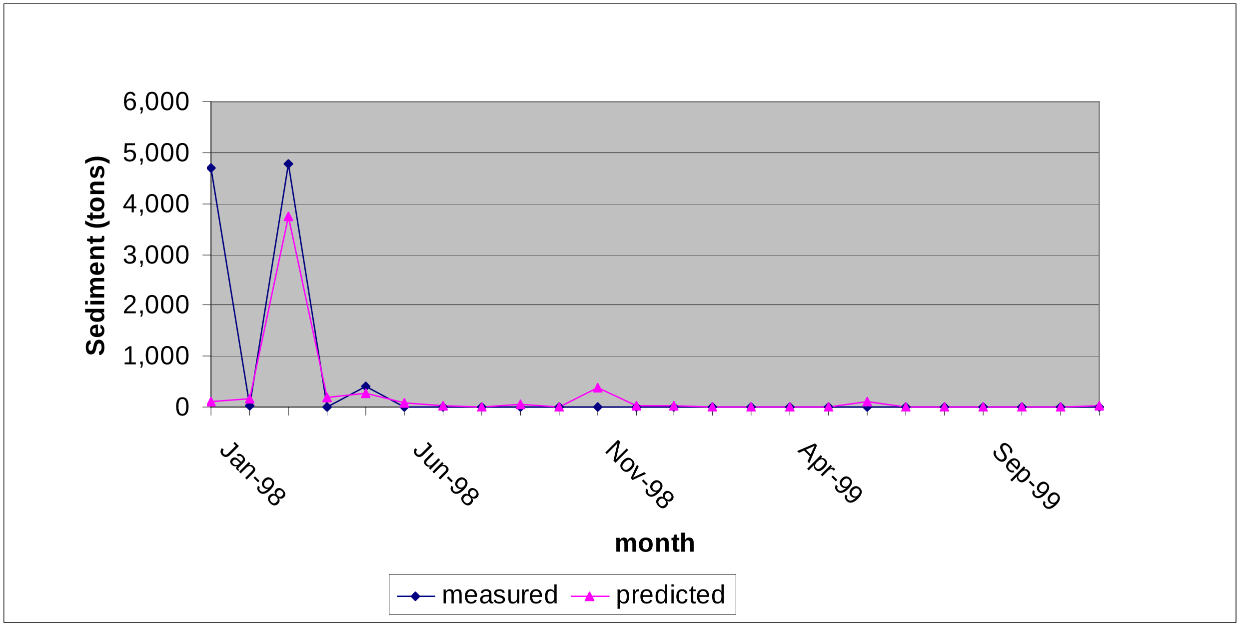


Figure 3-23 Monthly total sediment at BO020 during verification period (1998-1999)

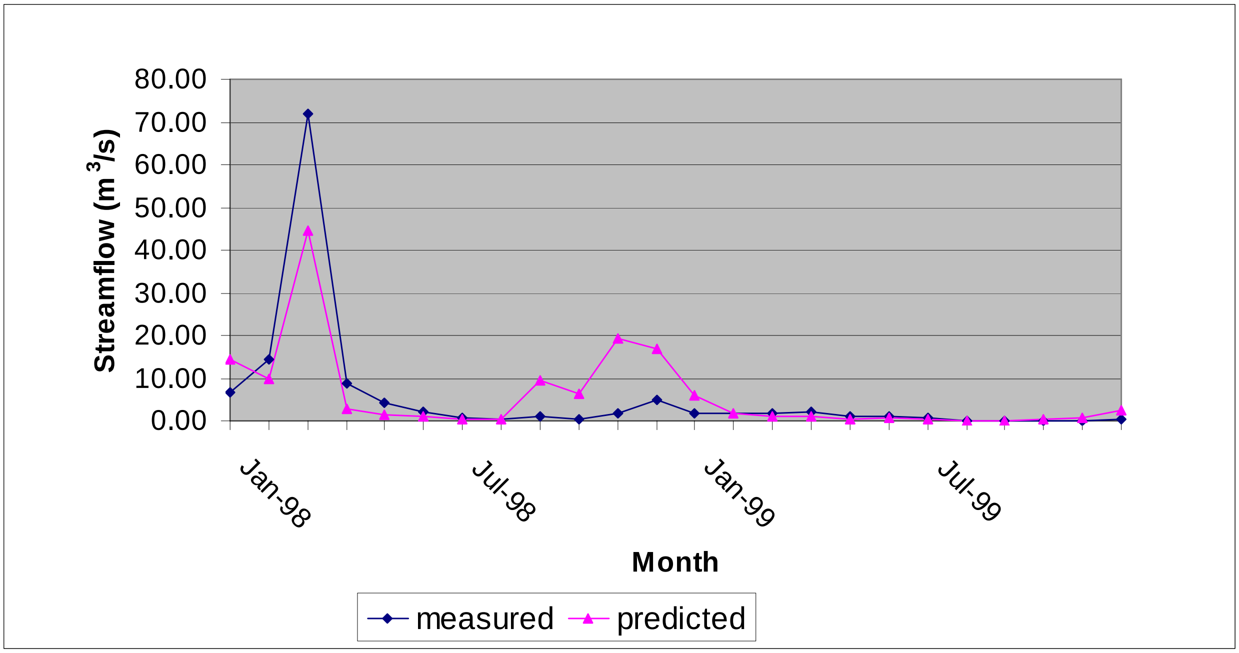


Figure 3-24 Monthly average streamflow at BO100 during verification period (1998-1999)

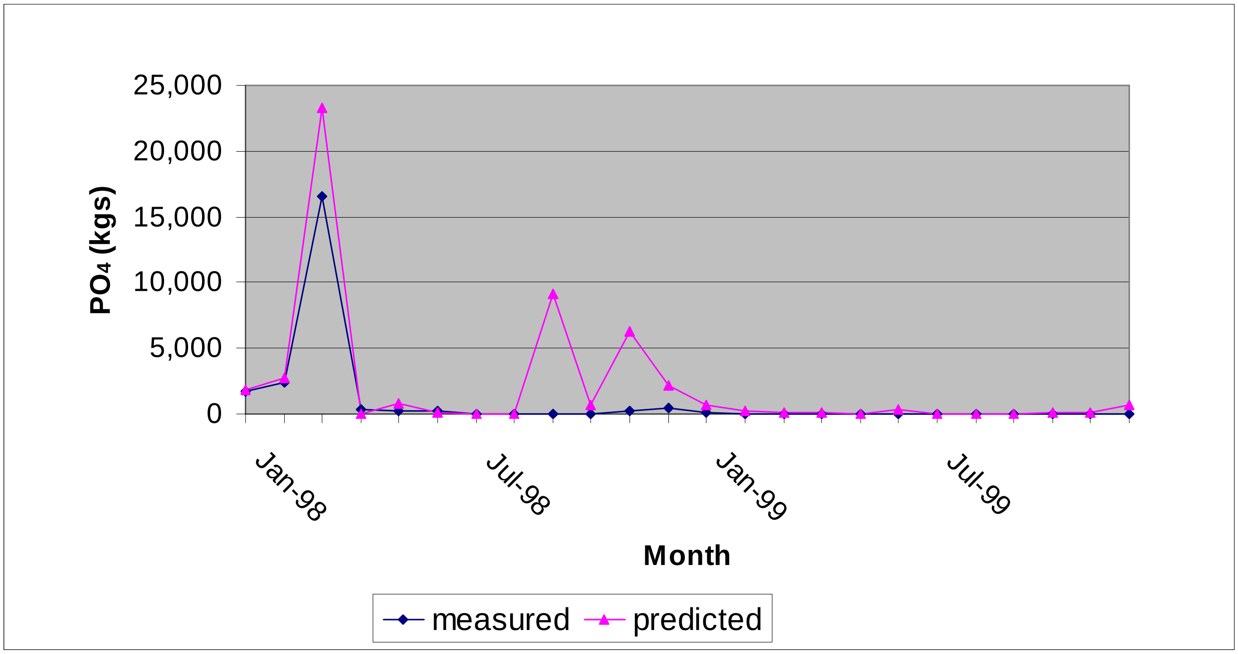


Figure 3-25 Monthly total PO_4 at BO100 during verification period (1998-1999)

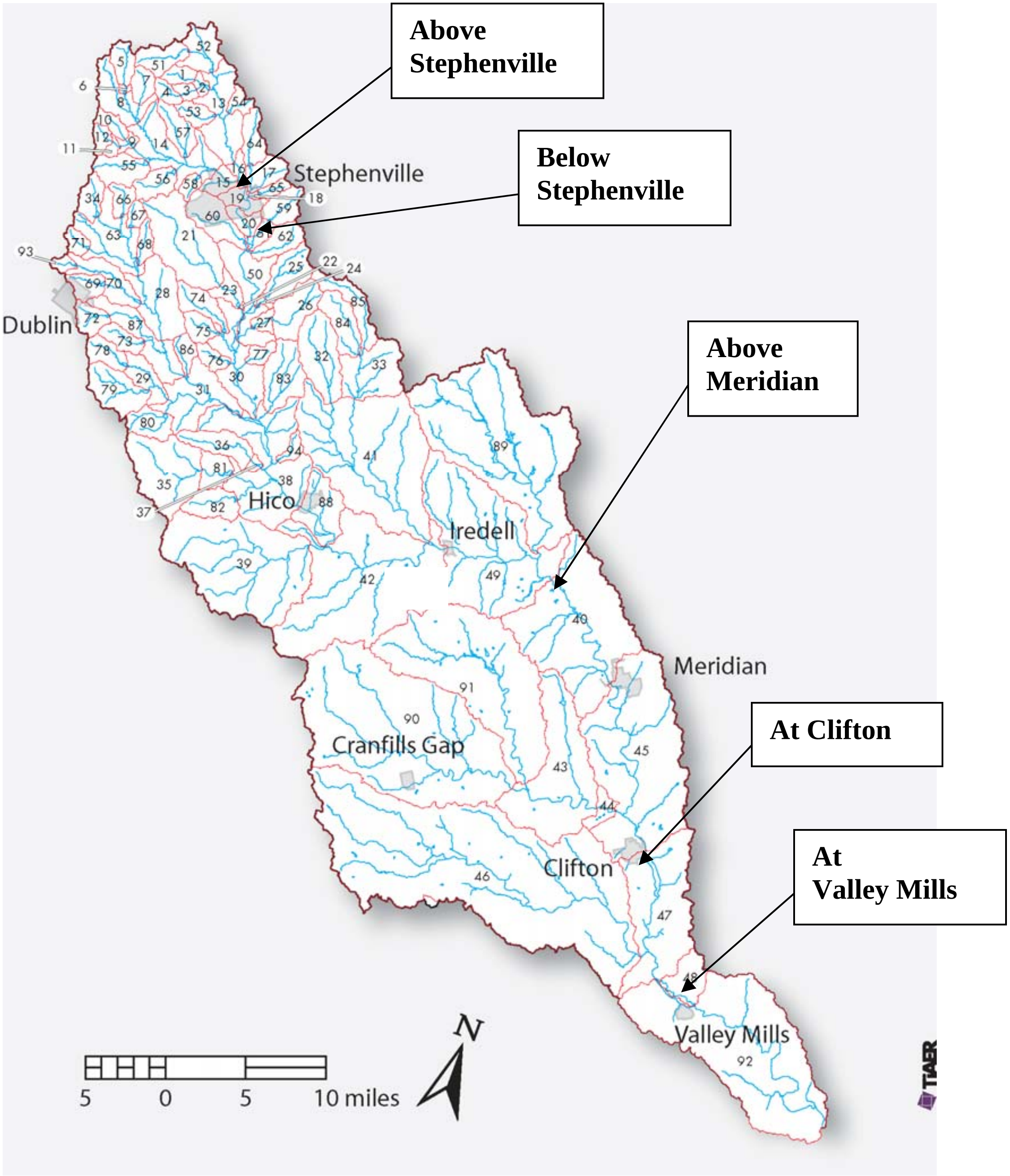


Figure 3-26 Five index stations for the TMDL in the NBR

SECTION 4

REASSESSMENT OF THE TMDL ALLOCATION

4.1 Introduction

One goal of the NBR phosphorus TMDLs as adopted in 2001 was a significant reduction (i.e., around 40 percent to 60 percent) in soluble reactive phosphorus (SRP or PO_4) to reduce the potential for problematic algae growth in the NBR and downstream waters. These reductions were to be based on average total-annual loading and annual daily-average concentrations, as measured at five index stations along the NBR (TNRCC, 2001). These five index stations on the NBR were described as above Stephenville, below Stephenville, above Meridian, at Clifton, and at Valley Mills (see Figure 3-26).

Through various scientific analyses it was concluded in the TMDL (TNRCC, 2001) that annual-average PO_4 concentrations of 50 parts per billion (ppb) or less would have a limiting effect on stream algal communities. As a lower bound for a target range of annual daily-average P concentrations, data from the least-disturbed reference stream in the watershed (Neils Creek) were assessed. That assessment indicated that an annual-average PO_4 concentration of 15 ppb approximates least-disturbed natural conditions. Thus, biological and chemical data established that achieving annual-average PO_4 concentrations between 15 and 50 ppb would probably have a significant limiting effect on algal growth. A “preliminary target” concentration within that range, i.e. 30 ppb, was estimated for a monitoring station immediately upstream of Meridian, and related to a monitored mid-1990s average concentration at the same site of 60 ppb. As a rough estimate, a 50 percent reduction in loading was presumed needed to attain a 50 percent reduction in average concentration in the vicinity of Meridian (TNRCC, 2001).

In order that the model simulations should account for the variability in nutrient concentrations or loading that occur due to normal variations in weather (e.g., wet, dry, and normal rainfall years), SWAT-TCEQ was operated for a 39-year period (the same period length used in the previous modeling effort) using actual records of daily precipitation and temperature for the years 1964 through 2002.[12] As further explanation on a point that sometimes causes confusion, the 39-year period was used to provide historical, daily rainfall for use as input to the model and the intent was not to predict actual conditions during 1964 through 2002 regarding conditions of land use and WWTP discharges.

In addition to the five original index stations, four other locations were included for the presentation of results from the reassessment of the TMDL effort (see Figure 4-1). The additional stations have drainage areas that include tributaries and locations where effects of specific control practices could be more closely observed. A brief description

---

[12] In order to build-up soil test P to approximate the same levels they had during model validation the actual simulation was run for 50 years, with the first 11 years being the same weather as 1988-1999 during the validation period, in order to allow soil test P to build up for 11 years.

of the nine stations for which reassessment results were developed is as follows:

- Index Station, NBR above Stephenville – The drainage area of this station captures the North and South Forks of the NBR and is physically located on the northeast boundary of Stephenville at the FM 8 bridge crossing of the river.
- Index Station, NBR below Stephenville – This station is located approximately 0.4 river kilometers (0.25 miles) below the outfall of the Stephenville WWTP at the bridge crossing of County Road (CR) 454.
- Index Station, NBR above Meridian – This station is located at the bridge crossing of Bosque CR 2371.
- Index Station, NBR at Clifton – This station is located near the bridge crossing of FM 219.
- Index Station, NBR at Valley Mills – This station is located near the bridge crossing of FM 56
- Additional Station, Scarborough Creek – This stream station has a small watershed containing a high density of dairy WAFs and is not affected by a PL-566 reservoir. The location also corresponds with a TCEQ Environmental Monitoring and Response System (EMRS) site.
- Additional Station, Green Creek – This station is located about 1.8 km (1.1 miles) upstream of the confluence of Green Creek and the NBR. The Green Creek watershed contains dairies, several PL-566 reservoirs, and the predominate land uses are wooded, rangeland, and improved pasture. The location also corresponds with an EMRS site.
- Additional Station, Duffau Creek outlet – All other stations selected for presentation of modeling results correspond to historical monitoring location, but this Duffau Creek outlet station was selected to include the entire drainage area of the creek to its confluence with the NBR. The watershed above this station contains several dairies in its headwaters, but the remainder of the watershed is predominately wooded and rangeland. At the time of this report, there were also some planned EMRS sites that could occur in this watershed (though not at the outlet of Duffau Creek).
- Additional Station, NBR at State Highway 6 - This station corresponds with an EMRS site and is located at the bridge crossing of the NBR by SH 6.

In the previous modeling application numerous predictive scenarios with different conditions and control practices were simulated. The description of scenarios provided in the report on the NBR phosphorus TMDLs (TNRCC, 2001) is as follows:

- Existing – represented conditions extant during the mid-1990s; used actual flows and concentrations of WWTPs, actual dairy cow numbers and WAF areas, etc., as measured during the monitoring/validation period.
- Future – represented "full-permitted" conditions for WWTPs and dairies, and projected urban populations and areas 20 years in the future; used maximum number of dairy cows allowable under then existing permits with corresponding WAF area, and maximum permitted WWTP flows with P concentrations as

measured during validation period; included hypothetical 0.6 million gallons per day (MGD) discharge to represent new point sources.

- TMDL-e – incorporated management measures for WAFs and WWTPs, using populations, WWTP flows, dairy cow numbers and WAF area corresponding to validation period; represented anticipated effect of TMDL under "existing conditions"
- TMDL-f – incorporated management measures for WAFs and WWTPs, using populations, WWTP flows, dairy cow numbers and WAF area corresponding to 20 years growth and full-permitted limits; represented anticipated effect of TMDL under "future growth" conditions; included hypothetical 0.6 MGD discharge to represent new point sources.

TNRCC (2001) also contains the following additional descriptions of these scenarios. The "existing condition" model scenario provided the initial or reference values for calculating percent reductions, and the "TMDL-e" model scenario defined the amount of reduction possible if a hypothetical suite of control practices was imposed on existing conditions. Similarly, the "future growth" model scenario provided the reference values, and the "TMDL-f" scenario estimated the amount of reduction, for calculating percent reductions that would occur under full-permitted and 20-year growth conditions.

The reassessment of the two phosphorus TMDLs replicated this previous effort with modifications based on more recent data and additional data refinements. The remainder of this section explains the different TMDL allocation scenarios which were simulated in this reassessment and the resultant effects on PO_4 loading and concentration at the five index stations and four additional sites. This reassessment focused on two elements of the TMDL process: linkage between sources and receiving waters and pollutant load allocations.

It should be noted that the model scenarios in this report section are not intended to represent actual permit provisions for beef and dairy animal feeding operations, municipal WWTPs, and any other regulated sources. The scenarios instead are modeling representations of various combinations of control practices that might be considered under certain land and manure management strategies and control measures. Further, while the scenarios are benchmarked to various pollutant source conditions (i.e., conditions in the 1990s and under full permitted capacity), they are not intended to represent regulatory standards or restrictions on livestock numbers and human populations in the watershed. The technologies and management practices that are applied to address loadings from pollutant sources ultimately determine actual water quality.

4.2 Reassessment of "Existing Conditions" Linkage Analysis and Load Reductions

The validated SWAT-TCEQ model of the NBR watershed was used to reassess the original TMDL modeling efforts including the linkage between sources and receiving waters. The following sections explain and show the results of the simulations in the refined TMDL which were meant to replicate the "existing conditions" and TMDL-e scenarios of the previous TMDL.

4.2.1 1990s Baseline Scenario

The 1990s reference (baseline) scenario was designed to replicate the "existing conditions" scenario of the previous modeling effort. The reassessment was based on the same conditions of land use, dairy operations, and municipal WWTP discharges in the NBR watershed that were used for model validation (see Section 3 – Model Validation). One difference from the model validation input was that for the WWTP output an average annual discharge and nutrient value was used based on the self-reported and TIAER measured nutrient data explained in Section 3.3.10. The refined number of dairy cows (40,350) from the model validation process differed from the original TMDL model application where the total number of dairy cows in the NBR watershed was about 39,900. The amount of PO_4 contributed by each WWTP for the 1990s baseline is shown in Table 4-1.

4.2.2 1990s Control Practices Scenario – Scenario 1

Scenario 1 replicated the previous TMDL-e scenario by including existing conditions in the 1990s and the following four P control practices that were mentioned in general terms in the Implementation Plan (TCEQ and TSSWCB, 2002):

- The P percentage in the diet of lactating cows was reduced from 0.5 percent to 0.4 percent, which resulted in a 13 percent reduction in TP from baseline using the newest ASABE algorithms (ASABE, 2005). It should be noted that under the TMDL-e scenario the percent reduction was estimated as a higher number of 29 percent based on less reliable information.
- Haul-off of 50 percent of collectible manure from the watershed (i.e. solid manure amounts were reduced by 50 percent in all the subbasins representing 39 percent of total manure P from dairy operations)
- Manure application based on 1990s Texas NRCS practice standard 590 for nutrient impaired watersheds (FOTG, 2000) and previous TMDL.[13]
    1. Apply manure at N agronomic rate when STP level less than or equal to 42 parts per million (ppm) at either the 6-inch depth for fields where manure was incorporated or the 2-inch depth when manure was not incorporated.
    2. Apply manure at P agronomic rate when STP level less than or equal to 200 ppm and greater than 42 ppm at 6 or 2 inches

---

[13] As implemented in SWAT-TCEQ, this control practice has the added benefit of providing replacement of commercial fertilizer by manure nutrients. When model simulated STP for a field exceeds thresholds in FOTG (2000), the model reduces the application rate to that field and finds another field to receive the leftover manure. SWAT-TCEQ selects as its first choice for another field pastureland that receives commercial fertilizer. The model then reduces the commercial fertilizer nutrients applied to the new application field by the amount of nutrients that are in the allowed manure application rate, thus effectively replacing commercial fertilizer with manure nutrients.

3. No application of manure when STP level greater than 200 ppm at 6 or 2 inches.

- 1 mg/l (ppm) P limits on Stephenville WWTP discharge (Table 4-1) and all other facilities remained at median measured discharge concentrations from 1990s.

The allocation scenario (Scenario 1) utilized the dynamic manure management component added to SWAT-TCEQ in order to model NRCS guidelines for manure management in the TMDL load allocation scenarios (see section 2.6 Dynamic Manure Management).

4.2.3 1990s Reassessment Results

To reassess the original TMDL linkage analysis and load reductions, the 1990s baseline and P control scenario (Scenario 1) conditions were simulated using SWAT-TCEQ. Predictions for the 39-year period of 1964 through 2002 were aggregated at the subbasin outlets representing the five index stations and annual daily-average PO_4 concentrations and total loadings were determined from the daily model output. To enhance model output interpretation and target evaluation, the SWAT-TCEQ predicted annual daily-average PO_4 concentrations and total annual loads were developed into exceedance probability graphs by ranking the annual results from highest to lowest and plotting exceedance probabilities for each annual value for the 1990s baseline and Scenario 1 (Figures 4-2 through 4-6). These figures include in pairs of plots first the reassessment exceedance plots and then the original TMDL exceedance plots.

The resulting graphs can thus be read as indicating the probability that a particular annual daily-average concentration (or annual total load) will be equaled or exceeded during any random year, or as the frequency at which a particular annual daily-average concentration will be equaled or exceeded during any group of years for both the baseline and Scenario 1 simulation. For instance, in Figure 4-4a, looking at the line representing Scenario 1 in the concentration-based graphs above the 0.4 exceedance probability marker, one reads the figure as predicting that the annual-average concentration would be greater than or equal to (approximately) 34 ppb in 40 percent of future years, and less than or equal to 34 ppb in 60 percent of future years above Meridian.

Comparison of the reassessment exceedance graphs with those of the previous TMDLs at the five index stations (Figures 4-2 through 4-6) showed that predictions are similar. Values in the exceedance charts differed between the reassessment and original model predictions as would be expected because of the differences in validation procedures for the two models, refined and additional input model data for the new model, and the dynamic manure management and instream water quality kinetics afforded by SWAT-TCEQ. Besides some general differences in trends indicated in the concentration and loading plots, perhaps the visually most obvious difference regards the annual loadings graphs at the lowest exceedance probability (e.g., the highest annual loading). The original TMDL prediction for this highest annual loading was typically at least 50 percent greater than the second highest loading, whereas the reassessment prediction for this highest loading was typically much closer in magnitude than the second highest value. There is no indication that there are errors in either the reassessment or original loading predictions, but this difference between the two sets of results does make visual comparison of graphs a little more difficult.

Closer evaluation of results indicated that the percent reductions of PO_4 39-yr annual daily-average concentration and annual-average loading at the five index stations for reassessment Scenario 1 when compared to the reassessment 1990s baseline were comparable to the "existing scenario" baseline and the TMDL-e scenario from the original TMDL evaluation (Tables 4-2 through 4-5). For instance, in the original TMDL above Meridian the TMDL-e scenario created an average 53 percent reduction in concentration of PO_4 compared to the "existing conditions" baseline (Table 4-2), while Scenario 1 in the reassessment of the TMDL created an average 64 percent reduction from the reassessed 1990s baseline (Table 4-3). The percent reductions in PO_4 loads created by the control practice scenarios in the original and reassessed TMDL were even more similar (Tables 4-4 and 4-5). Above Meridian TMDL-e created a 53 percent reduction in PO_4 load from the baseline (Table 4-4) and Scenario 1 in the reassessment created a 55 percent reduction in PO_4 load from the baseline (Table 4-5). In model applications of this sort, relative changes between different simulated conditions are more meaningful than exact values predicted.

Analysis of simulated baseline loadings of PO_4 from different land uses (e.g. dairy WAFs, pasture, range, etc.) at the five index stations showed a pattern somewhat similar to the land-use loadings calculated from export coefficients in the previous TMDL. However, the inclusion of a grazing land use for both pasture and range which had not been in the previous TMDL, as well as a different time frame (39-year simulated average for the TMDL reassessment as opposed to export coefficients derived from for the period of November 1995 through March 1998 for the original TMDL) complicated direct comparisons. In general the PO_4 contribution from the pasture land use was greater in the refined TMDL compared to the previous TMDL (Table 4-6)

Percent reductions in land-use (gross) loadings of PO_4 between the baseline and Scenario 1 were almost identical with the reduction in PO_4 loadings simulated in the stream (net) loadings at the five index stations (Table 4-7).

4.3 TMDL Future Full-Permitted Allocation Scenario

The following sections contain the discussion and results of the reassessment of the "full-permitted" scenarios of the previous TMDL. The reassessment conditions of the future (full-permitted) baseline and the various control measure scenarios are developed, followed by presentation of results.

4.3.1 Future (Full-Permitted) Baseline Scenario

A reassessment future (full-permitted) baseline was developed for comparison with the future TMDL allocation scenarios and for comparison to the original future baseline conditions and TMDL-f (control measures) scenario. Major aspects defining the reassessment include the following:

- A new land use/land cover layer developed by Spatial Science Laboratory (SSL) in College Station, Texas using selected LANDSAT-7 ETM satellite imagery from 2001, 2002 and 2003 (Figure 2-5).
- Fully-permitted dairy and other animal feeding operation (AFO) cow numbers (77,090) with no manure removed from the watershed. The cow numbers of 77,090 include 68,771 dairy cows and 8,319 beef cattle in confinement. The future condition for the original TMDL evaluation considered a future condition of 66,930 dairy cows with no beef cattle in confinement.
- Historical WAF soils initialized at a STP concentration of 200 ppm. (Historical WAFs are waste application fields for previously permitted dairies that are no longer in operation as of the year 2000).
- Application of effluent to WAFs by the Microgy Corporation at its natural gas production facility in the northern-most section of the NBR watershed (for the amount of N and P applied see Table 4-8).[14]
- A newly weighted composite manure developed with nutrient characteristics based on ASABE (2005) values for beef cattle and dairy cows and future numbers of beef cattle and dairy cows in the NBR watershed from permit applications as of February 2008.
- Division of manure into solid and liquid pools based on the number of freestalls and vacuum manure collection systems in the NBR watershed (Table 4-9). In a freestall operating with lane flushing the ratio was 85 percent liquid and 15 percent solid and for a freestall using vacuum collection systems the ratio was 15 percent liquid and 85 percent solid (from the project advisory group meeting of November 14, 2007).
- Fully-permitted WWTP discharges with no P removal (P loads based on average concentration measured during the 1990s); including a hypothetical 0.6 MGD of additional discharge (minus the new permitted discharges at Cranfills Gap and Northside Subdivision) to represent new point sources divided into 3 facilities, one upstream of the index station above Meridian, another upstream of the index station at Clifton, and the last one above the index station at Valley Mills (Table 4-1).[15]
- Manure applied at the N agronomic rate on dairy WAFs using new NRCS crop fertility guidelines as provided by the stakeholders (Table 4-10).
- No filter strips assumed on WAFs.
- Lagoon design based on the old requirement of 25-yr, 24-hr storm event.
- No reduction of P in diets of milking cows (assumed P content of diet of 0.5 percent).

---

[14] According to the Microgy permit, application on these fields would cut off once an STP of 100 ppm was reached. That limit was not exceeded on the majority of fields during the TMDL allocation simulation.

[15] The advisory committee for the original TMDL requested inclusion of the additional 0.6 MGD of potential future growth WWTP capacity above and beyond that in existing facilities. For this reassessment it was assumed that the recent Cranfills Gap and Northside Subdivision WWTPs were a realization of part of this potential future growth.

4.3.2 Future Scenario Control Practices

An initial TMDL future allocation scenario (Scenario A) designed to replicate the original TMDLs TMDL-f scenario, used P control measures based on the previous reassessment "Scenario 1" allocation, as well as conditions unique to the future condition. Specifically :

- A new land use/land cover layer developed by Spatial Science Laboratory (SSL) in College Station, Texas using selected LANDSAT-7 ETM satellite imagery from 2001, 2002 and 2003 (Figure 2-5).
- Sediment and nutrient removal by vegetative buffer/filter strips on all dairy WAFs which is required in new permit applications. The removal efficiencies for the filter strips derived from APEX simulations[16] are shown in Table 4-11.
- Fully permitted discharge and nutrient loads of WWTPs, including additional discharges based on future growth allocations (Table 4-1).
- New simulations of lagoon discharges and unauthorized municipal discharges. Lagoon discharges were based on design requirements for the 25-year, 10-day precipitation event and used the same matrix of management options A, B and C as used previously, and unauthorized municipal discharges increased from previous values by the ratio of full-permitted discharges to the discharges used in the 1990s-condition scenario.
- New NRCS crop fertility guidelines (Table 4-10).
- Manure application as recommended by the latest Texas NRCS practice standard 590 (FOTG, 2005).[17]
    - STP level less than 200 ppm at 6 or 2 inches
        - 2.0 times Annual Crop P *Requirement* (agronomic rate) (based on a medium "average" P index, see Table 4-12)[18]
    - STP level equal to or greater than 200 ppm at 6 or 2 inches
        - 1.0 times Annual Crop P *Removal*
    - STP level equal to or greater than 500 ppm at 6 or 2 inches

---

[16] APEX simulations were conducted to determine the parameters for filter strip calibration in SWAT-TCEQ. APEX is a multi-field model that includes features that allow mechanistic simulation of buffer and filter strips. Three crop types and three different soil types that corresponded to the dominant soil and crop types on WAFs in the NBR watershed were simulated with and without filter strips. NRCS guidance was used to determine width of filter strips. From these simulations, based on a weighted average taking into account the relative abundance of the different soil types, an average removal rate for filter strips was determined for organic N, NO_3, organic P, PO_4, and sediment. These removal efficiencies were then added to the SWAT-TCEQ code and applied to the management of WAFs. In addition, based on the average area of a filter strip and the number of WAFs in each subbasin, a total area of filter strip was derived and a specific HRU reflecting filter strip management was created in each subbasin with WAFs.

[17] As stated previously in Section 4.2.2, footnote 13 this control practice has the added benefit of providing replacement of commercial fertilizer by manure nutrients.

[18] HRUs within a SWAT subbasin have no spatial orientation; they are just the accumulated area within the subbasin of a particular land use and soil combination wherever those combinations may occur within the boundaries of the subbasin. Since some index points within the P index determination are assigned based on the proximity of the field to a stream, the current configuration of SWAT-TCEQ could not be used to assign individual P indexes to specific HRUs Therefore, an "average" P index value based on the average condition of WAFs in the NBR watershed was determined for use in the reassessment modeling.

        - 0.5 times Annual Crop P *Removal*
    - Delivery to third party field must be discontinued once STP is equal to or greater than 200 ppm at 6 or 2 inches
- Removal of 50 percent of solid manure from the NBR watershed representing 35 percent of total manure P from dairy operations

Subsequent future allocation scenarios were simulated utilizing different P control measures in an attempt to reduce PO_4 instream concentrations at the five index stations to levels similar to those created by the reassessment “Scenario 1” allocation simulation, which was based on 1990s conditions. The control measures for the “future” allocation scenarios are additive such that each sequential scenario includes the practice(s) from the previous scenarios. These control measures were developed at the November 2007 meeting of the project advisory group, which convened for the main purpose of defining additional control measures and discussing their feasibility. The scenarios and the additional control practices defining each scenario are summarized in Table 4-13 and defined as follows:

- Scenario B – Inclusion of three reservoirs, similar in function to existing PL-566 reservoirs, at locations south of Hico and in SWAT-TCEQ subbasins with WAFs and no existing downstream PL-566 reservoirs. The locations were chosen in order to capture streamflow from areas with a high density of WAFs that did not previously have PL-566 reservoirs (see Figure 4-7).
- Scenario C – P removal in the liquid waste at the Microgy Corporation so that the waste application stream nutrient content was a balanced fertilizer that supplied enough N for the crop and applied P at the crop P removal rate (Table 4-8).
- Scenario D – historical WAF remediation so that the STP concentration at the initiation of the simulation was 60 ppm rather than 200 ppm.
- Scenario E – 75 percent manure haul-off of collectible manure representing 52 percent of total manure P from dairy operations, 100 percent turkey litter haul-off, and haul-off of lagoon clean-outs
- Scenario F – Additional treatment requirements for all WWTPs to produce an effluent of 0.5 ppm TP (Table 4-1)
- Scenario G – To simulate enhanced management of grazing cattle, such as prescribed grazing, carrying capacity of range and pasture land was reduced by 25 percent based on the opinion of TIAER staff familiar with grazing in the NBR watershed. Reduction of carrying capacity reduced the number of animals per unit area on both range and pasture land thereby reducing the amount of manure deposited and the amount of biomass consumed.

4.3.3 Future Scenario Results at Index Stations

Percent reductions of 39-yr annual daily-average PO_4 concentration and annual-average loading at the five index stations for TMDL reassessment Scenario A when compared to the TMDL reassessment 1990s baseline were comparable to the “existing scenario” baseline and the TMDL-f scenario from the original TMDL evaluation (Tables 4-14 through 4-17). For instance, in the original TMDL for the NBR below Stephenville, the TMDL-f scenario was predicted to have an average reduction of 55 percent in concentration of PO_4 compared to the “existing conditions” baseline (Table 4-14), while Scenario A in the reassessment of the TMDL provided an average reduction of 53 percent from the reassessed 1990s baseline (Table 4-15). At the NBR above Stephenville reductions in concentration and load of PO_4 compared to the existing conditions or 1990s baseline were greater in the original TMDL for the TMDL-f scenario, than for the reassessed TMDL Scenario A; however, the reductions in the lower part of the watershed compared to the baseline for concentration and load of PO_4 were similar in both the original and reassessed future conditions TMDL (Tables 4-14 through 4-17). Scenario A actually created a greater reduction in PO_4 concentration above Meridian compared to the 1990s baseline than did TMDL-f (Tables 4-14 and 4-15). However, neither the original TMDL-f nor the reassessed TMDL Scenario A created enough reductions in PO_4 load or concentration to meet the original TMDLs’ goal of a 50 percent reduction from the existing or 1990s baseline for the NBR above Meridian. Therefore, additional control practices in the future TMDL allocation scenarios were assessed.

Simulated 39-year annual daily-average PO_4 concentrations and annual-average total PO_4 loads for all the future TMDL scenarios (A-G) and baselines as well as the average percent reduction in PO_4 concentration and load from those baselines created by the control practices in each scenario are shown in Tables 4-18 through 4-23. Exceedance probability graphs were created for Scenarios A and G with the 1990s baseline and future (full-permitted) baselines included (Figures 4-8 though 4-12). One thing revealed by these figures is that the loading plots seemed to converge at the higher exceedances (i.e., lowest rainfall years), except at the index station below Stephenville (Figure 4-9) which was heavily impacted by the largest WWTP discharge in the watershed. The greatest reductions from the two baselines in the TMDL reassessment allocation scenarios A and G were predicted in the upper part of the watershed (Figure 4-8, 4-9 and 4-10). Near the bottom of the watershed for the NBR at Clifton (Figure 4-11) and Valley Mills (Figure 4-12), Scenario A created a reduction below the 1990s baseline for only about 50 percent of possible years; however, Scenario G created a reduction below the 1990s baseline for almost 100 percent of the possible years.

As stated in the TMDL document (TNRCC, 2001) and restated in Section 4.1, biological and chemical data established that achieving annual-average PO_4 concentrations between 15 and 50 ppb would probably have a significant limiting effect on algal growth and average values within that range were simulated at the index station on the NBR above Meridian by the control practices in Scenarios F and G (Table 4-18). In Scenario G for the NBR above Meridian annual daily-average concentrations of PO_4 below 50 ppb were predicted for 65 percent of the simulated years while PO_4 concentrations 30 ppb or less were predicted for 20 percent of the years (Figure 4-10). As pointed out in the section on model validation, Since PO_4 concentrations were consistently over-predicted by the model compared to measured values in the lower end of the watershed, the predicted values probably correspond to a measured concentration that would actually be lower in the real stream system. Furthermore, because of the limitations and uncertainties inherent in dynamic watershed modeling, relative changes between scenarios are typically more meaningful than predictions of concentrations. In the TMDL document (TNRCC, 2001), it was presumed, as a rough estimate, that a 50 percent reduction in loading was needed to attain a 50 percent reduction in average concentration in the vicinity of Meridian. Scenarios F and G both achieved at the NBR above Meridian an average 50 percent reduction in PO_4 concentration from the 1990s baseline (Table 4-19) and Scenario G achieved a 45 percent reduction in average PO_4 load (Table 4-22). Daily PO_4 concentration, rather than load, is the true driving force of algae growth in the NBR, though loadings can be important to downstream receiving waters such as Waco Lake.

To enhance understanding of the sources of landscape and point source loadings, analyses were performed that accumulated actual SWAT-TCEQ simulated loadings from each type of land use and the WWTP point sources. These loadings can be defined as "gross" loadings as opposed to "net" instream loadings that have undergone changes as a result of transport and kinetic processes as represented in SWAT-TCEQ. The defined land uses and point sources are WAFs, third party fields (3WAF), historical WAFs (HWAF), Microgy WAFs (MICR), filter/buffer strips (FLTR), range (RNGE), pasture (PAST), forest (FRST), row crop (AGRR), urban (URLD), WWTP, turkey WAFs (TURK), dairy lagoon overflows or discharges (lagoon), and unauthorized WWTP discharges (WWTP unauthorized). The gross loading analyses are presented in a series of pie-chart graphics for the five index stations (Figures 4-13 through 4-17). In addition, the figures show the area of different land uses above each index station for both the baseline and future scenarios. For instance, Figure 4-15 shows that for the NBR above Meridian in the 1990s baseline scenario, the 39-year average annual contribution of PO_4 from active dairy WAFs[19] was 36,834 kgs or about 55 percent of the total PO_4 loading contributed by land uses and point sources above Meridian. This amount was contributed by 5,010 ha of WAFs or about 3.0 percent of the total land area. For the NBR above Meridian the 39-year average contribution of WAFs and third party fields (3WAF) in Scenario A was reduced to 14,194 kgs which accounted for about 26 percent of the total loadings from land uses and point sources.[20] The final area of WAFs above Meridian in Scenario A was 13,270 ha or about 7.5 percent of the total land area, and 6,230 ha of the WAFs were third party fields.[21] The average percent reduction in PO_4 loadings from all land uses and point source for the NBR above Meridian between the 1990s baseline and Scenario A was 19 percent which was below the predicted instream load reduction of PO_4 (29 percent) (Table 4-22). In Scenario G for the NBR above Meridian the percent reduction in loading from point sources and land uses is 34 percent compared to the 1990s baseline (Figure 4-15), due to reductions in loads from WAFs, third party fields, historical WAFs

---

[19] "Active" WAFs differ from permitted WAFs due to the fact that with manure application at the nitrogen (N) agronomic rate with the simulated cow numbers not all of the permitted WAFs were needed for manure disposal.

[20] The chart shows a percentage of about 21 for WAF and 3WAF combined; however, that was determined with the "reduced load" percentage of the pie chart included. 26 is the WAF percentage of just the contributed loading.

[21] Unlike the baseline which has a consistent area of WAFs each year, the total area of WAFs in the "future" scenarios increased over time as manure application rates changed in response to STP concentrations in the WAFs. The reported WAF area was the area in the last year of the "future" simulation.

and WWTPs. The predicted instream load reduction of PO_4 for Scenario G compared to the 1990s baseline is 45 percent at the NBR above Meridian (Table 4-22).

The "net" PO_4 load in the NBR at each index station is less than the "gross" land-use and point source contribution of P above the index station due to losses and transformations of PO_4 in the stream system. For instance, at the Clifton index station the average total PO_4 loading from land uses above the station in the 1990s baseline simulation was 74,781 kg (Figure 4-16), while the average PO_4 load simulated in the stream during the same time period was 41,713 kg (Table 4-21).

Comparisons of land use and point source loadings and land area of Scenarios A and G compared to the full-permitted baseline are shown in Appendix A (Figure A-1 through A-5).

4.3.4 Future Scenario Results – Additional Sites

The predictions and comparison of predictions from the additional sites (Tables 4-24 through 4-29; Figures 4-18 through 4-29) help illustrate more clearly the effects of some individual control practices that were harder to recognize at the main stem NBR index station sites due to their large drainage area sizes and the general heterogeneous mix of land uses above these main stem sites. For instance, additional site NF020 represented a small drainage area of about 8.1 km^2 (810 ha). Therefore, the total loading from the site was relatively small compared to the index stations and other additional sites (Table 4-27) even though the concentrations were quite high (Table 4-24) due to the density of dairy WAFs and Microgy Corporation WAFs (Figure 4-26). The benefit of the Microgy effluent remediation of Scenario C could be seen at NF020 (Tables 4-24 and 4-27) whereas the effect of Scenario C was less evident at the index station sites (Tables 4-18 and 4-21). Similarly the impact of new reservoirs was revealed at Duffau Creek in Scenario B (Tables 4-24 and 4-27), while no effect was seen in any of the other additional sites since they were not located immediately below any of the new reservoirs in Scenario B (Figure 4-1 and Figure 4-7). NF020 also revealed the significant impact of removing more solid manure in Scenario E which caused a 23 and 46 percent decrease in PO_4 concentration (Table 4-25) and load (Table 4-28) respectively compared to the 1990s baseline. Scenario E was actually the first scenario that created a decrease in concentration from the 1990s baseline at NF020 (Table 4-25). Concentration at the main stem site (NBR@SH6) was most affected by the reduction of PO_4 discharge from WWTPs in Scenario F (Table 4-24) which had no effect on any of the other additional sites since they were not impacted by WWTP discharges (Table 4-24).

4.4 Evaluation of TMDL Reassessment

For the same set of proposed control practices, the TMDL reassessment results for percent reductions of concentration and load of PO_4 for conditions during the 1990s support the findings of the original TMDL. The reassessment showed similar levels of reduction at all five index stations and achieved the targeted goal of 50 percent reduction in load and concentration for the NBR above Meridian compared to the baseline (Tables

4-2 through 4-5). The TMDL reassessment actually indicated that the proposed control practices potentially could create even more reduction in PO_4 than predicted by the original TMDL.

The original TMDL allocation scenarios based on future conditions (TMDL-f), however, did not create the targeted PO_4 concentration and loading reduction of 50 percent above Meridian compared to the 1990s baseline (Tables 4-14 and 4-16). These findings were supported by the TMDL reassessment's Scenario A allocation simulation which was designed to replicate the control practices of the original TMDLs' TMDL-f scenario (Tables 4-15 and 4-17). Scenario A gave essentially the same amount of reduction in PO_4 concentration from the 1990s baseline as did the TMDL-f scenario of the original TMDL (Tables 4-14 and 4-15), but tended to give less reduction in load (Tables 4-16 and 4-17). However, while TMDL-f and Scenario A each represented the same control practices, the total number of permitted confined cows was approximately 20 percent greater under Scenario A than TMDL-f. The greater number of cows included in Scenario A is the most likely reason for less load reduction under that scenario as compared to TMDL-f.

Since neither the TMDL-f scenario nor the reassessment with Scenario A produced the desired reductions in PO_4 compared to the 1990s baseline, more alternatives for control measures were evaluated in the reassessment in order to create reductions similar to those created by the original TMDL-e scenario and the reassessment Scenario 1. It was demonstrated that with additional controls the goal of 50 percent reduction from the 1990s baseline was obtainable for the future scenarios (Tables 4-19 and 4-22), though admittedly through a fairly extensive suite of control practices.

The average PO_4 concentration of the NBR above Meridian in Scenario G (44.8 ppb) does not meet the suggested target concentration of 30 ppb from the TMDL document (TNRCC, 2001), though that target concentration was nearly met in Scenarios F and G at Clifton and Valley Mills (Table 4-18). However, since the model over-predicted PO_4 concentrations in the lower reaches of the watershed, these predicted values would most likely represent a lower real measured instream concentration value. In addition, the previous TMDL had suggested as a rough estimate, a 50 percent reduction in loading was presumed needed to attain a 50 percent reduction in average concentration in the vicinity of Meridian (TNRCC, 2001). Scenarios F and G both achieved in the NBR above Meridian a 50 percent level of reduction in PO_4 concentration from the 1990s baseline (Table 4-19) and Scenario G achieved a 45 percent reduction in average PO_4 load (Table 4-22). Daily PO_4 concentration, rather than load, is considered to be the true driving force of algae growth (TNRCC, 2001). So, it appears in the full-permitted future TMDL allocation scenarios the goals of the original TMDL, based on the 1990s baseline or "existing conditions," were approached. Given the uncertainty in the model predictions, control practices may be capable of reaching the goals outlined in the original TMDL even under fully-permitted conditions.

In conclusion, this reassessment of the NBR TMDL indicated that the control practices originally assessed in the TMDL-e scenario would be sufficient to lower concentration levels to the suggested target if conditions do not change in the watershed regarding major contributors of PO_4. This finding supports the validity of the present TMDLs and their associated load allocations and initial suite of P control practices. The TMDL reassessment also confirmed the findings of the original TMDL's future scenario (TMDL-f).

SECTION 4

TABLES

Table 4-1 WWTP PO_4 contributions for different reassessment scenarios

WWTP	1990s Baseline (kg/d)	Scenario 1 (kg/d)	Future Baseline (kg/d)	Scenario A (kg/d[a])	Scenario F kg/d[a])
Northside	--	--	0.310	0.117	0.059
Stephenville	18.42	6.23	28.50	10.85	5.34
Hico	1.05	1.05	2.43	1.36	0.356
Iredell	0.24	0.24	0.490	0.772[b]	0.087
Additional	--	--	0.600	0.217	0.114
Meridian	1.78	1.78	5.11	2.52	0.800
Cransfill Gap	--	--	0.375	0.169	0.071
Additional	--	--	0.600	0.217	0.114
Clifton	1.97	1.97	4.23	2.99	1.16
Additional	--	--	0.600	0.217	0.114
Valley Mills	0.869	0.869	3.64	1.28	0.640

[a] Based on a weighted average of measured data dividing total P into 94 percent PO_4 and 6 percent OrgP
[b] The new permit for Iredell has a TP load limit which results in a higher PO_4 concentration than was measured at Iredell by TIAER in the 1990s. Once this load limit is reached, however, the Iredell WWTP will have to go to a 1 ppm TP concentration limit for its discharge. All of the WWTPs in the NBR that reach their TP load limits will have to meet the 1 ppm TP concentration limit, however, for all of them except Iredell the load limit is close to a 1 ppm concentration.

Table 4-2 39-yr annual daily-average PO_4 concentration at the 5 index stations for the original TMDL "existing conditions" (1990s) baseline and TMDL-e scenarios and the percent reduction of 39-yr annual daily-average PO_4 concentration at the 5 index stations for TMDL-e compared to the "existing conditions" baseline [a]

	Above Stephenville	**Below Stephenville**	**Above Meridian**	**Clifton**	**Valley Mills**
Existing conditions (ppb)	203	1,143	117	52.2	41.3
TMDL-e (ppb)	114	448	54.5	30.3	27.5
% reduction	**44**	**61**	**53**	**42**	**33**

[a] From TCEQ (2001)

Table 4-3 **39-yr annual daily-average PO_4 concentration at the 5 index stations for the TMDL reassessment 1990s baseline and Scenario 1 scenarios and the percent reduction of 39-yr annual daily-average PO_4 concentration at the 5 index stations for Scenario 1 compared to the 1990s baseline**

	Above Stephenville	**Below Stephenville**	**Above Meridian**	**Clifton**	**Valley Mills**
1990s baseline (ppb)	216	1,227	93.1	45.0	45.3
Scenario 1 (ppb)	98.0	463	33.8	20.0	24.5
% reduction	**55**	**62**	**64**	**56**	**47**

Table 4-4 **39-yr average annual PO_4 load at the 5 index stations for the original TMDL “existing conditions” (1990s) baseline and TMDL-e scenarios and the percent reduction of 39-yr average annual PO_4 load at the 5 index stations for TMDL-e compared to the “existing conditions” baseline [a]**

	Above Stephenville	**Below Stephenville**	**Above Meridian**	**Clifton**	**Valley Mills**
Existing conditions (kg/yr)	4,061	10,068	22,117	26,990	28,832
TMDL-e (kg/yr)	1,556	4,173	10,479	15,498	17,625
% reduction	**62**	**59**	**53**	**43**	**39**

[a] From TCEQ (2001)

Table 4-5 **39-yr average annual PO_4 load at the 5 index stations for the TMDL reassessment 1990s baseline and Scenario 1 scenarios and the percent reduction of 39-yr average annual PO_4 load at the 5 index stations for Scenario 1 compared to the 1990s baseline**

	Above Stephenville	**Below Stephenville**	**Above Meridian**	**Clifton**	**Valley Mills**
1990s baseline (kg/yr)	5,340	13,707	38,880	41,713	44,549
Scenario 1 (kg/yr)	2,741	6,252	17,504	21,521	24,524
% reduction	**49**	**54**	**55**	**48**	**45**

Table 4-6 Percent contributions from different land uses to the total PO_4 loadings from the original TMDL (Orig)[a] and the reassessed TMDL (Reas)[b]

	Above Stephenville		Below Stephenville		Above Meridian		At Clifton		At Valley Mills	
Source	Orig	Reas	Orig	Reas	Orig	Reas	Orig	Reas	Orig	Reas
Urban	2%	0.6%	6%	1.2%	6%	0.8%	6%	1.3%	6%	1.3%
Crop	2%	0.1%	2%	0.1%	4%	0.2%	5%	0.3%	6%	0.4%
Pasture	9%	41%	5%	27%	7%	23%	8%	24%	9%	25%
Wood/Range	7%	7%	5%	4%	18%	12%	22%	14%	24%	14%
WWTP	0%	0%	28%	35%	10%	11%	9%	10%	10%	11%
WAF	80%	52%	54%	33%	55%	55%	50%	49%	45%	46%

[a] Export coefficients derived from for the period of November 1995 through March 1998 using water quality analysis (net loadings) and land use information (McFarland and Hauck, 1999) not simulated model output.

[b] Based on the 39-year simulated average contributions of land uses (gross loadings) from the reassessed TMDL 1990s baseline simulation.

Table 4-7 Percent reduction of PO_4 load at the 5 index stations for Scenario 1 compared to the 1990s baseline for the land-use and WWTP (gross) loadings and the instream (net) loadings.

Loadings	**Above Stephenville** %	**Below Stephenville** %	**Above Meridian** %	**Clifton** %	**Valley Mills** %
Gross	48	53	53	48	45
Net	49	54	55	48	45

Table 4-8 Nutrient application rates on WAFs by the Microgy Corporation at its natural gas production facility (application rates based on Microgy permit application)

	Application Rate in Microgy Permit Application		Crop P removal
Landuse	N [a] (kg/ha/yr)	P [a] (kg/ha/yr)	P [b] (kg/ha/yr)
Coastal/small grain	874	90	49
Coastal	714	74	36
Sorghum/small grain	533	55	40
Range	115	12	12

[a] Amount of nutrient which will be applied to the respective crop types each year based on discharge rates and nutrient content of Microgy effluent reported in the Microgy permit application

[b] Amount of P which will be applied to each of the respective crop types with the control practice utilized in TMDL allocation Scenario C that removes some P from the Microgy effluent in order to create a balanced fertilizer

Table 4-9 Number of head in freestall vs. open lot and the number of flush vs. vacuum manure collection systems in the NBR

Total Number of Head Requested in Permit Application	# Head in Open Lot	# Head in Freestall	Type Freestall (Vacuum or Flush)
2800	800	2000	flush
2,200	0	2,200	flush
1,830	630	1,200	flush
999	774	225	flush
990	0	990	flush
990	0	990	flush
1525	1075	450	flush
1499	399	1100	flush
1600	900	700	flush
3000	3000	0	NA
1838	1838	0	NA
500	500	0	NA
1570	1570	0	NA
450	450	0	NA
700	700	0	NA
1500	1500	0	NA
750	750	0	NA
999	999	0	NA
1800	1800	0	NA
2300	2300	0	NA
999	0	999	scraped[a]
990	190	800	vacuum
3,000	100	2,900	vacuum
2,950	1,150	1,800	vacuum
3,000	500	2500	vacuum
990	0	990	vacuum
990	0	990	vacuum
999	0	999	vacuum
990	0	990	vacuum
3,600	3,000	600	vacuum

[a] Scraped was treated as vacuumed

Table 4-10 Fertility recommendations for modeling of crops grown in the North Bosque River watershed for the future TMDL scenarios (source: http://www.tx.nrcs.usda.gov/ the s-crop 2007 document)

Crop	Nutrient Recommendations		
	N agronomic[a] (kg N/ha/yr)	P agronomic[b] (kg P/ha/yr)	P crop removal [c] (kg P/ha/yr)
Coastal bermudagrass	336	61	36
Winter wheat	179	51	12
Sorghum or sudan	179	27	27
Bermudagrass overseeded with winter wheat[d]	515	112	48
Sorghum or sudan double-cropped with winter wheat	358	78	39
Alfalfa	336	39	20
Corn	280	64	37
Range	45	27	12
Peanut	56	34	5

[a] Application rate used for the baseline simulations, for non-WAFs and for TMDL allocation simulations when the 1990s FOTG 590 practice standards are used and STP is less than 200 ppm on WAFs (see Section 4.2.2)

[b] Application rate used for TMDL allocation simulations when the 1990s FOTG 590 practice standards are used and STP is between 42 and 200 ppm on WAFs (see Section 4.2.2), and 2 times this rate when the STP level is less than 200 ppm on WAFs for the future TMDL allocation scenarios when the new FOTG 590 standards are used (see Section 4.3.2).

[c] Application rate used to determine application rates on WAFs for the future TMDL allocation scenarios when the new FOTG 590 standards are used and STP is above 200 ppm (see section 4.3.2).

[d] In actual practice the nutrient recommendations for bermudagrass overseeded with winter wheat are not strictly additive due to the competitive nature of the two crops. However, SWAT currently cannot simulate two crops at once, but simulates the bermudagrass and winter wheat as two separate crops (one without the other).

Table 4-11 Filter strip removal efficiencies for SWAT-TCEQ as determined by APEX simulations

	OrgN	NO_3	OrgP	PO_4	Sediment
Percent removal	39.3	7.7	38.8	14.1	77.5

Table 4-12 Calculation of average P index for WAFs in the NBR watershed

Parameter	Value	Index points[a]
Soil Test P	very high	8
P fertilizer	none	0
OrgP fertilizer	avg. 94 lbs P_2O_5	3
P fertilization method	none	0
OrgP fertilization method	mixture of all – avg.	2
Proximity to stream	avg. 500-900 ft	2.5
Runoff class	avg. slope 3.6; avg. CN2 75	2.5
Soil erosion	avg. 1 to 3 tons/ac	1.5
	TOTAL	19.5 = medium

[a] From NRCS (2000b)

Table 4-13 Summary of future reassessment scenarios and the control practices for each

Control Practice	Scenario						
	A	B	C	D	E	F	G
Filter strip	X	X	X	X	X	X	X
WWTP 1.0 ppm P discharge	X	X	X	X	X		
New lagoon	X	X	X	X	X	X	X
50% manure haul-off	X	X	X	X			
NRCS 590 guidance	X	X	X	X	X	X	X
New Reservoirs		X	X	X	X	X	X
Microgy remediation			X	X	X	X	X
HWAF remediation				X	X	X	X
75% manure haul-off					X	X	X
WWTP 0.5 ppm P discharge						X	X
Reduced grazing							X

Table 4-14 39-yr annual daily-average PO_4 concentration at the 5 index stations for the original TMDL "existing conditions" (1990s) baseline and TMDL-f scenarios and the percent reduction of 39-yr annual daily-average PO_4 concentration at the 5 index stations for TMDL-f compared to the "existing conditions" baseline

	Above Stephenville	Below Stephenville	Above Meridian	Clifton	Valley Mills
Existing conditions (ppb)	203	1,143	117	52.2	41.3
TMDL-f (ppb)	130	513	87.3	47.5	40.0
% reduction	**36**	**55**	**25**	**9**	**3**

Table 4-15 39-yr annual daily-average PO_4 concentration at the 5 index stations for the TMDL reassessment 1990s baseline and Scenario A scenarios and the percent reduction of 39-yr annual daily-average PO_4 concentration at the 5 index stations for Scenario A compared to the 1990s baseline

	Above Stephenville	Below Stephenville	Above Meridian	Clifton	Valley Mills
1990s baseline (ppb)	216	1,227	93.1	45.0	45.3
Scenario A (ppb)	164	582	60.9	40.0	44.8
% reduction	**24**	**53**	**35**	**11**	**1**

Table 4-16 39-yr average annual PO_4 load at the 5 index stations for the original TMDL "existing conditions" (1990s) baseline and TMDL-f scenarios and the percent reduction of 39-yr average annual PO_4 load at the 5 index stations for TMDL-f compared to the "existing conditions" baseline

	Above Stephenville	Below Stephenville	Above Meridian	Clifton	Valley Mills
Existing conditions (kg/yr)	4,061	10,068	22,117	26,990	28,832
TMDL-f (kg/yr)	1,978	6,329	13,700	19,263	21,384
% reduction	**51**	**37**	**38**	**29**	**26**

Table 4-17 **39-yr average annual PO_4 load at the 5 index stations for the TMDL reassessment 1990s baseline and Scenario A scenarios and the percent reduction of 39-yr average annual PO_4 load at the 5 index stations for Scenario A compared to the 1990s baseline**

	Above Stephenville	**Below Stephenville**	**Above Meridian**	**Clifton**	**Valley Mills**
1990s baseline (kg/yr)	5,340	13,707	38,880	41,713	44,549
Scenario A (kg/yr)	4,653	10,102	27,523	32,364	36,201
% reduction	**13**	**26**	**29**	**22**	**19**

Table 4-18 **39-yr annual daily-average PO_4 concentration at the five index stations for the 1990s and the future fully-permitted baseline and each TMDL allocation scenario**

Scenario	**Above Stephenville** (ppb)	**Below Stephenville** (ppb)	**Above Meridian** (ppb)	**Clifton** (ppb)	**Valley Mills** (ppb)
Full baseline	275.3	1,407.8	149.2	64.6	76.8
90s baseline	215.5	1,226.8	93.1	45.0	45.3
Scenario A	164.1	582.2	60.9	40.0	44.8
Scenario B	164.1	582.2	58.9	38.2	43.1
Scenario C	162.8	581.3	58.9	38.1	43.1
Scenario D	160.1	578.0	57.3	37.2	42.2
Scenario E	139.7	565.2	53.6	35.1	40.0
Scenario F	139.7	326.8	46.8	33.7	32.4
Scenario G	135.0	323.3	44.8	32.2	31.0

Table 4-19 **Percent reduction from 1990s baseline for reassessment scenarios of future conditions using 39-yr annual daily-average PO_4 concentrations**

Scenario	**Above Stephenville** (%)	**Below Stephenville** (%)	**Above Meridian** (%)	**Clifton** (%)	**Valley Mills** (%)
Scenario A	24	53	35	11	1
Scenario B	24	53	37	15	5
Scenario C	24	53	37	15	5
Scenario D	26	53	38	17	7
Scenario E	35	54	42	22	12
Scenario F	35	73	50	25	29
Scenario G	37	74	52	28	32

Table 4-20 Percent reduction from fully-permitted baseline for reassessment scenarios of future conditions using 39-yr annual daily-average PO_4 concentrations

TMDL Scenario	**Above Stephenville** %	**Below Stephenville** %	**Above Meridian** %	**Clifton** %	**Valley Mills** %
Scenario A	40	59	59	38	42
Scenario B	40	59	61	41	44
Scenario C	41	59	61	41	44
Scenario D	42	59	62	42	45
Scenario E	49	60	64	46	48
Scenario F	49	77	69	48	58
Scenario G	51	77	70	50	60

Table 4-21 39-yr annual-average total PO_4 load at the five index stations for the 1990s and the future fully-permitted baseline and each TMDL allocation scenario

TMDL Scenario	**Above Stephenville** (kgs)	**Below Stephenville** (kgs)	**Above Meridian** (kgs)	**Clifton** (kgs)	**Valley Mills** (kgs)
Future baseline	7,054	19,457	42,851	46,280	50,505
90s base	5,340	13,707	38,880	41,713	44,549
Scenario A	4,653	10,102	27,523	32,364	36,201
Scenario B	4,653	10,102	25,391	30,198	34,033
Scenario C	4,629	10,082	25,372	30,180	34,016
Scenario D	4,502	9,889	24,603	29,432	33,275
Scenario E	4,075	9,404	22,940	27,729	31,147
Scenario F	4,075	7,355	22,391	27,304	30,441
Scenario G	3,935	7,193	21,384	26,023	28,977

Table 4-22 Percent reduction from 1990s baseline for reassessment scenarios of future conditions using 39-yr annual daily-average PO_4 loads

TMDL Scenario	**Above Stephenville** %	**Below Stephenville** %	**Above Meridian** %	**Clifton** %	**Valley Mills** %
Scenario A	13	26	29	22	19
Scenario B	13	26	35	28	24
Scenario C	13	26	35	28	24
Scenario D	16	28	37	29	25
Scenario E	24	31	41	34	30
Scenario F	24	46	42	35	32
Scenario G	26	48	45	38	35

Table 4-23 Percent reduction from future fully-permitted baseline for reassessment scenarios of future conditions using 39-yr annual daily-average PO_4 loads

TMDL Scenario	**Above Stephenville** %	**Below Stephenville** %	**Above Meridian** %	**Clifton** %	**Valley Mills** %
Scenario A	34	48	36	30	28
Scenario B	34	48	41	35	33
Scenario C	34	48	41	35	33
Scenario D	36	49	43	36	34
Scenario E	42	52	46	40	38
Scenario F	42	62	48	41	40
Scenario G	44	63	50	44	43

Table 4-24 39-yr annual daily-average PO_4 concentration at the four additional sites for the 1990s and future fully-permitted baseline and each TMDL allocation scenario.

TMDL Scenario	**NF020** (ppb)	**NBR@SH6** (ppb)	**GC100** (ppb)	**Duffau Creek** (ppb)
Full baseline	606.8	859.5	237.1	101.7
98 baseline	390.3	548.5	179.6	84.7
Scenario A	441.7	269.5	134.3	77.1
Scenario B	441.7	269.5	134.3	67.5
Scenario C	394.9	269.2	134.3	67.5
Scenario D	394.9	265.5	131.2	65.7
Scenario E	301.6	254.0	123.0	59.2
Scenario F	301.6	132.2	123.0	59.2
Scenario G	288.9	129.0	118.1	57.4

Table 4-25 39-yr annual daily-average PO_4 concentration at the four additional sites - percent reduction from 1990s baseline

TMDL Scenario	**NF020** %	**NBR@SH6** %	**GC100** %	**Duffau Creek** %
Scenario A	-13	51	25	9
Scenario B	-13	51	25	20
Scenario C	-1	51	25	20
Scenario D	-1	52	27	22
Scenario E	23	54	32	30
Scenario F	23	76	32	30
Scenario G	26	76	34	32

Table 4-26 Percent reduction from future fully-permitted baseline for 39-yr annual daily-average PO_4 concentration at the four additional sites

TMDL Scenario	NF020 %	NBR@SH6 %	GC100 %	Duffau Creek %
Scenario A	27	69	43	24
Scenario B	27	69	43	34
Scenario C	35	69	43	34
Scenario D	35	69	45	35
Scenario E	50	70	48	42
Scenario F	50	85	48	42
Scenario G	52	85	50	44

Table 4-27 39-yr annual average PO_4 load at the four additional sites for the 1990s and future fully-permitted baseline and each TMDL allocation scenario

TMDL Scenario	NF020 (kgs)	NBR@SH6 (kgs)	GC100 (kgs)	Duffau Creek (kgs)
Full baseline	3,214	18,698	11,247	11,378
98 baseline	2,744	15,132	8,760	11,929
Scenario A	2,283	10,442	6,541	8,188
Scenario B	2,283	10,442	6,541	6,631
Scenario C	2,037	10,421	6,541	6,631
Scenario D	2,037	10,122	6,311	6,333
Scenario E	1,478	9,420	5,938	5,646
Scenario F	1,478	8,279	5,938	5,646
Scenario G	1,428	7,193	5,697	5,433

Table 4-28 39-yr annual-average total PO_4 load at the four additional sites - percent reduction from 1990s baseline

TMDL Scenario	NF020 %	NBR@SH6 %	GC100 %	Duffau Creek %
Scenario A	17	31	25	31
Scenario B	17	31	25	44
Scenario C	26	31	25	44
Scenario D	26	33	28	47
Scenario E	46	38	32	53
Scenario F	46	45	32	53
Scenario G	48	52	35	54

Table 4-29 Percent reduction from future fully-permitted baseline for 39-yr annual-average total PO_4 load at the four additional sites

TMDL Scenario	**NF020** %	**NBR@SH6** %	**GC100** %	**Duffau Creek** %
Scenario A	29	44	42	28
Scenario B	29	44	42	42
Scenario C	37	44	42	42
Scenario D	37	46	44	44
Scenario E	54	50	47	50
Scenario F	54	56	47	50
Scenario G	56	62	49	52

SECTION 4

FIGURES

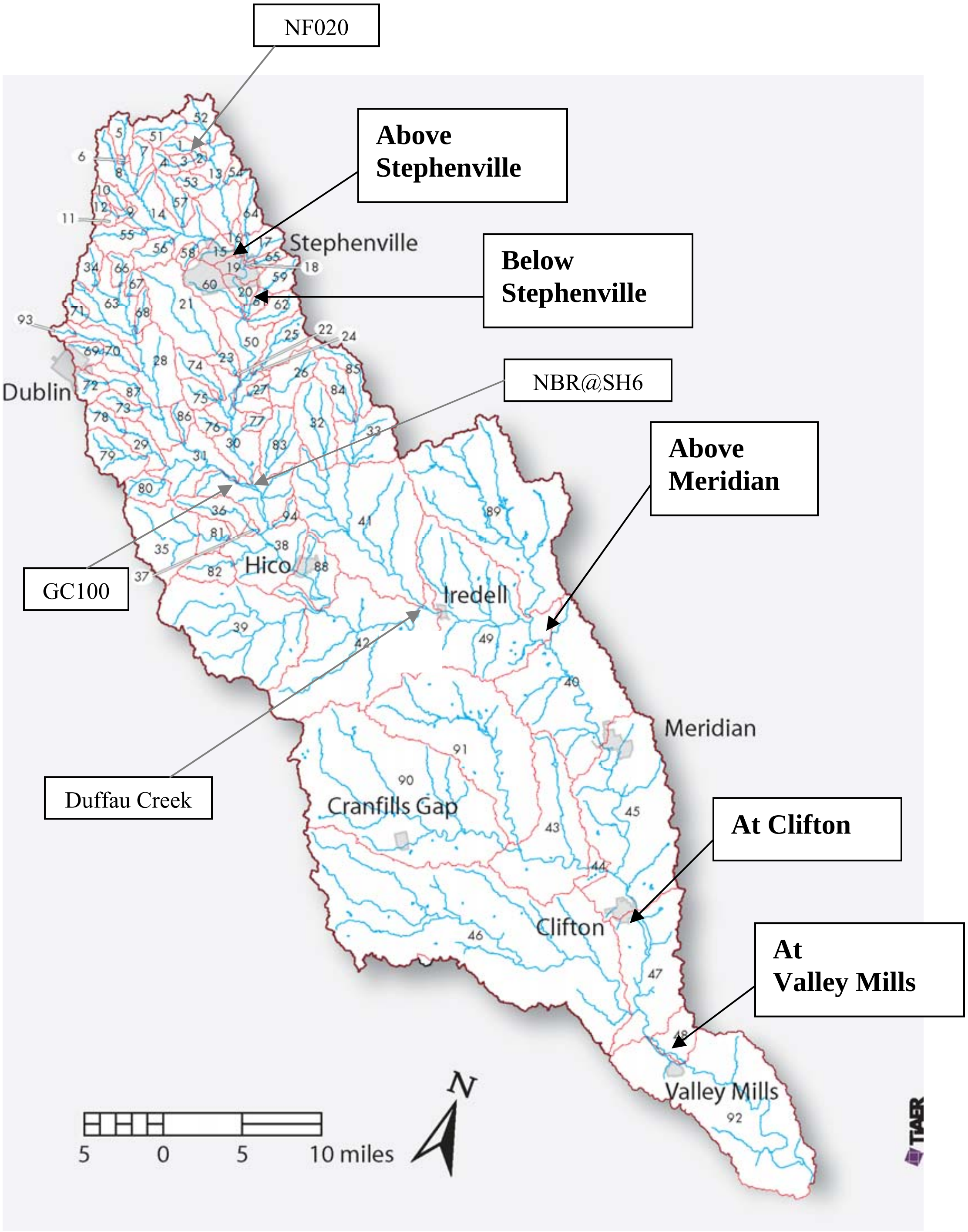
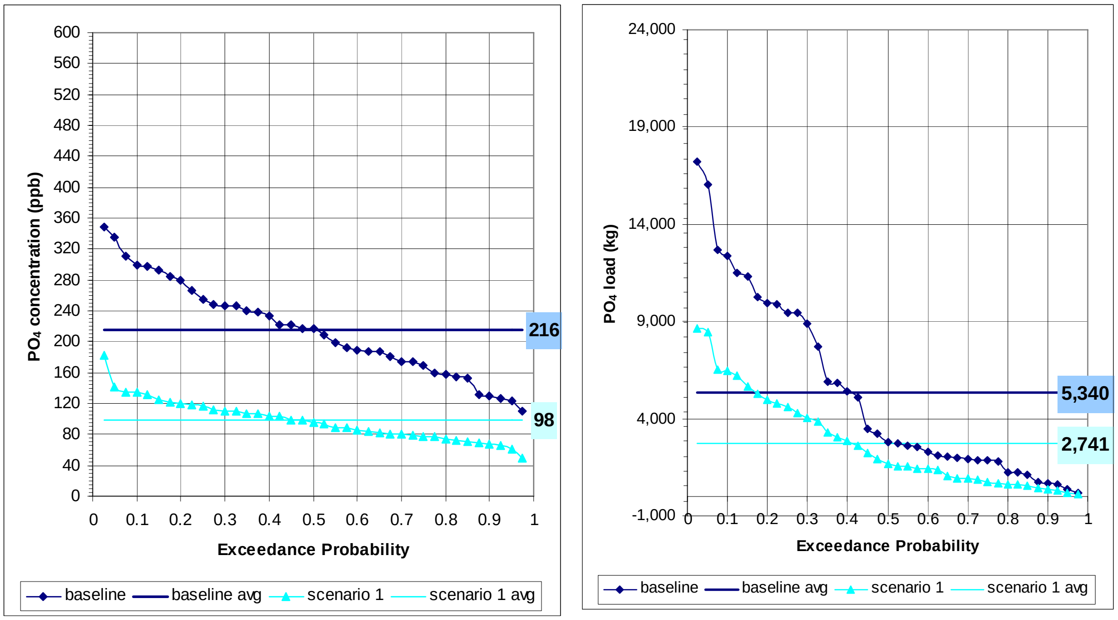
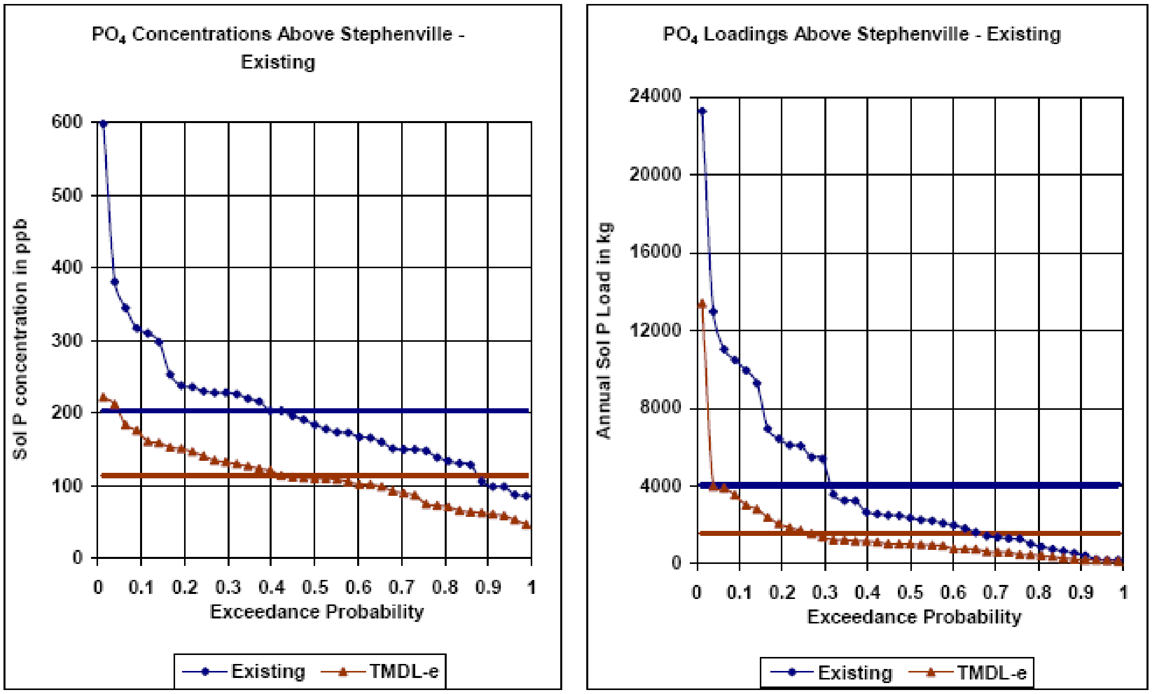


Figure 4-1 **Five index stations and the four additional sites for the TMDL in the NBR**

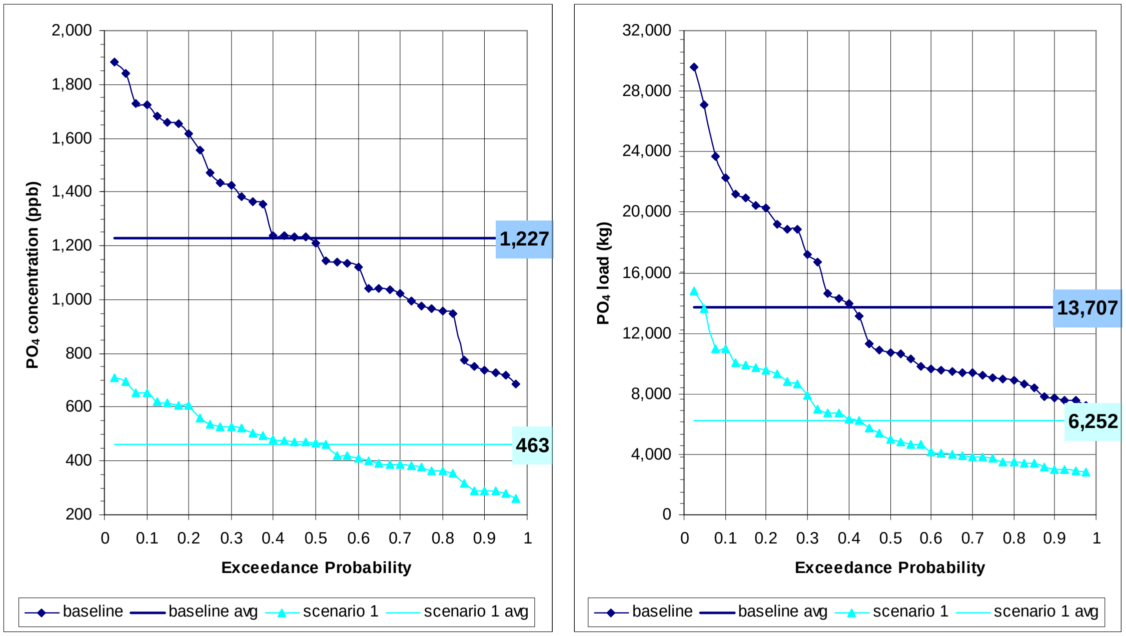


a) Reassessment, 1990s baseline and control practice scenario (Scenario 1)

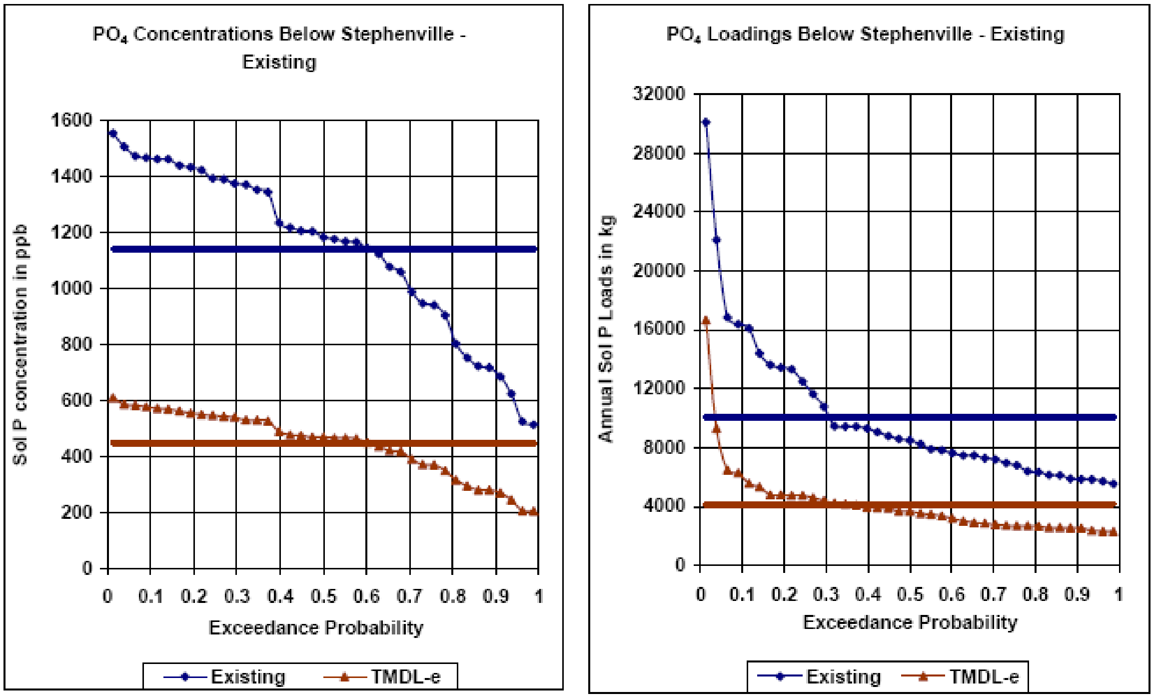


b) Original TMDL, "existing conditions" (1990s) baseline and TMDL-e

Figure 4-2 Comparison of annual daily-average PO_4 (Sol P) concentration and annual PO_4 (Sol P) loadings for NBR above Stephenville

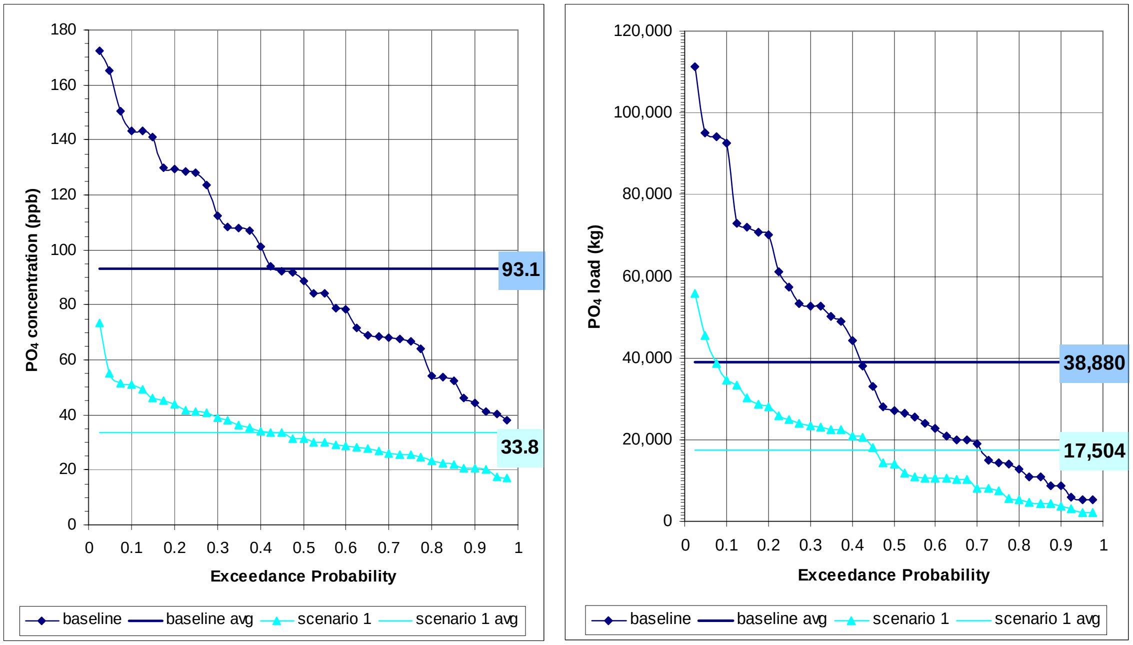


a) Reassessment, 1990s baseline and control practice scenario (Scenario 1)

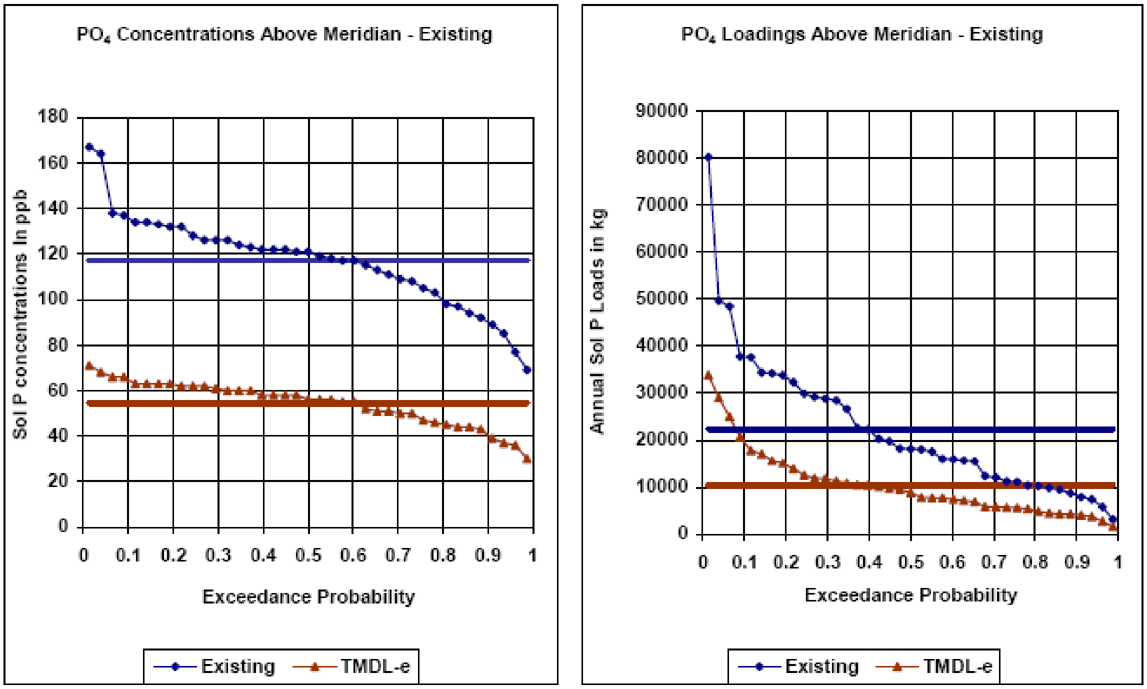


b) Original TMDL, “existing conditions” (1990s) baseline and TMDL-e

Figure 4-3 Comparison of annual daily-average PO_4 (Sol P) concentration and annual PO_4 (Sol P) loadings for NBR below Stephenville

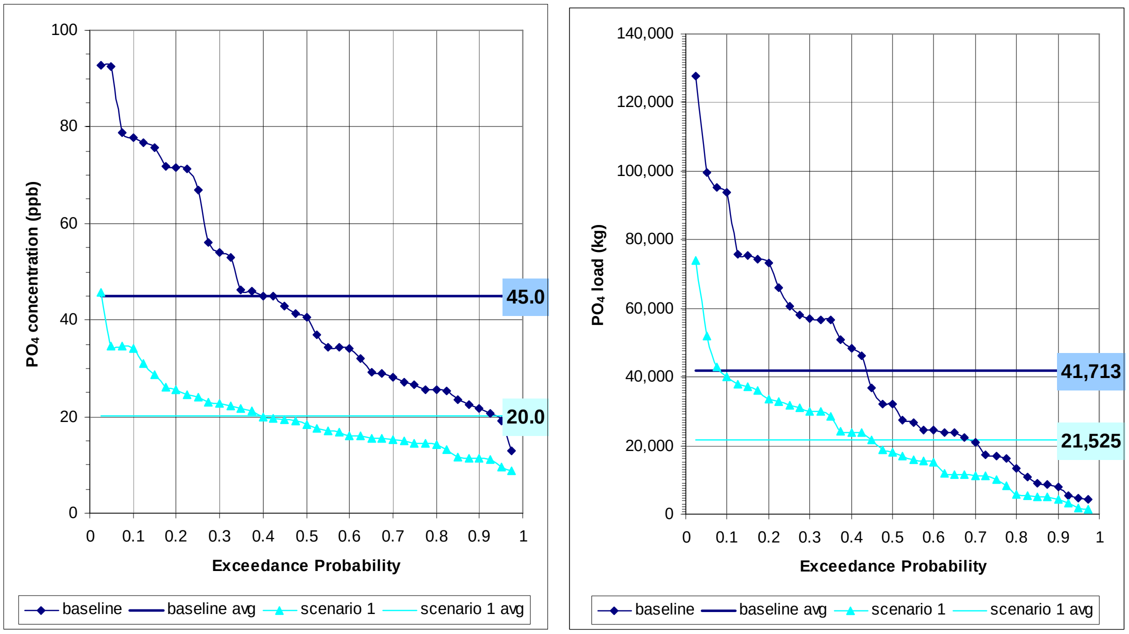


a) Reassessment, 1990s baseline and control practice scenario (Scenario 1)

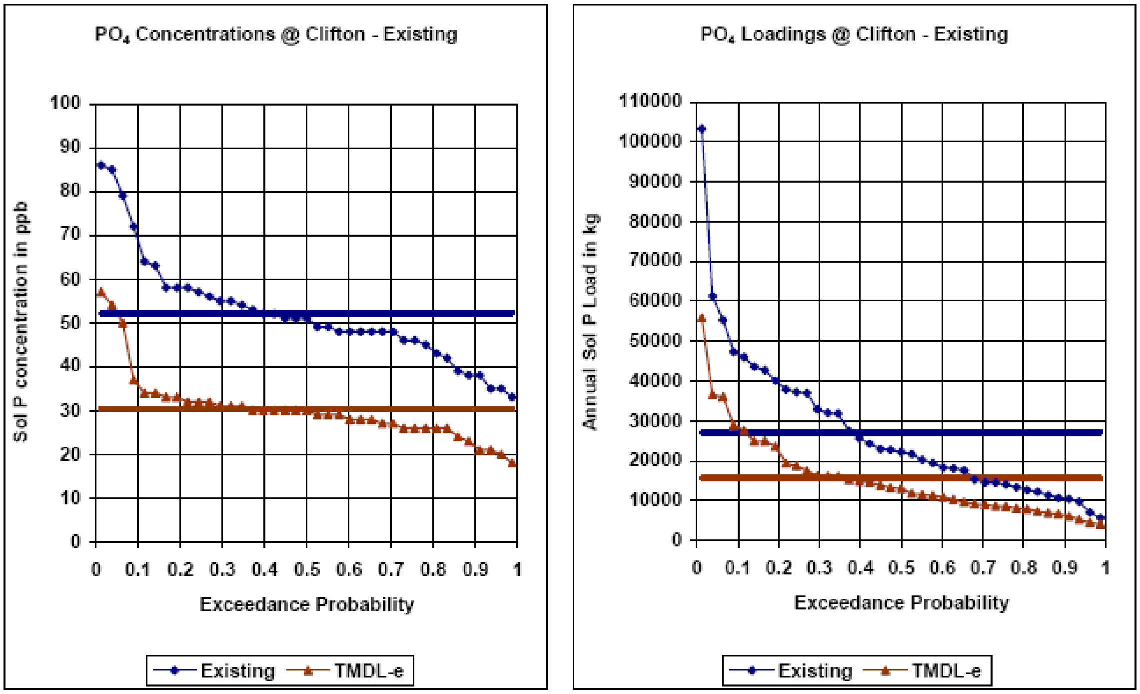


b) Original TMDL, “existing conditions” (1990s) baseline and TMDL-e

Figure 4-4 Comparison of annual daily-average PO_4 (Sol P) concentration and annual PO_4 (Sol P) loadings for NBR above Meridian

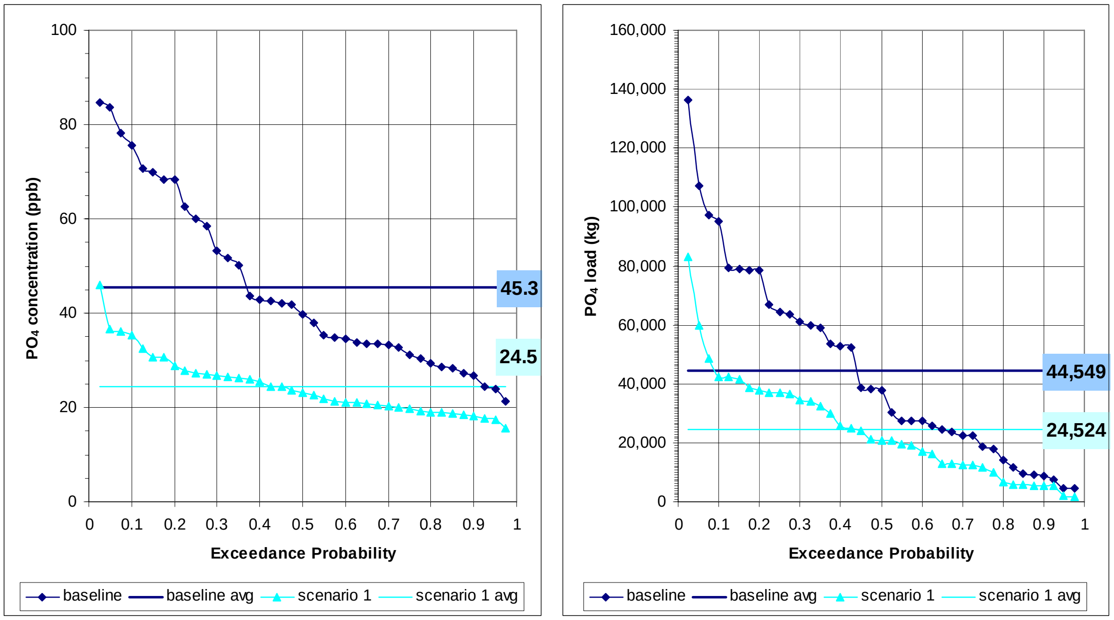


a) Reassessment, 1990s baseline and control practice scenario (Scenario 1)

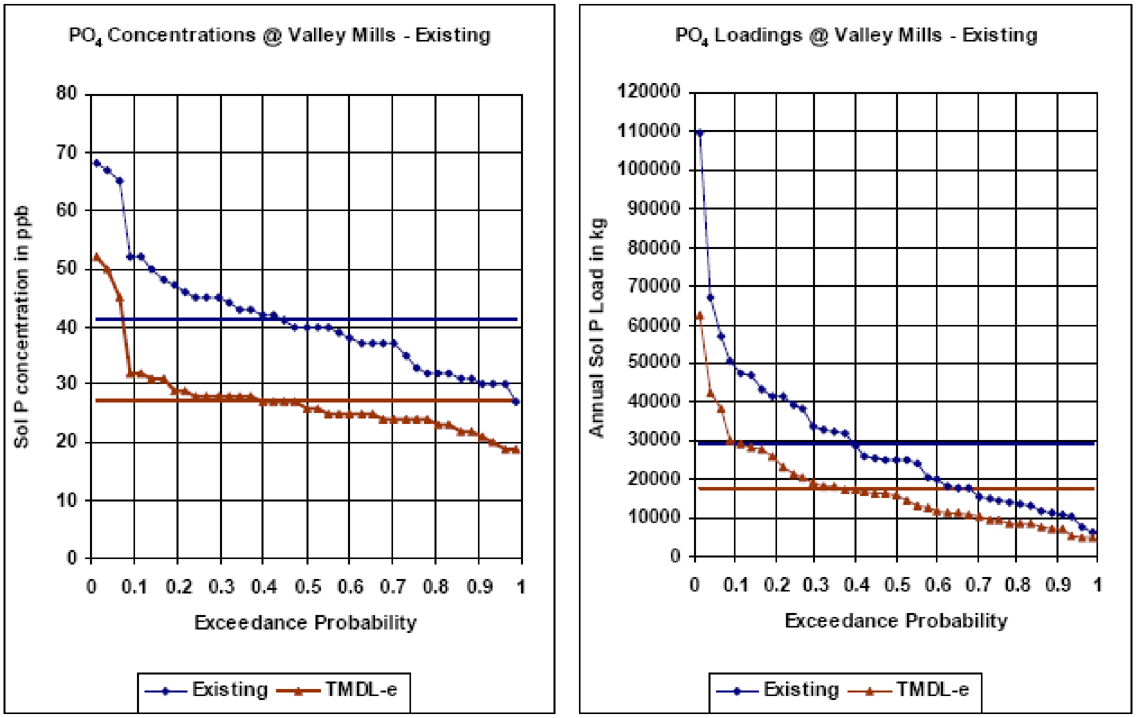


b) Original TMDL, “existing conditions” (1990s) baseline and TMDL-e

Figure 4-5 Comparison of annual daily-average PO_4 (Sol P) concentration and annual PO_4 (Sol P) loadings for NBR at Clifton



a) Reassessment, 1990s baseline and control practice scenario (Scenario 1)



b) Original TMDL, "existing conditions" (1990s) baseline and TMDL-e

Figure 4-6 Comparison of annual daily-average PO_4 (Sol P) concentration and annual PO_4 (Sol P) loadings for NBR at Valley Mills

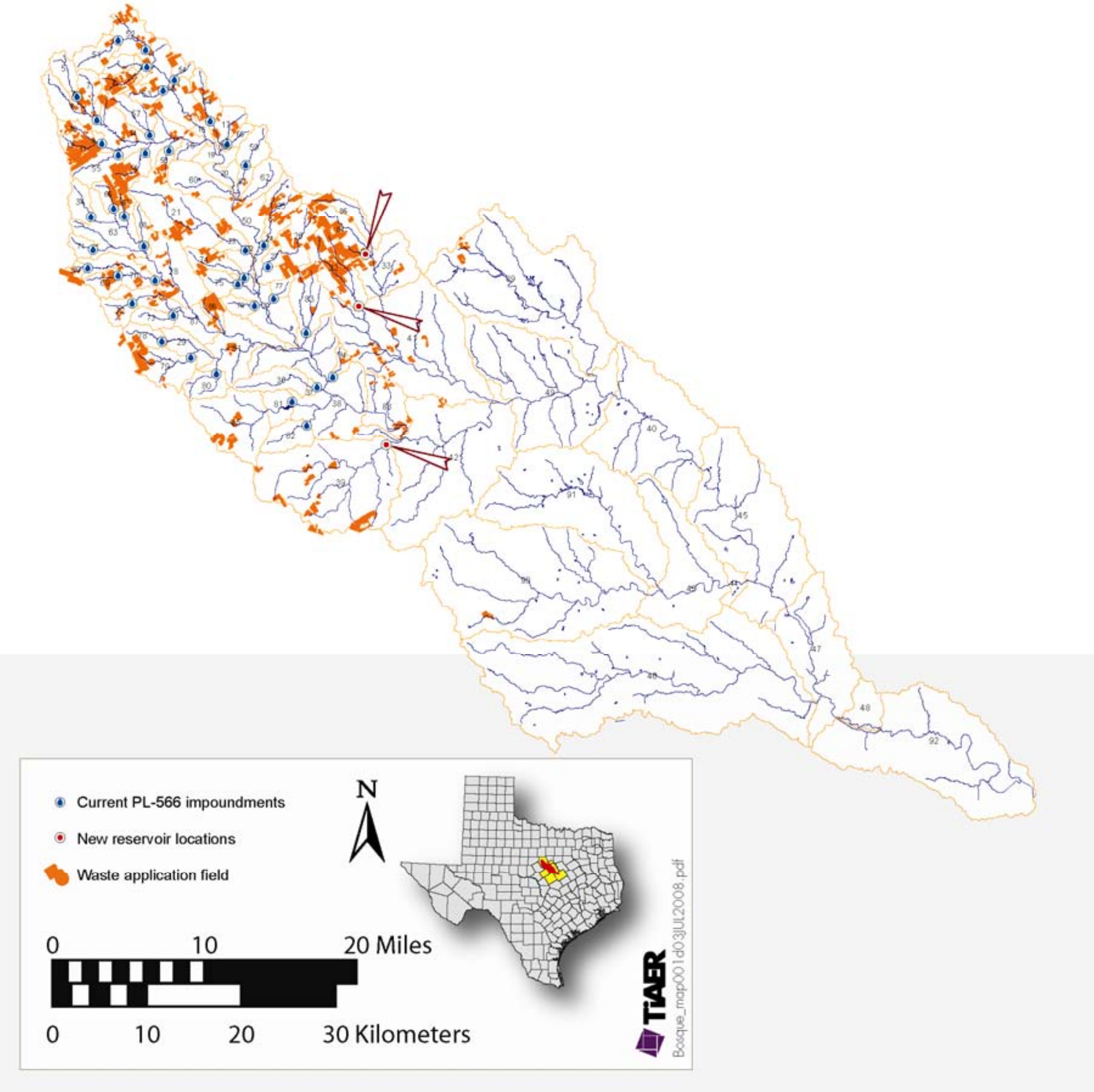


Figure 4-7 Original PL-566 location and new reservoir locations for Scenario B

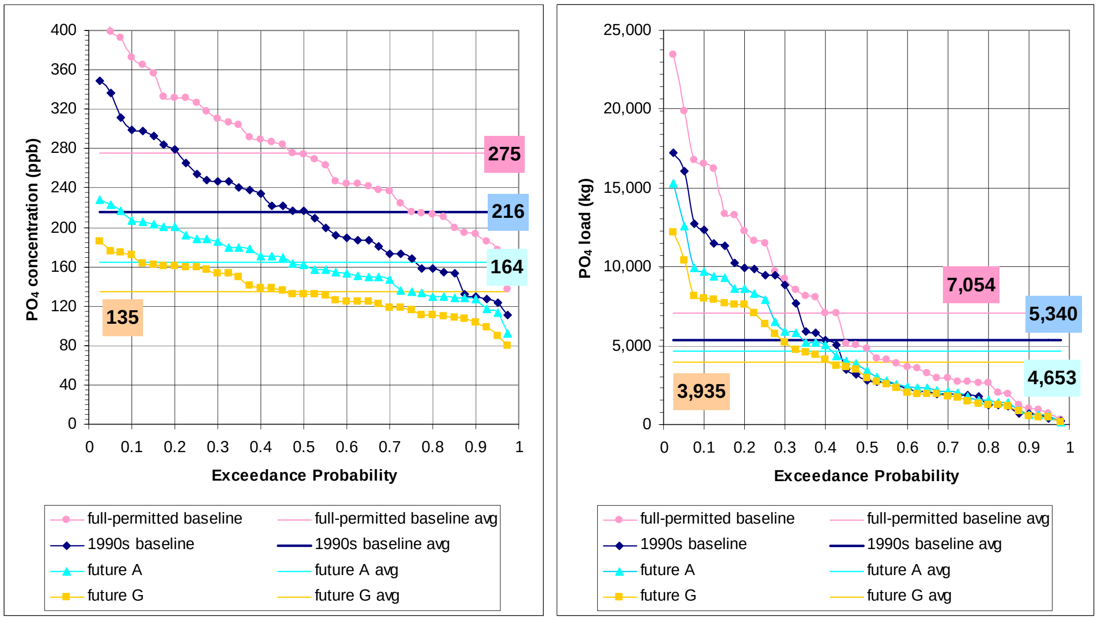


Figure 4-8 **Comparison of annual daily-average PO$_4$ concentration and annual total PO$_4$ loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations for NBR above Stephenville**

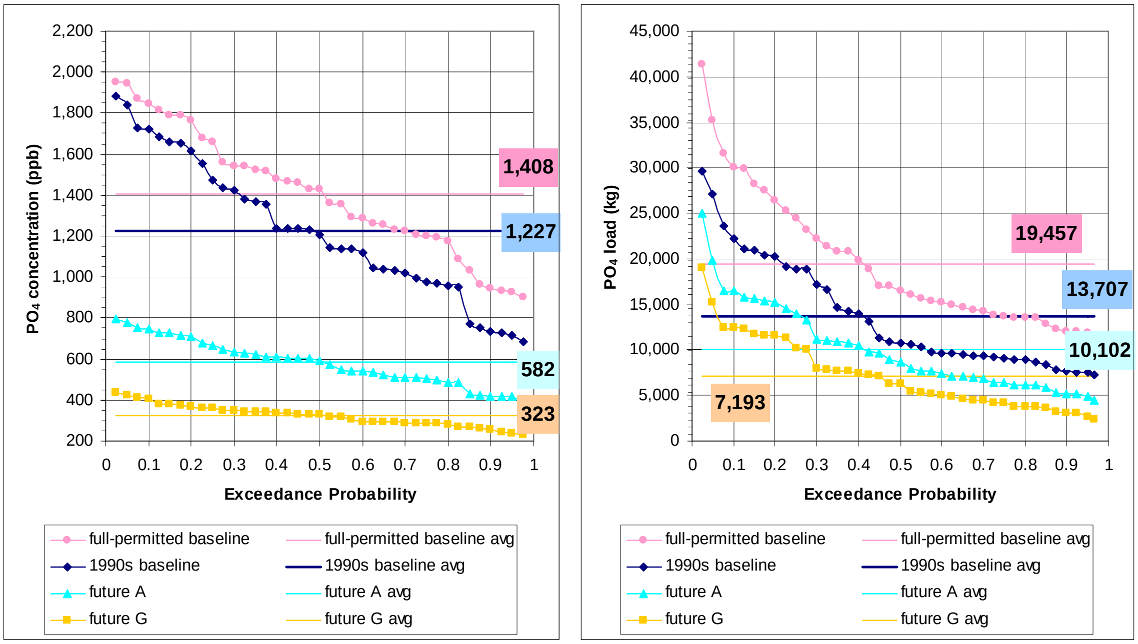


Figure 4-9 **Comparison of annual daily-average PO$_4$ concentration and annual total PO$_4$ loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations for NBR below Stephenville**

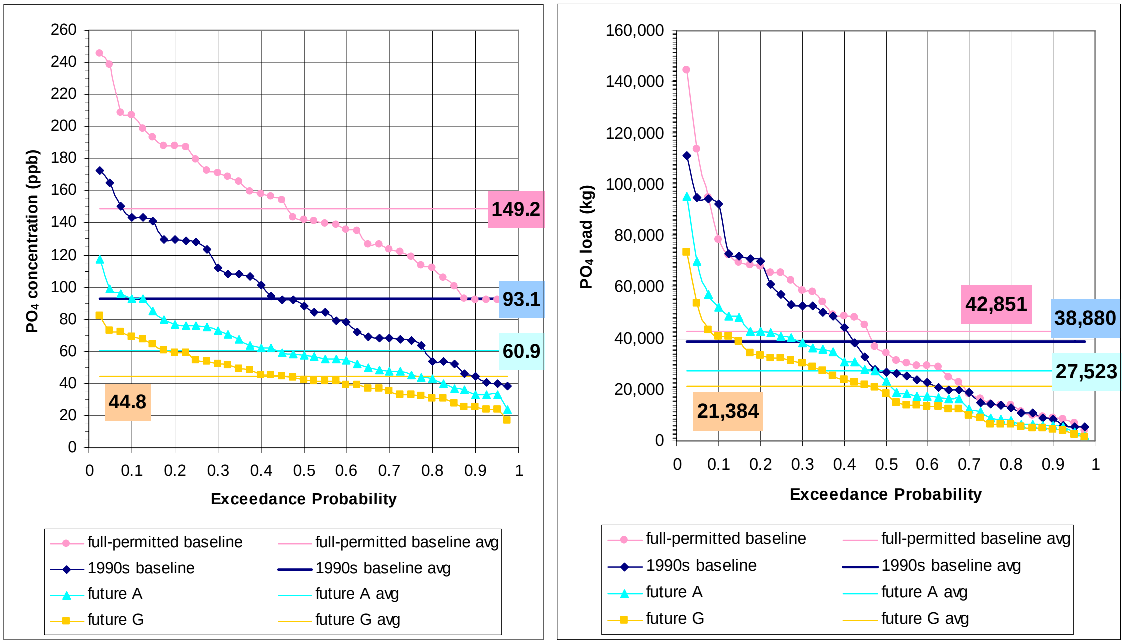


Figure 4-10 **Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the 1990s baseline and future fully-permitted baseline and Scenario A and G simulations for NBR above Meridian**

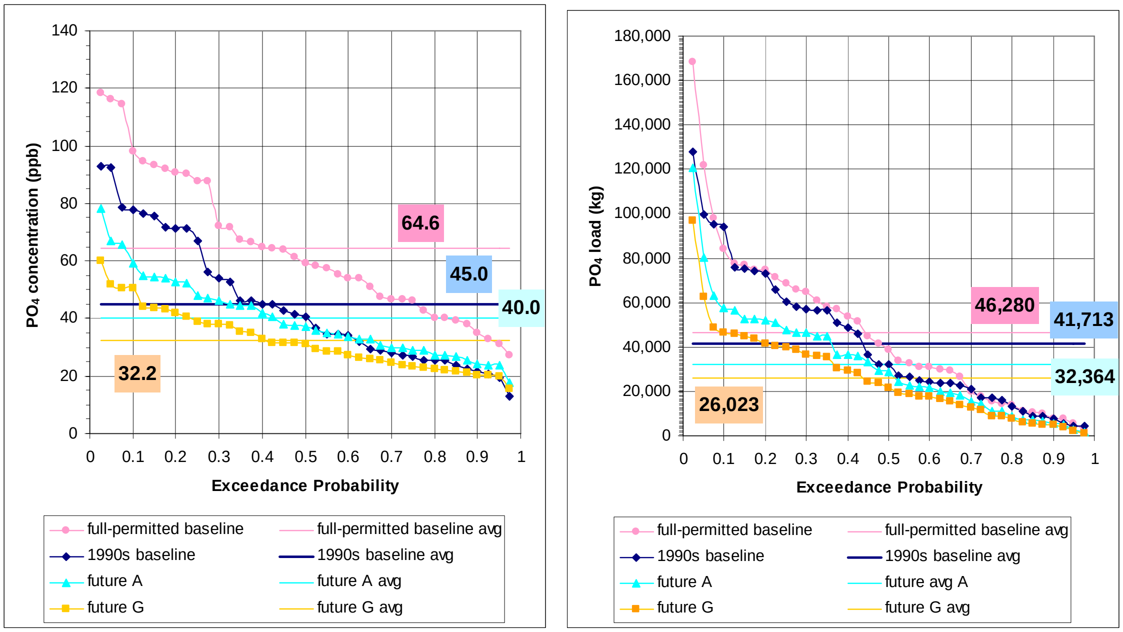


Figure 4-11 **Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations for NBR at Clifton**

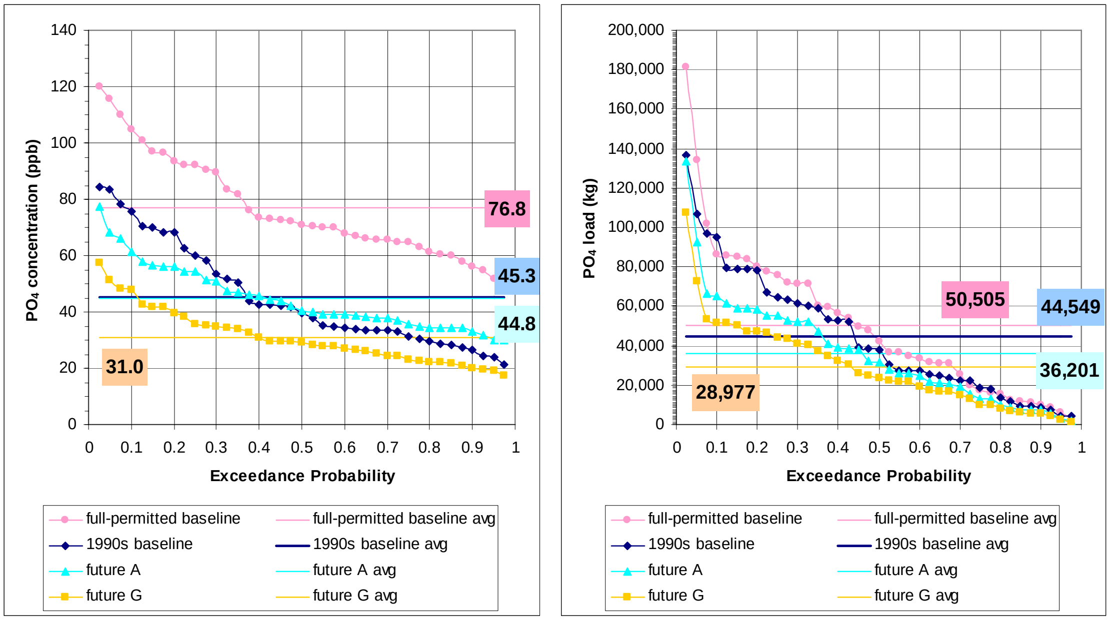
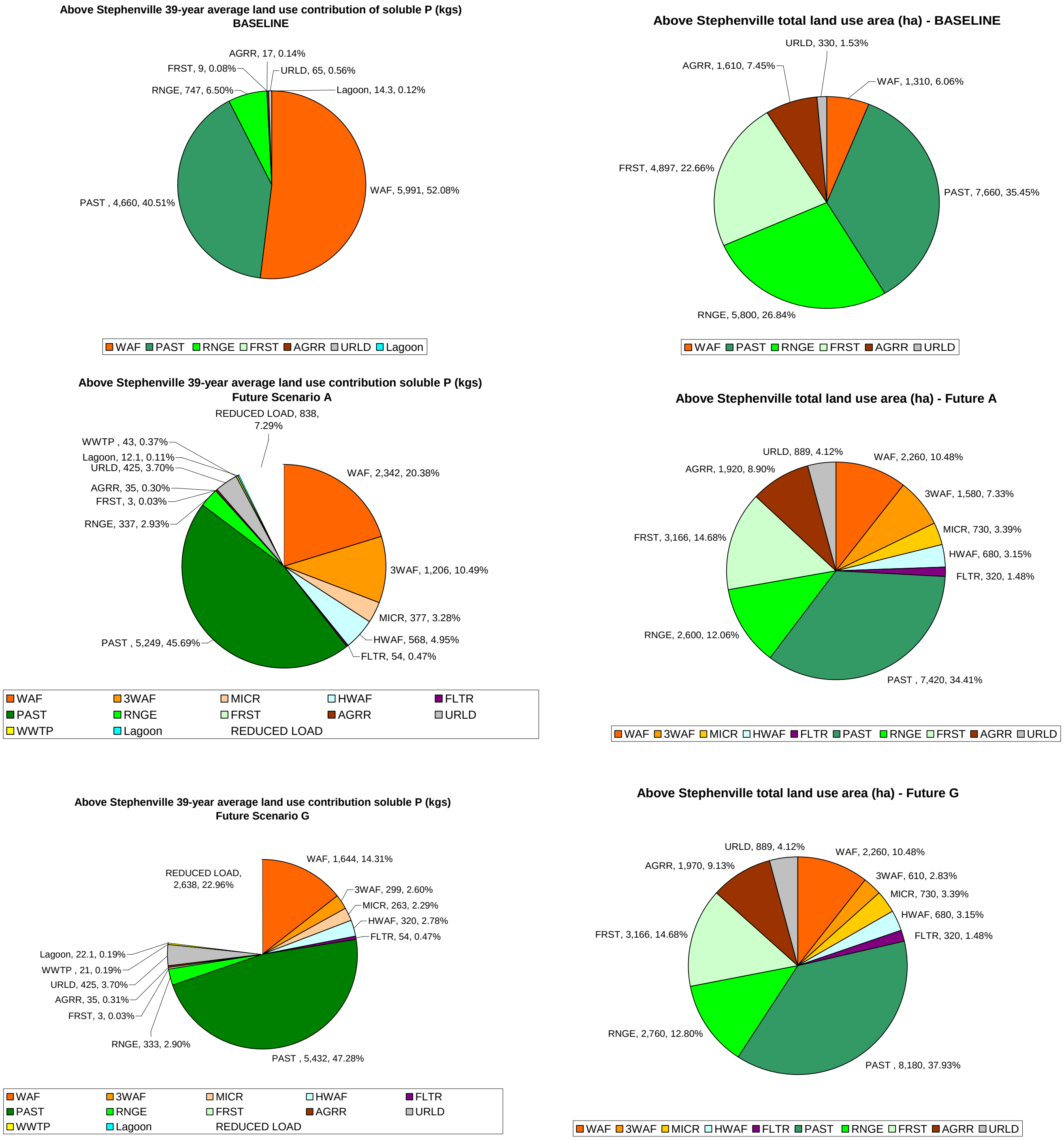


Figure 4-12 **Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations for NBR at Valley Mills**



Total Soluble P (kgs)

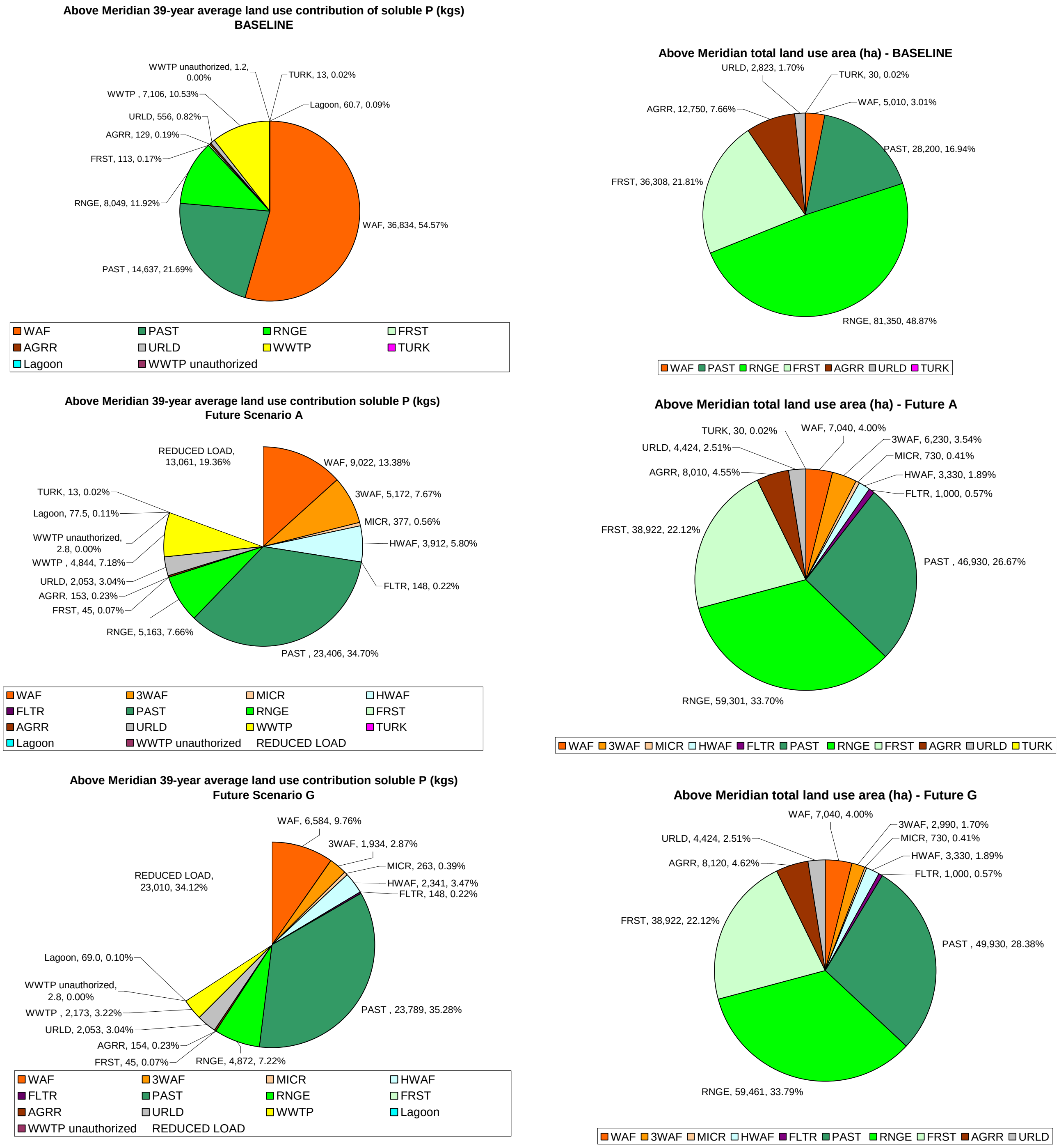
Baseline	FutureA	Reduction	FutureG	Reduction
11,489	10,651	7%	8,851	23%

Figure 4-13 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR above Stephenville

Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
19,433	16,122	17%	12,174	37%

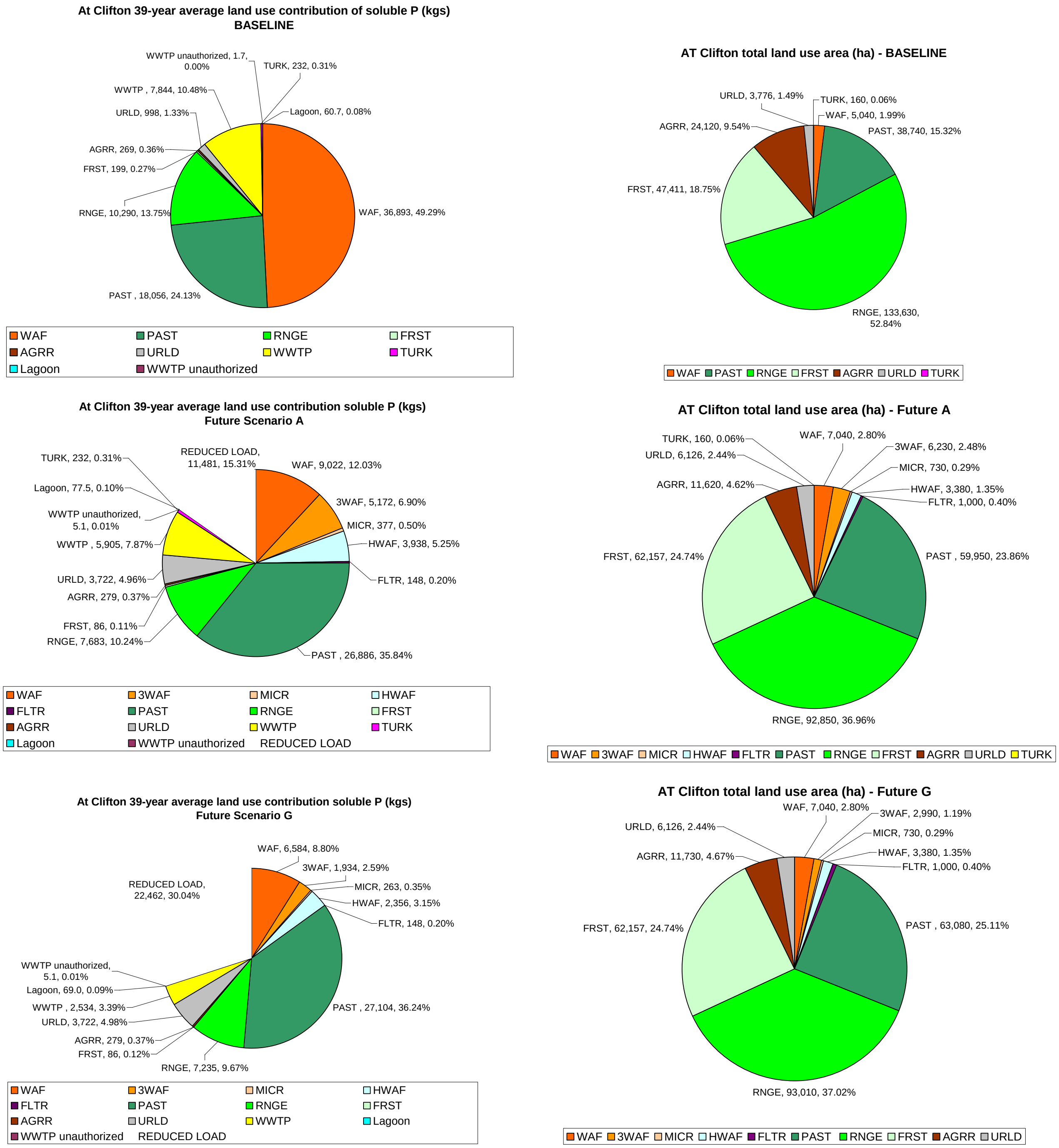
Figure 4-14 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR below Stephenville



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
67,436	54,375	19%	44,426	34%

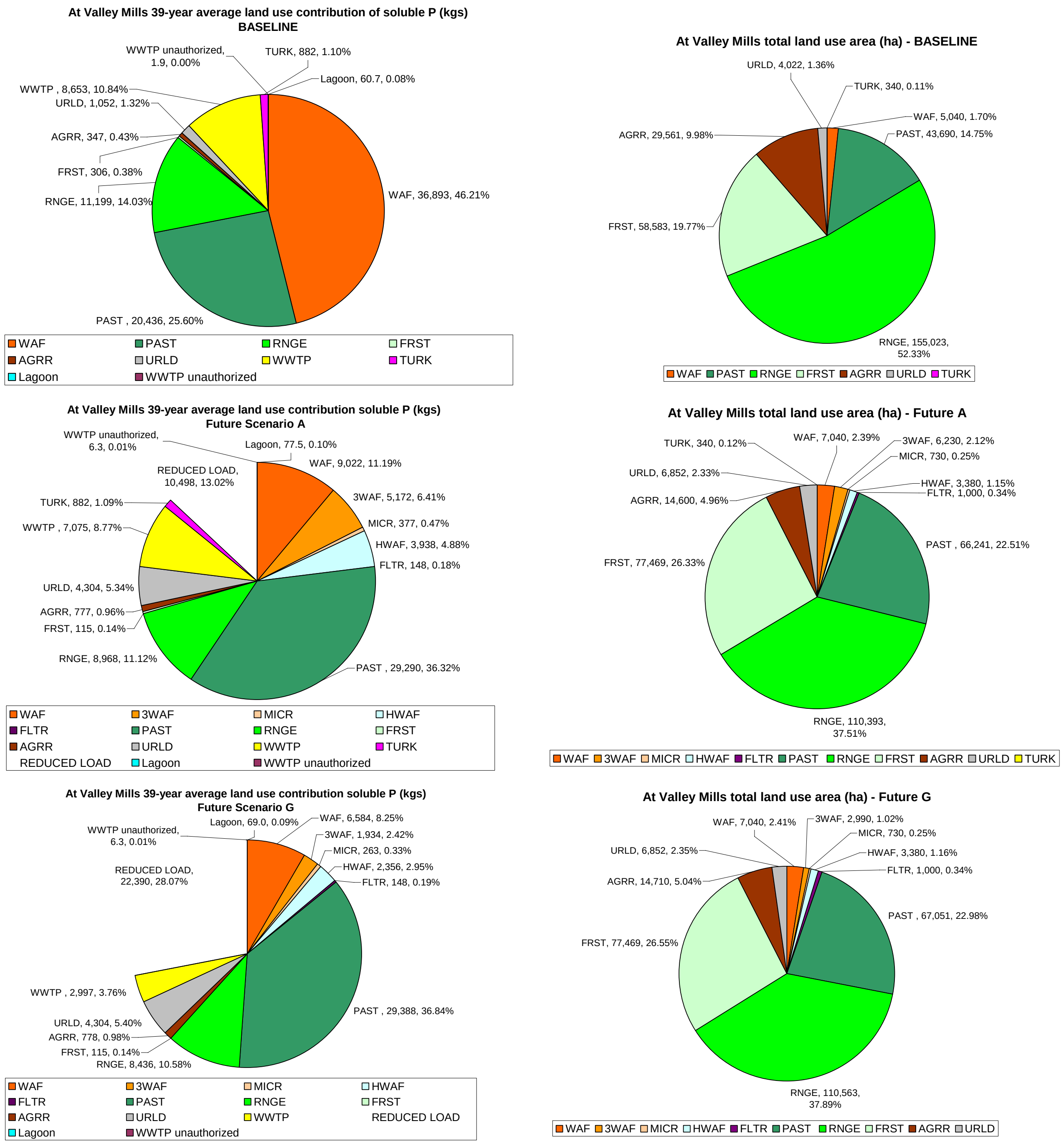
Figure 4-15 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR above Meridian



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
74,781	63,300	15%	52,319	30%

Figure 4-16 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR at Clifton



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
79,768	69,270	13%	57,378	28%

Figure 4-17 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR at Valley Mills

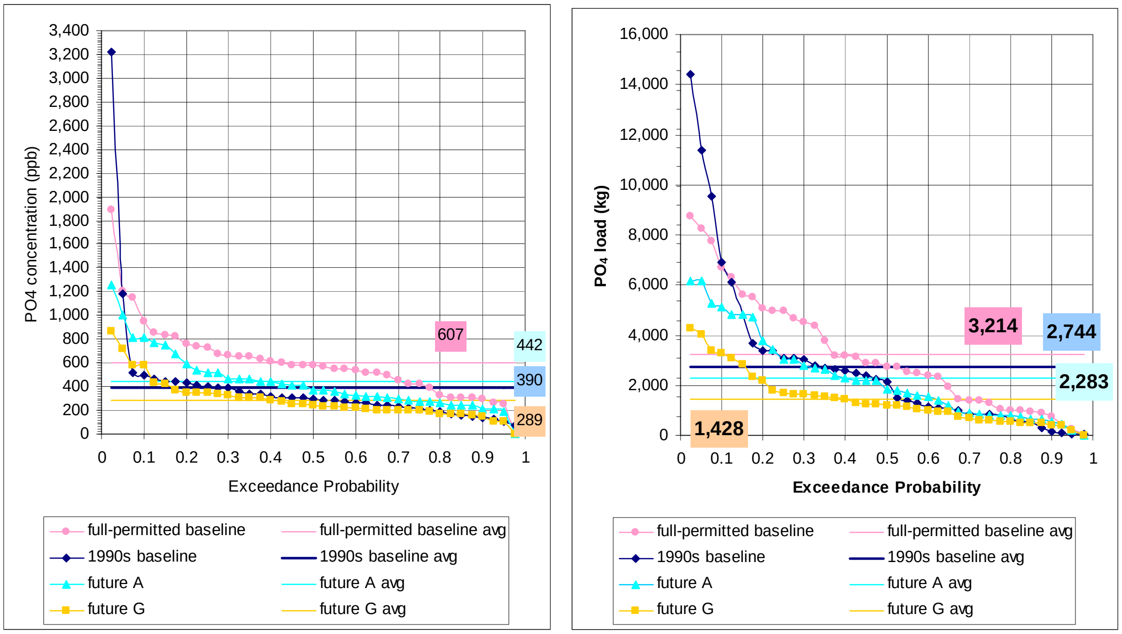


Figure 4-18 **Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations at NF020**

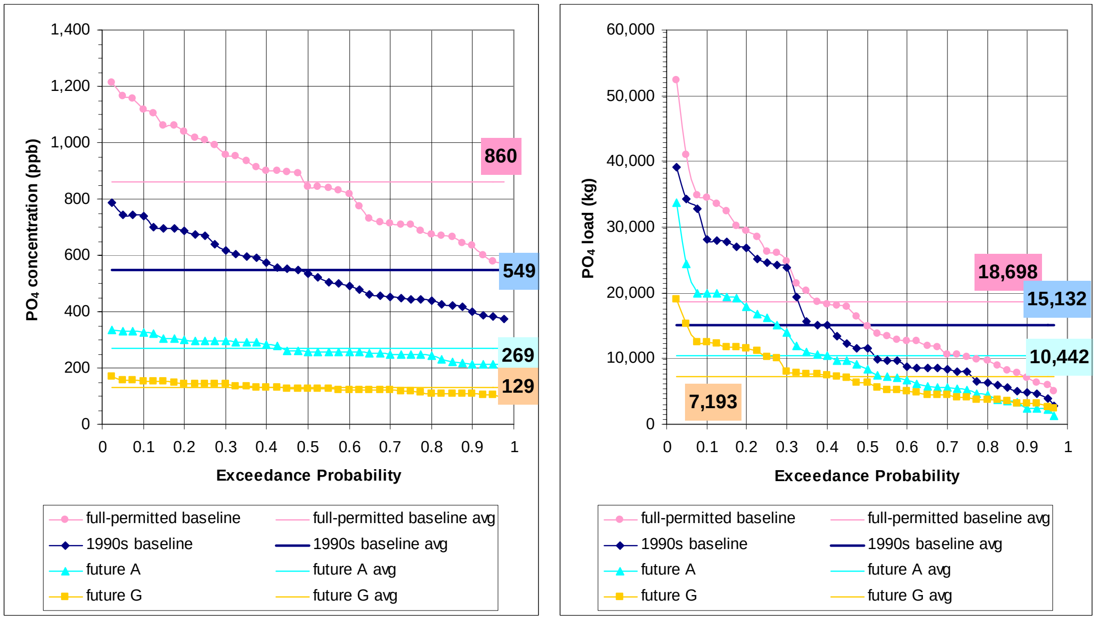


Figure 4-19 **Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations at NBR@SH6**

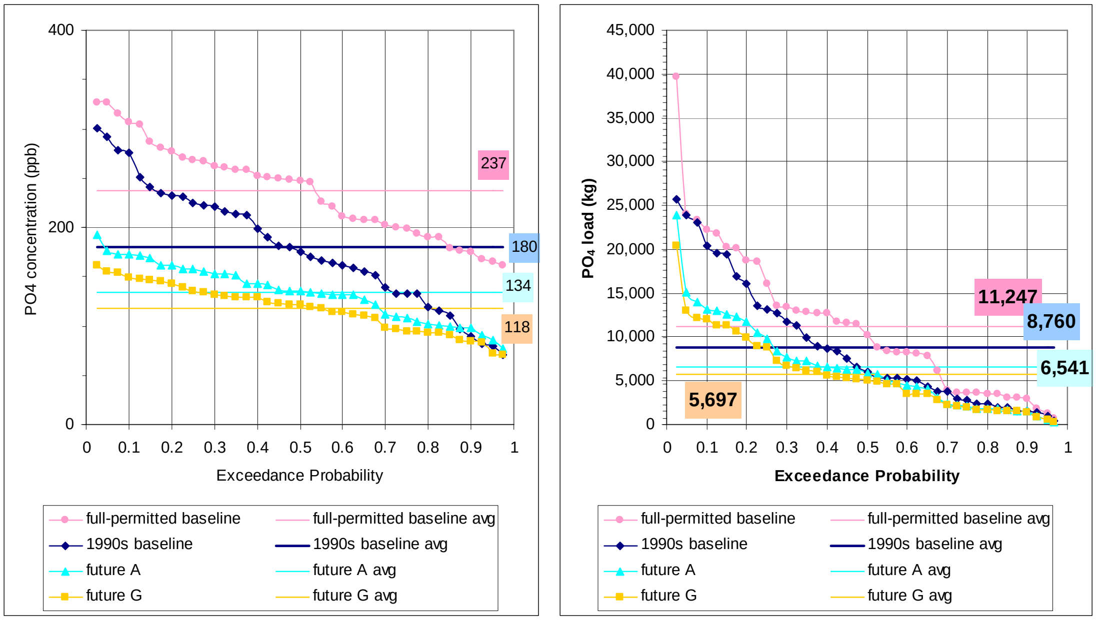


Figure 4-20 Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations at GC100

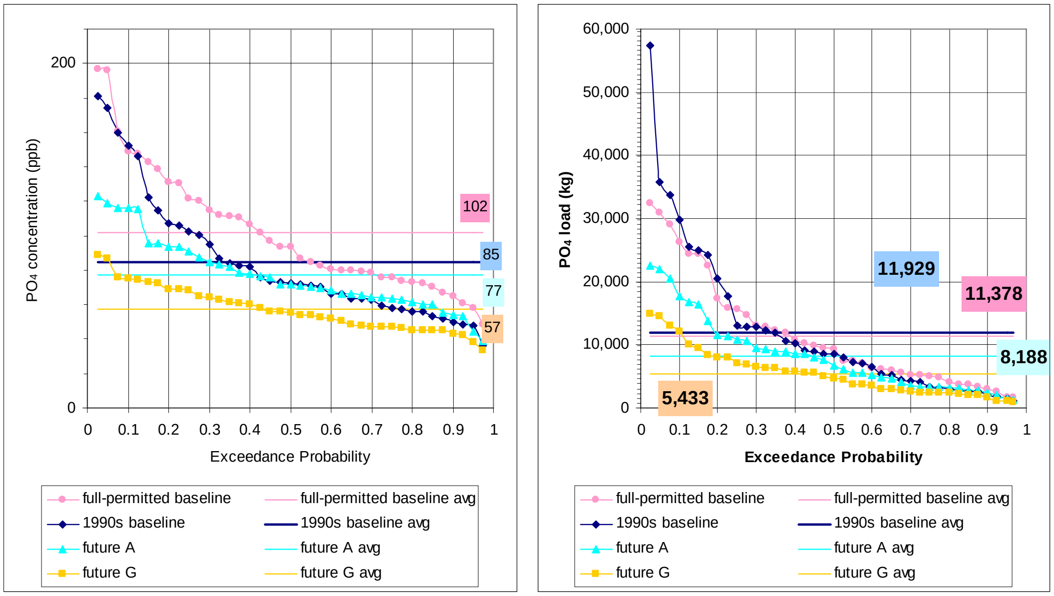
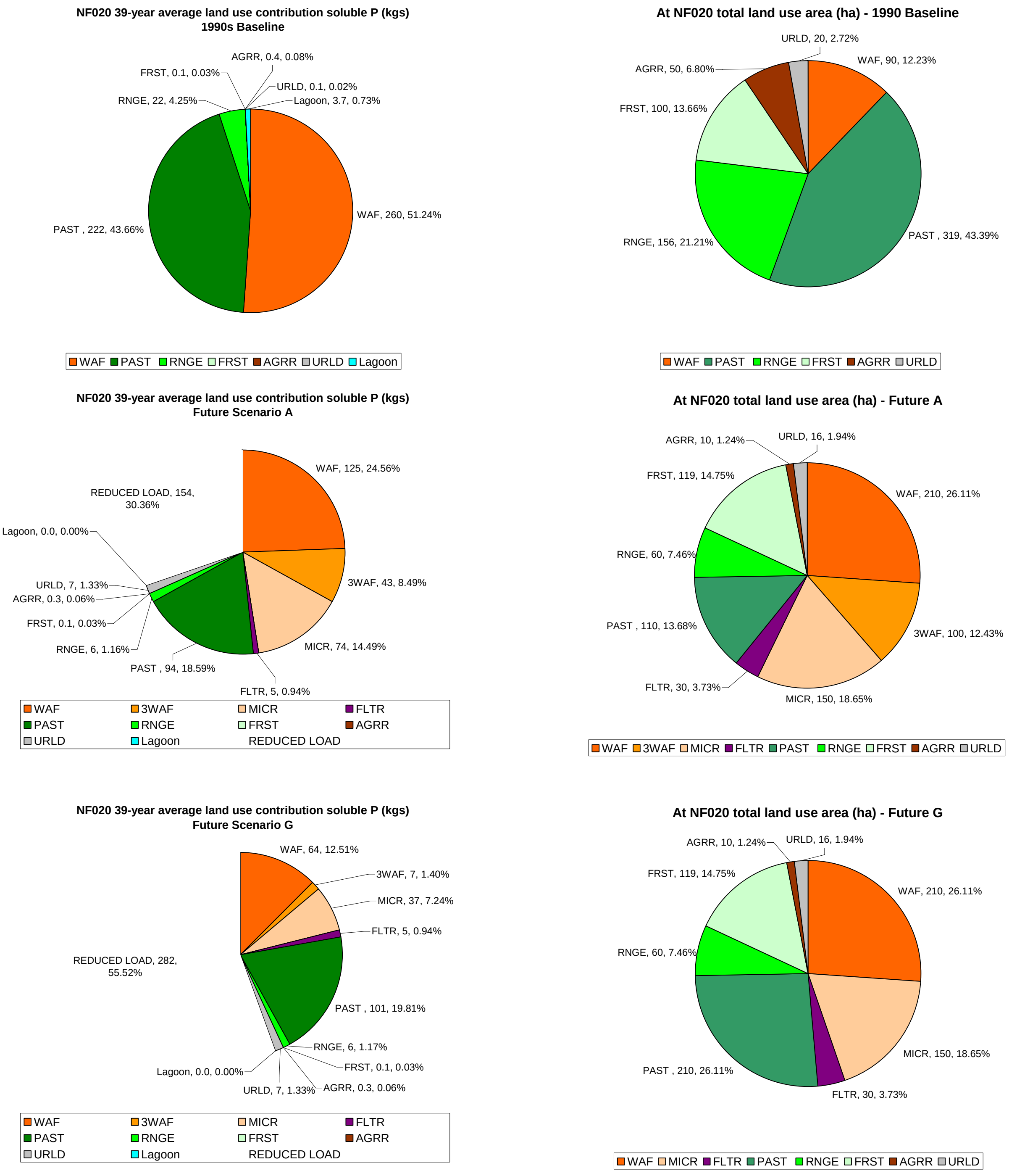


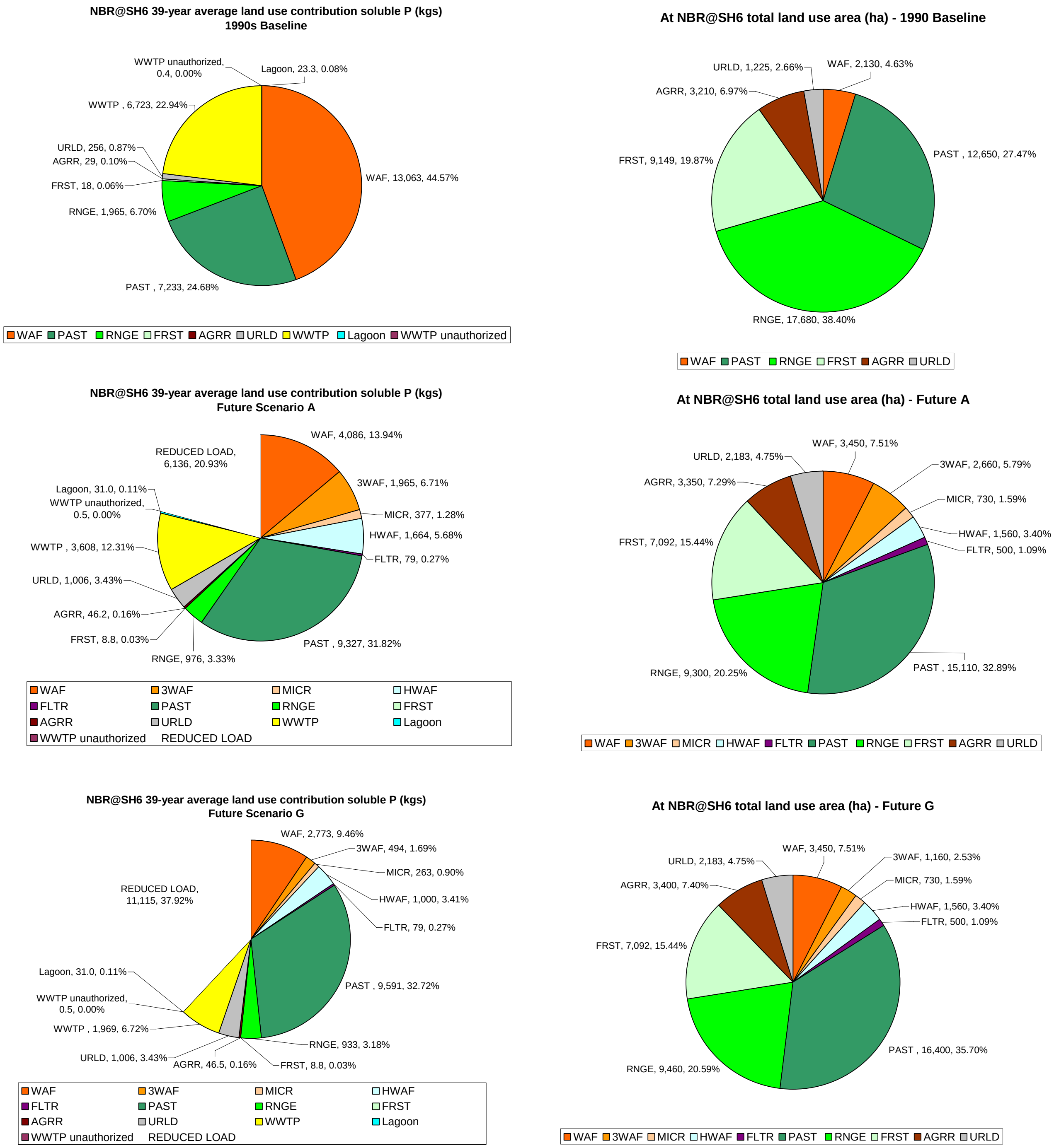
Figure 4-21 Comparison of annual daily-average PO_4 concentration and annual total PO_4 loadings for the TMDL reassessment 1990s baseline and future fully-permitted baseline and Scenario A and G simulations at Duffau Creek



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
508	354	30%	226	56%

Figure 4-22 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at NF020



Total Soluble P (kgs)

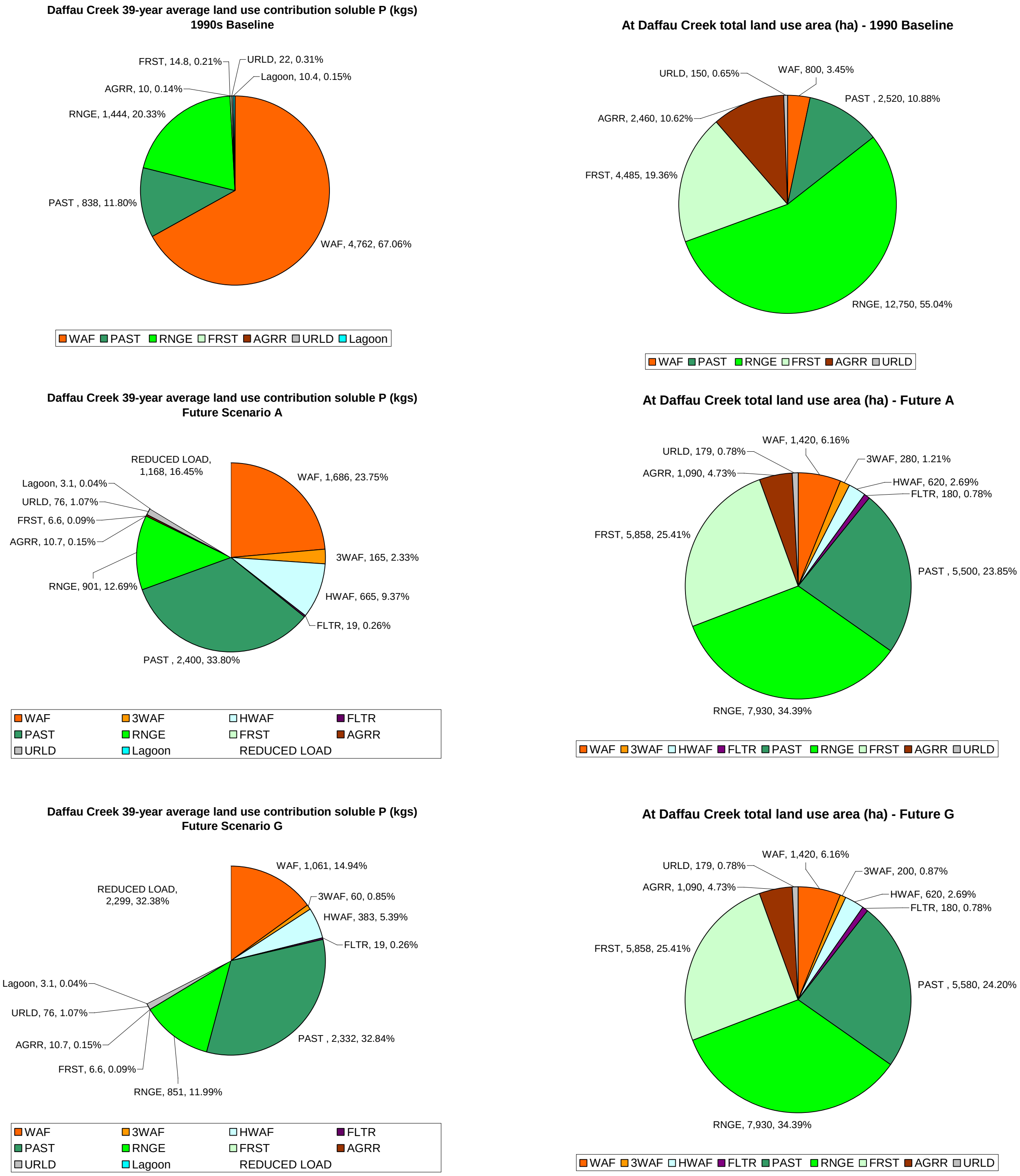
Baseline	FutureA	Reduction	FutureG	Reduction
29,310	23,174	21%	18,195	38%

Figure 4-23 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at NBR@SH6

Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
15,336	12,250	20%	10,716	30%

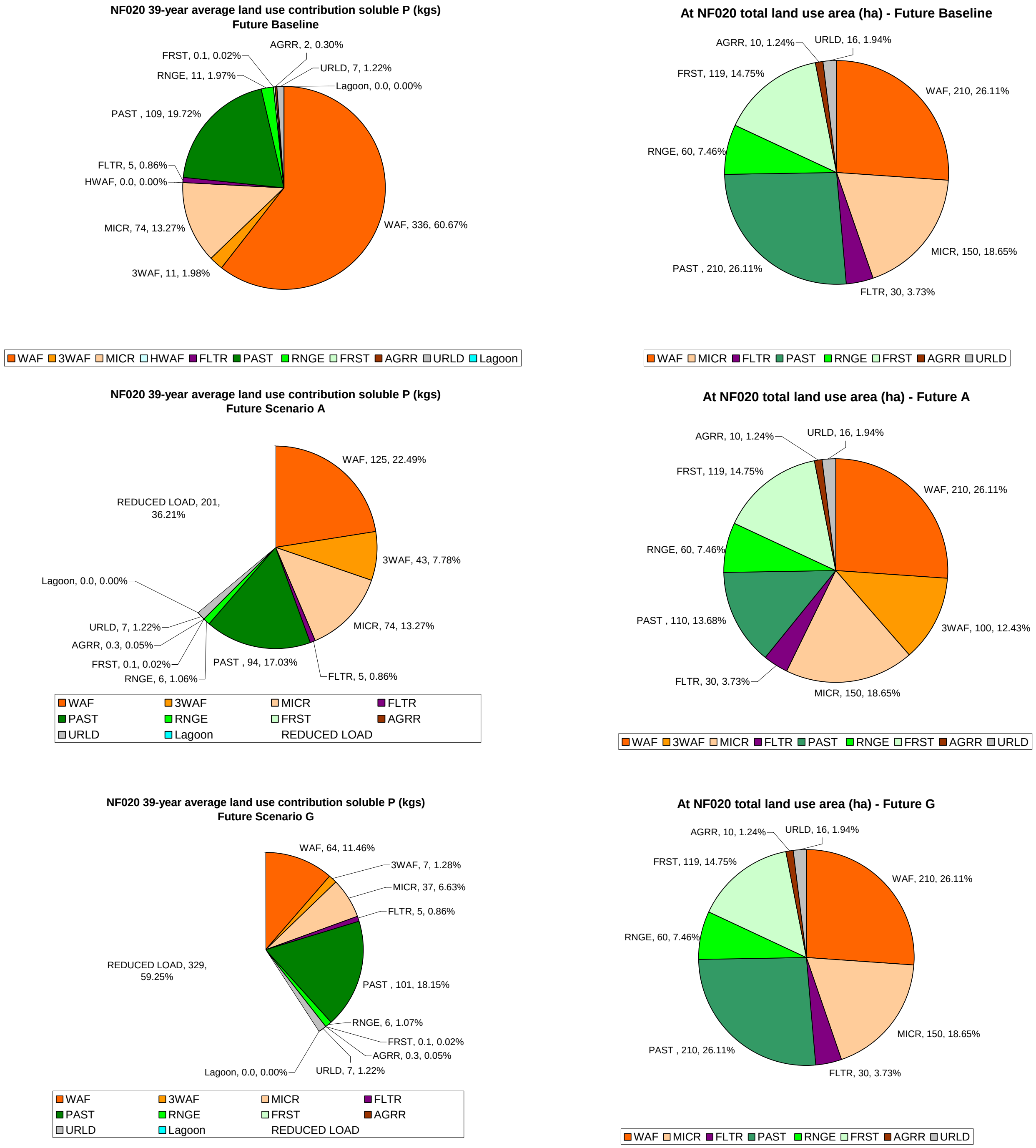
Figure 4-24 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at GC100



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
7,100	5,932	16%	4,802	32%

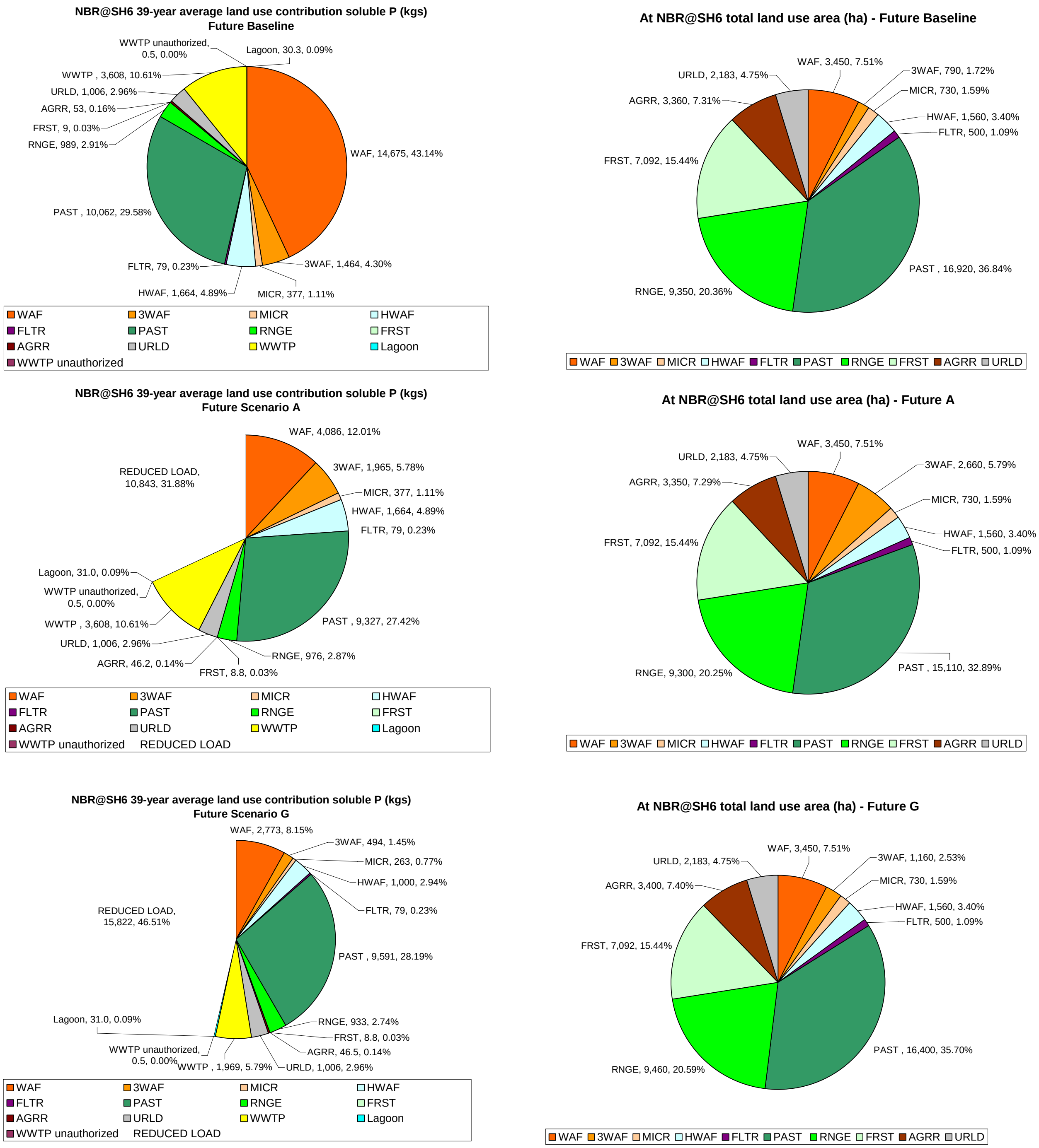
Figure 4-25 TMDL reassessment 1990s Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at Duffau Creek



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
555	354	36%	226	59%

Figure 4-26 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at NF020



Total Soluble P (kgs)

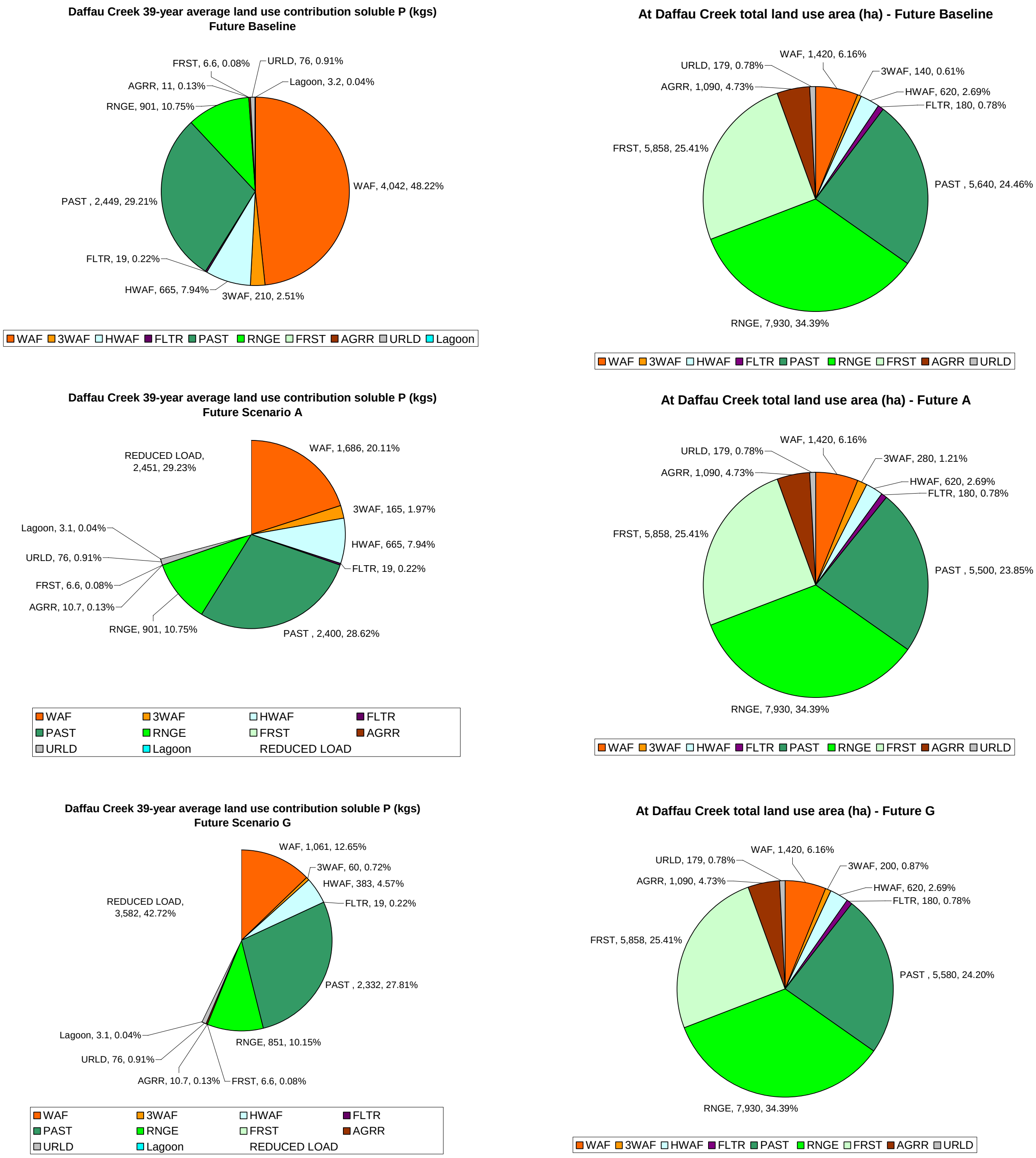
Baseline	FutureA	Reduction	FutureG	Reduction
34,017	23,174	32%	18,195	47%

Figure 4-27 **TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at NBR@SH6**

Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
20,175	12,250	39%	10,716	47%

Figure 4-28 **TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at GC100**



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
8,383	5,932	29%	4,802	43%

Figure 4-29 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) at Duffau Creek

SECTION 5

REFERENCES

Arnold, J.G.., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment. Part 1: Model development. Journal of the American Water Resources Association. 34(1): 73-89.

ASABE; American Society of Agricultural and Biological Engineers. 2005. ASABE Standards: Manure Production and Characteristics. ASABE, St. Joseph, MI. ASAE D384.2 MAR2005.

Baca, R.G., and R.C. Arnett. 1976. A Limnological Model for Eutrophic Lakes and Impoundments. Battelle, Inc., Pacific Northwest Laboratories, Richland, Washington (as cited in Bowie et al., 1985).

BRA (Brazos River Authority). 2003. Quality Assurance Project Plan for the Bosque/Leon Watershed Composting Water Quality Monitoring and Water Quality Data Collection Project. Revision 0. Brazos River Authority, Waco, Texas.

CDM; Camp, Dresser & McKee. 1998. Brazos River Authority: Erath County Animal Waste Management Study. Camp Dresser & McKee Inc., Austin, Texas.

Di Luzio, M., R. Srinivasan, and J.G. Arnold. 2000. *AVSWAT: An ArcView GIS extension as tool for the watershed control of point and nonpoint sources*. Proceedings of the Twentieth Annual ESRI User Conference, 2000. [Online] Available at http://training.esri.com/campus/library/index.cfm (accessed 15 September 2006).

FOTG (Field Office Technical Guide). 2000. Natural Resources Conservation Service, Conservation Practice Standard – Nutrient Management Code 590. FOTG, Section 4. pp. 590-1 to 590-18.

FOTG (Field Office Technical Guide). 2005. Natural Resources Conservation Service, Conservation Practice Standard – Nutrient Management Code 590. FOTG, Section 4. pp. 590-1 to 590-18.

Gass, W.B. 1987. Compilation of Crop Yield Goals and Suggested Fertilizer Rates. Soil, Plant and Water Testing Laboratory, Texas Agricultural Extension Service, College Station and Lubbock, Texas (AGR 11-B)

Gassman, P.W. 1997. The National Pilot Program Integrated Modeling System: Environmental Baseline Assumptions and Results for the APEX Model. Livestock Series Report 9. Staff Report 97-SR 85, November 1997. pp 69.

Grenney, W.J., and A.K. Kraszewski. 1981. Description and Application of the Stream Simulation and Assessment Model: Version IV (SSAM IV). Instream Flow Information

Paper. U.S. Fish and Wildlife Service, Fort Collins, Colorado, Cooperative Instream Flow Service Group (as cited in Bowie et al., 1985).

Harmel, R.D., R.J. Cooper, R.M. Slade, R.L. Haney and J.G. Arnold. 2006. *Cumulative uncertainty in measured streamflow and water quality data for small watersheds*. *Trans.* ASABE 49 (2006) (3), pp. 689–701.

Hauck, L., T. Jones, and Tina L. Coan. 1994. Report on the Role of Two PL-566 Reservoirs in Agricultural Pollution Control North Bosque River Basin Earth County, Texas. Tarleton State University, Texas Institute for Applied Environmental Research, Stephenville, Texas.

Houser, J. B., and R. Pitt. 2008. *Simulation of Soil Loss and Available Water Content to Assess the Sustainability of Selected Farm Practices.* Journal of Sustainable Agriculture. Vol. 32(3), pp. 507-527.

Houser, J.B., 2004: SWAT in-stream kinetics. Tech. Memo., Texas Institute for Applied Environmental Research, Tarleton State University.

Houser, J. B., and L. M. Hauck. 2004. Evaluating Performance of Environmental Models: Comparison of Three In-stream Water Quality Models (SWAT, QUAL2E, and HSPF). Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas. TR0407. August, 2004. pp. 108.

Hudson, B. D. 1994. *Soil organic matter and available water capacity*. Journal of Soil and Water Conservation 49:189-194.

Jones, C.A., C.V. Cole, A.N. Sharpley, and J.R. Williams. 1984. A simplified soil and plant phosphorus model: I. Documentation. Soil Science Society of America Journal 48:800-805.

Jordan, E., and S. Stokes. 1998. *Extension Update: Reducing nitrogen and phosphorus loading from dairy cattle production systems*, pp. 17-28. In: Proceedings of the Mid-South Ruminant Nutrient Conference, Irving, Texas.

Kiesling, R., A. McFarland, and L.M. Hauck. 2001. Nutrient Targets for Lake Waco and the North Bosque River: Developing Ecosystem Restoration Criteria. TIAER Report # TR0107. Stephenville, TX: Texas Institute for Applied Environmental Research, Tarleton State University.

Lewis, D.R. and M.B. McGechan. 2002. *A review of field scale phosphorus dynamic models*. Biosystem Engineering 82, pp. 359–380.

McFarland, A. and L. Hauck. 1997. Livestock and Environment: A National Pilot Project – Report on Stream Water Quality in the Upper North Bosque River Watershed. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas (PR 97-03).

McFarland, A., and Hauck, L. 1999. *Relating agricultural land uses to in-stream stormwater quality*. Journal of Environmental Quality. 28: 836-844.

McFarland, A., A. Saleh, and L. Hauck. 2000. Section 319: Nonpoint Source Pollution Control Program Demonstration Project: Demonstration of Phosphorus Best Management Practices in the North Bosque River Basin. TR0002, September 2000. Texas Institute for Applied Environmental Research, Tarleton State Univ., Stephenville, Texas

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith. 2007. *Model evaluation guidelines for systematic quantification of accuracy in watershed simulations.* Transactions of the American Society of Agricultural and Biological Engineers, 50 (3), 885–900.

Mukhtar, S., J.L. Ullman, B.W. Auvermann, S.E. Faegley, and T.A. Carpenter. 2004. *Impact of anaerobic lagoon management on sludge accumulation and nutrient content for dairies*. Transactions of American Society of Agricultural Engineers. 47(1):251-257.

MWPS, MidWest Plan Service. 1985. Livestock Waste Facilities Handbook (Second Edition). MWPS, Iowa State University, Ames, Iowa (MWPS-18).

Nash, J.E., and J.E. Sutcliff. 1970. *River flow forecasting through conceptual models: Part 1. A discussion of principles*. Journal of Hydrology 10(3):262-272.

Neitsch, S., J. Arnold, J. Kiniry, J. Williams and K. King. 2002. Soil and Water Assessment Tool Theoretical Documentation, Version 2000. Temple: Agricultural Research Service and Blacklands Research Center.

Nennich, T.D., J.H. Harrison, L.M VanWieringen, D. Meyer, A.J. Heirichs, W.P. Weiss, N.R. St-Pierre, R.L. Kincaid, D.L. Davidson, and E. Block. 2005. *Prediction of manure and nutrient excretion from dairy cows*. Journal of Dairy Science 88:3721-3733.

NRCS, (Natural Resources Conservation Service, United States Department of Agriculture). 1996. National Engineering Handbook: Part 651, Agricultural Waste Management Field Handbook. United States Department of Agriculture, Washington, D.C. (revised).

NRCS, (Natural Resources Conservation Service, United States Department of Agriculture). 2000. Comprehensive Nutrient Management Planning: Technical Guidance. December 1, 2000. pp. 66.

NRCS, (Natural Resources Conservation Service, United States Department of Agriculture). 2003. Soil Survey Geographic (SSURGO) Database for Bosque, Coryell, Erath, Hamilton, McLennan and Somerville counties, Texas. Available online at http://soildatamart.nrcs.usda.gov accessed 9/17/2003.

Osei, Edward, P.G. Lakshminarayan, S. Neibergs, A. Bouzaher, and S.R. Johnson. 1995. Livestock and the Environment: A National Pilot Project – The Policy Space, Economic Model, and Environmental Model Linkages. Livestock Series Report 4. Center for Agriculture and Rural Development (CARD), Iowa State University, Ames, Iowa. (Staff Report 95-SR 78).

Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland. 2000. *Application of SWAT for the Upper North Bosque River watershed.* Transactions of the ASAE. Vol. 43(5): 1077-1087.

Saleh, A., and B. Du. 2004. *Evaluation of SWAT and HSPF within BASINS program for the Upper North Bosque River watershed in central Texas*. Trans. ASAE 47(4): 1039-1049.

SCS, (Soil Conservation Service). 1992. National Engineering Handbook: Part 651, Agricultural Waste Management Field Handbook. United States Department of Agriculture, Washington, D.C.

Stokes, S., and E. Jordan. Undated. Impact of Nutrition on Manure Nutrients. Educational handout, Texas Agricultural Extension Service, College Station, Texas.

Sweeten, J.M., M. McFarland, B.L. Harris, G. Westmoreland, C. Baird, and L. Manning. 1991. Animal Waste Management. Texas Agricultural Extension Service, College Station, Texas, and Texas State Soil and Water Conservation Board, Temple, Texas. (L-5044).

TCEQ (Texas Commission on Environmental Quality) and TSSWCB (Texas State Soil and Water Conservation Board). 2002. An Implementation Plan for Soluble Reactive Phosphorus in the North Bosque River Watershed for Segments 1226 and 1255. TCEQ Strategic Assessment Division, TMDL Team, Austin, Texas and TSSWCB TMDL Team, Temple, Texas.

TIAER (Texas Institute for Applied Environmental Research). 1993. Quality Assurance Project Plan for the National Pilot Project. Tarleton State University, Texas Institute for Applied Environmental Research, Stephenville, Texas.

TIAER (Texas Institute for Applied Environmental Research). 2005b. United States Department of Agriculture Bosque River Initiative Quality Assurance Project Plan, Revision 5. TIAER, Tarleton State University, Stephenville, Texas.

TIAER (Texas Institute for Applied Environmental Research). 2006. Sampling History Report: Final Project Report for Monitoring to Support North Bosque River Model Refinement. TR0613. Stephenville, TX: Texas Institute for Applied Environmental Research, Tarleton State University.

TNRCC (Texas Natural Resource Conservation Commission). 2001. Two Total Maximum Daily Loads for Phosphorus in the North Bosque River for Segments 1226 and 1255. The Strategic Assessment Division, TNRCC, Austin, Texas (adopted February 2001: approved by EPA December 2001).

USDA (United States Department of Agriculture). 1980. CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Conservation Research Report Number 26.

USEPA (United States Environmental Protection Agency). 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (2nd Edition). EPA/600/3-85/040 June 1985. Environmental Research laboratory, Athens, GA 30613.

USEPA (United States Environmental Protection Agency). 1991. Guidance for water quality-based decisions: The TMDL Process, EPA 440/4-91-001.Washington, DC-http://www.epa.gov/owow/tmdl/decisions.html

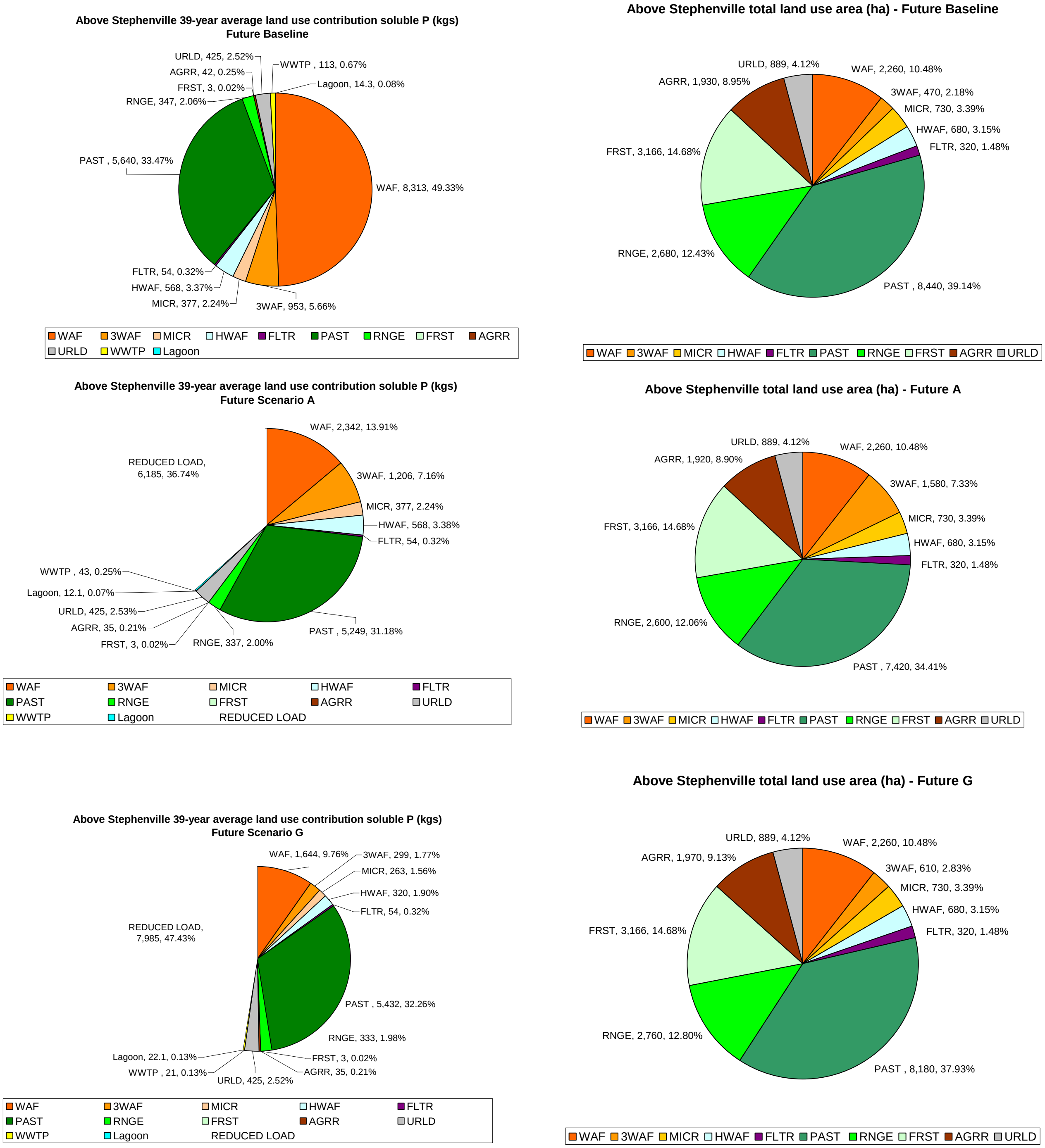
USEPA (United States Environmental Protection Agency). 2006. Establishing TMDL "Daily" Loads in Light of the Decision by the U.S. Court of Appeals for the D.C. Circuit in Friends of the Earth, Inc. v. EPA, et al., No. 05-5015, (April 25, 2006) and Implications, for NPDES Permits. http://www.epa.gov/OWOW/tmdl/dailyloadsguidance.html

USGS (United States Geological Service). 1999. USGS National Elevation Database, EROS Data Center, Sioux Falls, SD. http://edcnts12.cr.usgs.gov/ned/ned.html

van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., Srinivasan, R. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. Journal of Hydrology 324, 10-23.

APPENDIX A

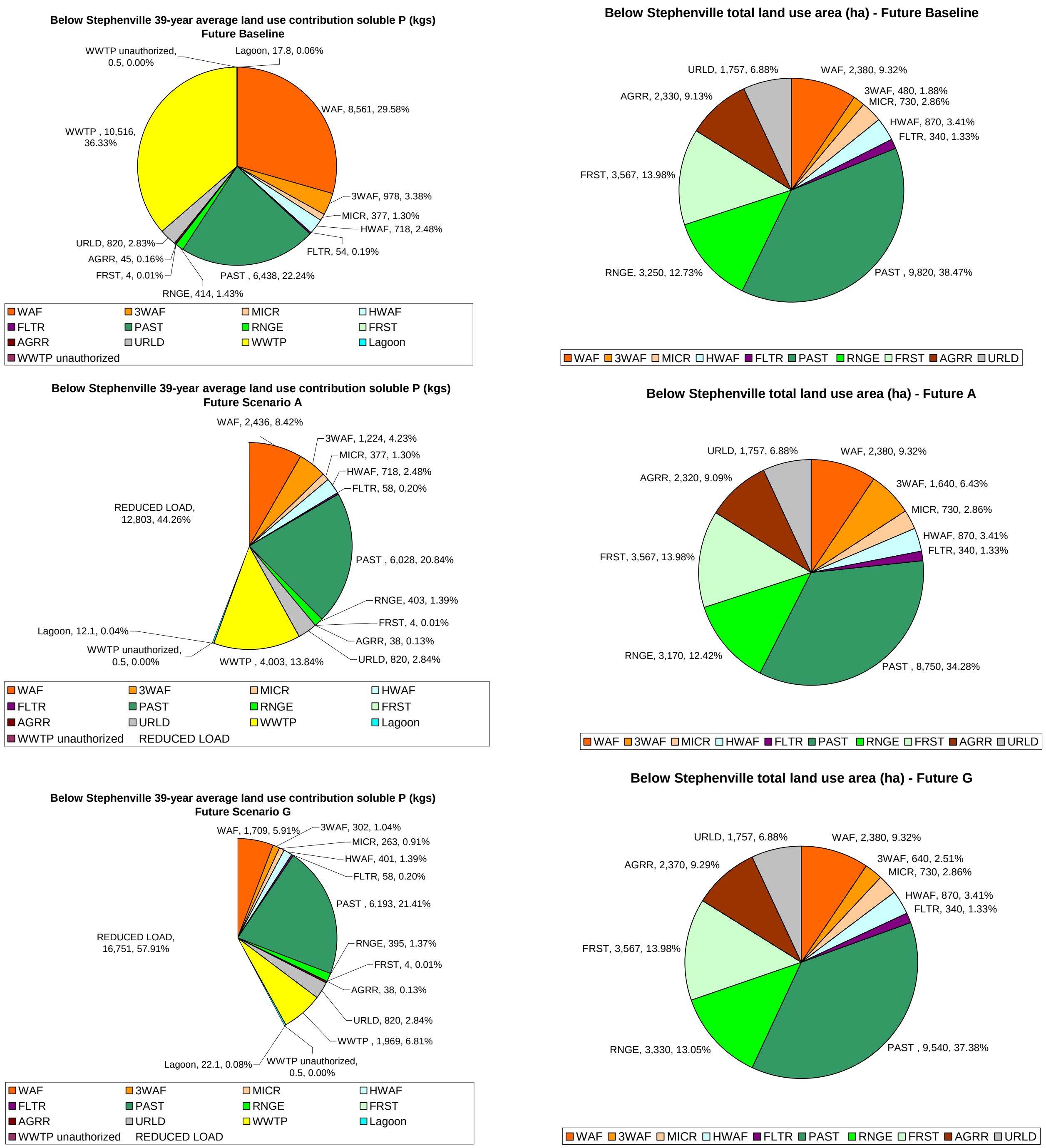
COMPARISONS OF LAND USE AND POINT SOURCE LOADINGS AND LAND AREA OF SCENARIOS A AND G COMPARED TO THE FULL-PERMITTED BASELINE



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
16,836	10,651	37%	8,851	47%

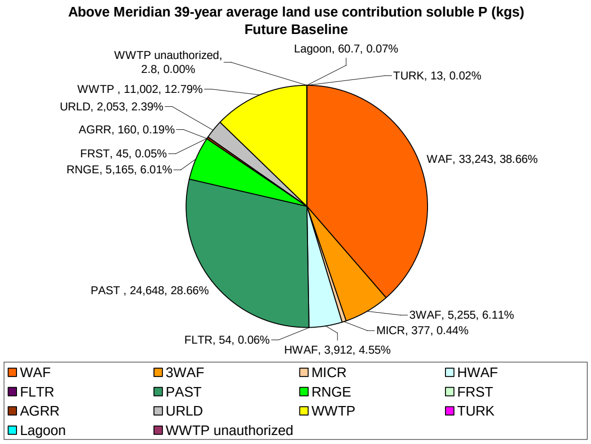
Figure A-1 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR above Stephenville



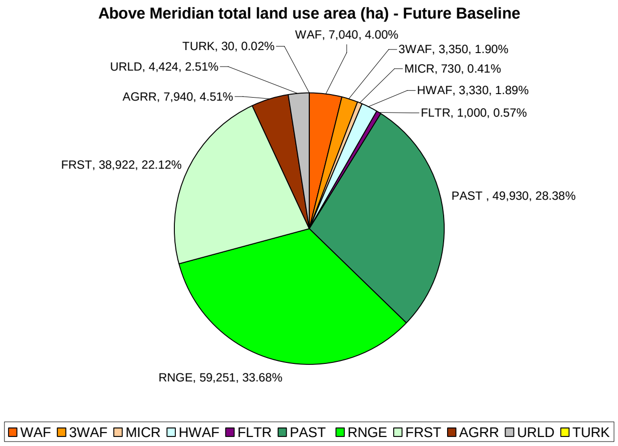
Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
28,925	16,122	44%	12,174	58%

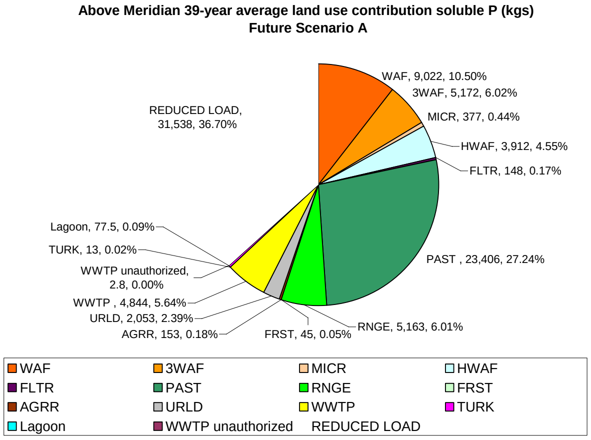
Figure A-2 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR below Stephenville



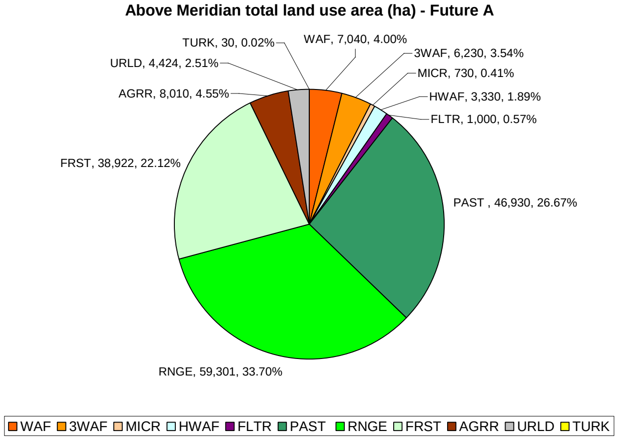
Above Meridian 39-year average land use contribution soluble P (kgs)
Future Baseline



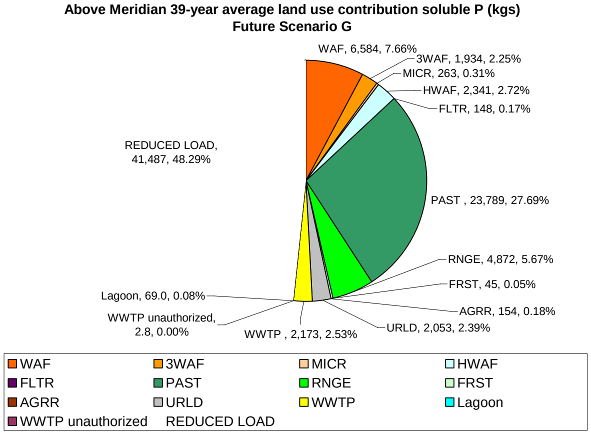
Above Meridian total land use area (ha) - Future Baseline



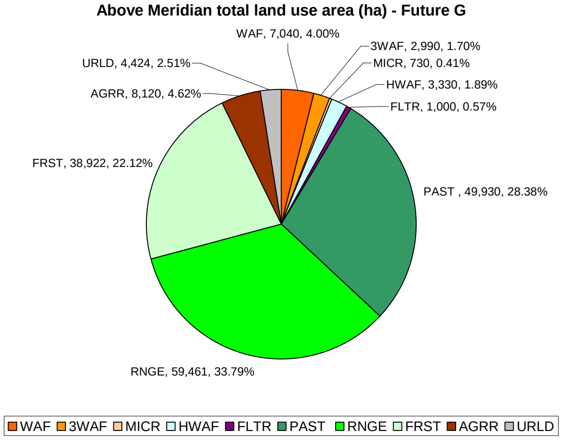
Above Meridian 39-year average land use contribution soluble P (kgs)
Future Scenario A



Above Meridian total land use area (ha) - Future A



Above Meridian 39-year average land use contribution soluble P (kgs)
Future Scenario G

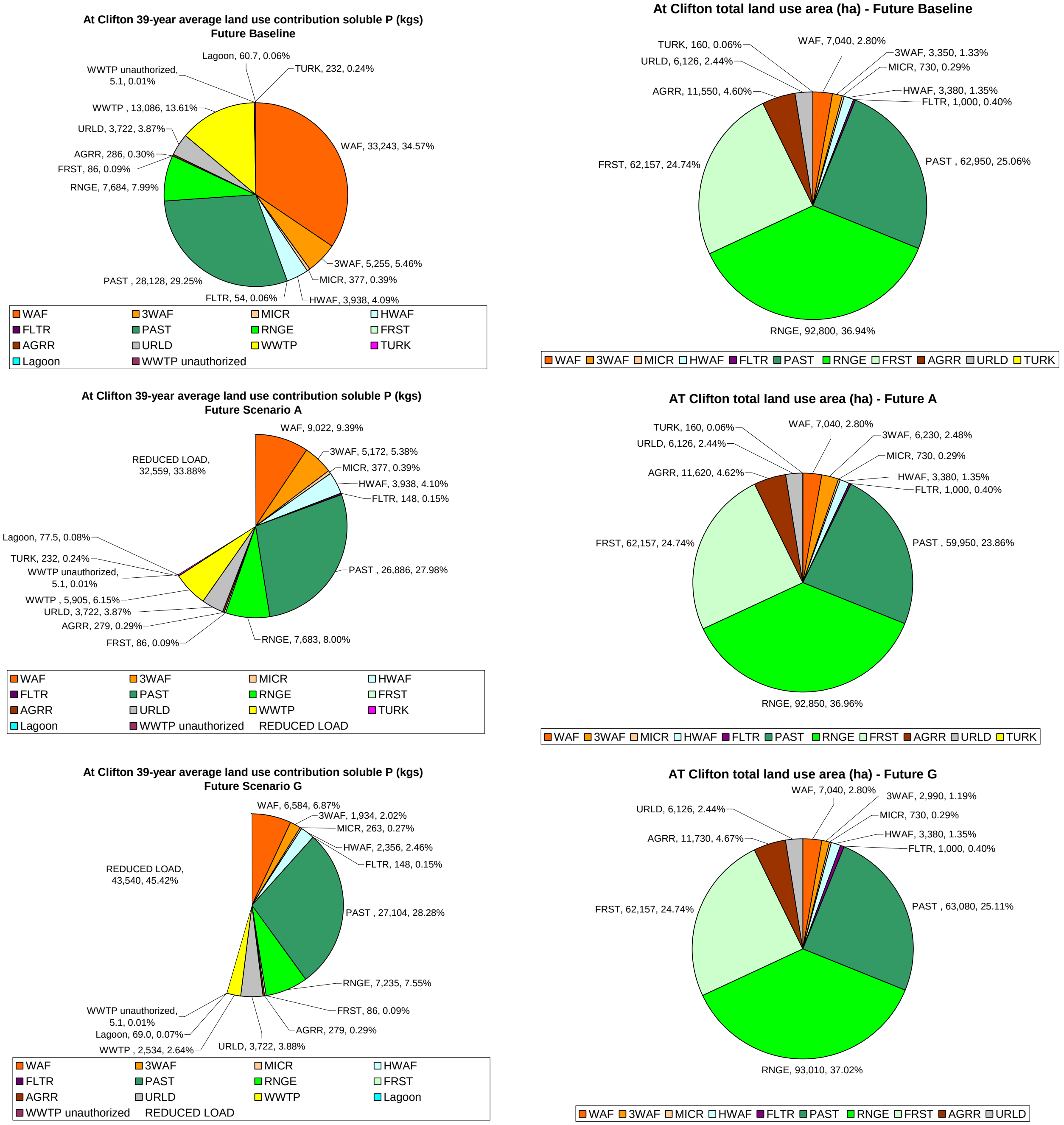


Above Meridian total land use area (ha) - Future G

Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
85,914	54,375	37%	44,426	48%

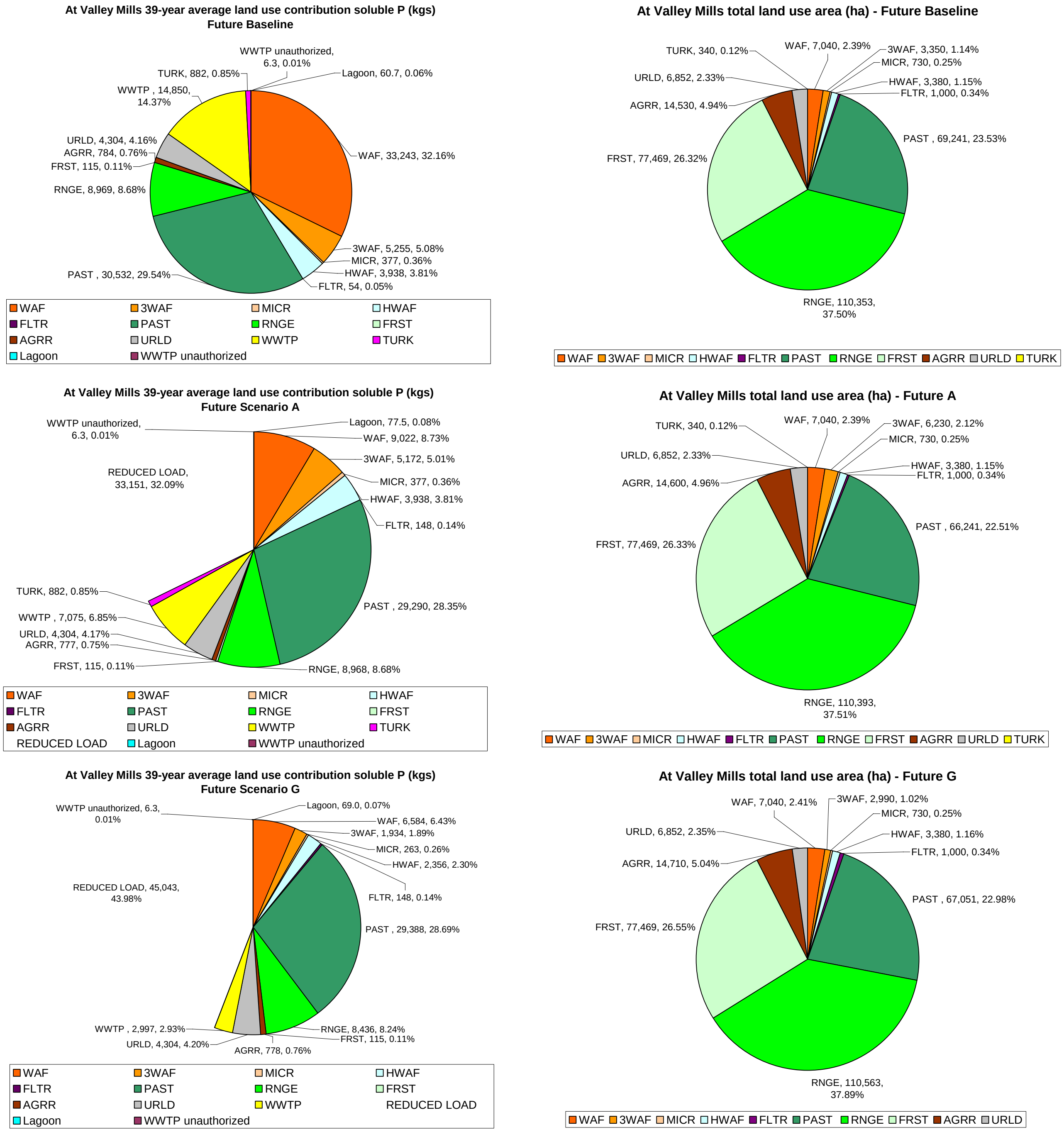
Figure A-3 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR above Meridian



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
95,859	63,300	34%	52,319	45%

Figure A-4 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR at Clifton



Total Soluble P (kgs)

Baseline	FutureA	Reduction	FutureG	Reduction
102,421	69,270	32%	57,538	44%

Figure A-5 TMDL reassessment Future Baseline vs. Scenario A and G land use & point source loadings (kgs) and area (ha) for NBR at Valley Mills