LAKE GRANBURY WATER QUALITY MODELING PROJECT
PHASE 1 Draft Report – Data Trend Analysis, Modeling Overview and Recommendations

Prepared for:

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EXECUTIVE SUMMARY

A number of coves and canals adjacent to Lake Granbury have exhibited undesirable concentrations of bacteria. The Brazos River Authority (BRA) has been performing long-term Clean Rivers Program water quality monitoring at three stations in the main body of the lake. BRA also initiated additional water quality monitoring in 2001 for additional selected cove areas to determine the locality and severity of the bacteria problem. In 2006, US Environmental Protection Agency (EPA) funding became available allowing the Texas Commission on Environmental Quality (TCEQ) and BRA to develop a Watershed Protection Plan (WPP) to improve and protect water quality within the Lake Granbury and the supporting watershed.

A phased scope of work was developed to complete the WPP. This report describes the water quality data and preliminary modeling evaluation component of the WPP. The objectives of this study are to:

- Evaluate existing data sources and recommend additional data collection as needed;
- Determine sources and impacts of present problems;
- Recommend strategies to be included in the WPP for protecting or improving water quality.

As part of this report, data was collected and compiled from the BRA, TCEQ, Texas Natural Resources Information System (TNRIS), Texas Water Development Board (TWDB), National Climatic Data Center (NCDC), University of Texas Bureau of Economic Geology (UTBEG) and US Geological Survey (USGS). The data collected in the main body of Lake Granbury as well as the coves were evaluated in terms of nutrients and bacteria.

Results of the data evaluation indicate that there is an increasing trend in nutrients in the main body of Lake Granbury. Decreasing trends in overall DO concentrations, daytime DO increases from photosynthesis, decreasing trends in secchi depth and increasing trends in chlorophyll-a concentrations were also observed in this initial data review. Elevated bacteria concentrations in the main body of the lake do not occur regularly nor are periods of high concentration persistent. Background levels of bacteria in the main body of Lake Granbury are less than 10 MPN per 100 mL. However, high levels of bacteria were found in many of the coves of Lake Granbury.

Several recommendations were developed as part of this report, including: additional water quality sampling, evaluation of circulation patterns between the coves and main body of Lake Granbury and bacteria modeling. Additional investigation into nutrient concentrations through the development of a nutrient budget is recommended. Additional data collection is recommended for nutrients in the main body to evaluate potential trends exhibited by long-term monitoring data. Investigation should include determination of nitrogen and phosphorus loads into the main lake body, particularly potential for increase in these loads associated with transition from on-site treatment facilities to regional treatment that discharges into the lake.

For modeling canal water quality, additional data is required to quantify the exchange of water between the main lake body and each cove. Data is needed to quantify circulation within each cove to identify sources and movement of water and constituents. These data will include but may not be limited to estimated wind speeds, wind effects, level of downward mixing, stratified flow, convective flow, current patterns, specialized eddy flow, etc.

Additionally, to determine the sources of bacteria, or to validate the hypothesis that bacteria in canals is primarily from leaky septic systems, the injection of dye into existing septic systems is recommended. The canals with the highest and most persistent bacteria concentrations are Port Ridglea, Sky Harbor and Oak Trail Shores; therefore, these locations are recommended for testing. Rolling Hills Shores could also
be tested if funds are available. The treatment facility Blue Water Shores should also be investigated if possible.

Finally, a segmented well-mixed mass balance model is recommended for modeling each canal system. The model will consider gradients of bacteria concentrations from the lake boundary to the upper dead-end reaches of the canal system. These models will then be utilized to determine the impacts to water quality of the coves when part or all of the bacteria loading is removed. Investigations utilizing these models will assist in the development of best management practices (BMPs) for the coves.
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1.0 BACKGROUND

1.1 PROJECT OVERVIEW

A number of coves and canals adjacent to Lake Granbury have exhibited undesirable concentrations of bacteria. The Brazos River Authority (BRA) has been performing long-term Clean Rivers Program water quality monitoring at three stations in the main body of the lake. BRA also initiated additional water quality monitoring in 2001 for additional selected cove areas to determine the locality and severity of the bacteria problem. In 2006, US Environmental Protection Agency (EPA) funding became available allowing the Texas Commission on Environmental Quality (TCEQ) and BRA to develop a Watershed Protection Plan (WPP) to improve and protect water quality within the Lake Granbury and the supporting watershed.

A phased scope of work was developed to complete the WPP. This report describes the water quality modeling study component of the WPP. The objectives of this water quality modeling study are to:

- Evaluate existing data sources and collect additional data as needed;
- Determine sources and impacts of present problems;
- Determine assimilative capacity of cove and lake water bodies;
- Recommend strategies to be included in the Watershed Protection Plan for protecting or improving water quality.

To meet these stated objectives, this three-year study is composed of two phases, consisting of ten tasks. Phase 1 consists of the completion of a preliminary investigation of the water quality of Lake Granbury and the water quality modeling needs to meet the requirements of the EPA and the TCEQ for the WPP. Phase 1 activities will be presented to the Lake Granbury Watershed Protection Plan Stakeholders Group. Phase 2 activities will include: data collection to develop model, model development, alternatives analysis, reporting and further stakeholder meeting participation.

This report summarizes work completed to date associated with Phase 1. Per the project Scope of Work, Data Analysis (Task 1) is presented Sections 2 and 3, with summary and recommendations presented in Section 5. The results of Data Collection (Task 2) and Preliminary Modeling Analysis (Task 3) are summarized and presented in Section 4.
2.0 HISTORICAL DATA DESCRIPTION

2.1 DATA SOURCES

Data was compiled from numerous sources including BRA, TCEQ, Texas Natural Resources Information System (TNRIS), Texas Water Development Board (TWDB), National Climatic Data Center (NCDC), University of Texas Bureau of Economic Geology (UTBEG) and US Geological Survey (USGS). Data were analyzed for spatial and temporal trends.

Time-series data included TCEQ’s Surface Water Quality Monitoring data; USGS elevation and flow gage data; BRA elevation, precipitation and evaporation data; NCDC precipitation, wind speed and direction data; and special study data. Spatial Geographic Information System (GIS) datasets, further detailed within Section 2.4, include streets, elevations, geology, Hood County data on subdivisions and septic systems, land use, aerial imagery, soils data, lake bathymetry and watershed boundaries.

2.2 CURRENT REGULATORY STATUS

Lake Granbury, located near Granbury, Texas, is an impoundment of the Brazos River created in 1969 with completion of DeCordova Bend Dam. BRA manages and operates the lake for municipal and industrial water supply and recreation (TWDB 2003). Conservation Pool Elevation (CPE) is 692.00 feet above NGVD29 datum. The lake exhibits 7,945 surface acres and contains 129,011 acre-feet of water at CPE. Drainage area to the lake comprises 25,679 square miles. Reduction in volume resulting from sedimentation was estimated as 21,907 acre-feet between 1969 and 1994, and an additional 4,582 acre-feet between 1994 and 2003 (287 acre-feet per year) (TWDB 2003).

Designated uses for Lake Granbury are Contact Recreation, High Aquatic Life Use and Public Water Supply (30 TAC §307.10(1)). Applicable water quality standards for Lake Granbury are shown in Table 2-1 by designated use type. Additionally, applicable water quality criteria from TCEQ and EAP are shown in Table 2-2. These screening levels were developed by TCEQ in the Guidance for Assessing Surface and Finished Drinking Water Quality Data report (2002) and the EPA Ambient Water Quality Criteria Recommendations for Lakes and Reservoirs (2000). TCEQ is currently evaluating nutrient and chlorophyll-a standards for lakes in Texas.

Within segment 1205, a site-specific receiving water assessment exists for McCarty Branch; it is classified as a Low Aquatic Life Use intermittent stream with DO standard of ≥3.0 mg/L (30 TAC §307.10(4)).

The Brazos River below Possum Kingdom Lake (Segment 1206) near Lake Granbury (Segment 1205) is not listed in the 2004 Texas 303(d) List. The 2004 Texas Water Quality Inventory Status and Category of All Waters designated Segment 1205 and Segment 1206 as Assessment Unit Category 2 which is defined as attaining some of the designated uses; no use is threatened; and insufficient or no data and information are available to determine if the remaining uses are attained or threatened. Designated uses include aquatic life use, recreation use, general use, fish consumptive use, public water supply use, oyster waters use, and overall use. All sections of each segment were fully supporting for all uses assessed.
Table 2-1: Applicable Water Quality Standards for Segment 1205

**Domestic Public Water Supply:**
- ≤ 1,000 mg/L mean Chlorides
- ≤ 600 mg/L mean Sulfate
- ≤ 2,500 mg/L mean TDS

**Recreation:**
- ≤ 126 geometric mean indicator bacteria (E. coli) per 100mL (or Fecal coli 200 per 100mL)
- < 394 indicator bacteria (E. coli) per 100mL (or Fecal coli 400 per 100mL)

**High Aquatic Life Use:**
- ≥ 5.0 mg/L mean DO
- ≥ 3.0 mg/L minimum DO not to extend more than 8 hours per 24-hour day
- Spring criteria (first half of year when Temperature is 63 to 73˚F)
  - ≥ 5.5 mg/L mean DO spring
  - ≥ 4.5 mg/L minimum DO spring, not to extend more than 8 hours per 24-hour day

**Additional criteria:**
- 6.5 to 9.0 pH
- ≤ 93˚ F Temperature

<table>
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<tr>
<th>Nutrient Parameter</th>
<th>TCEQ Secondary Concern Screening Level</th>
<th>EPA Range of Level III Sub-region Reference Condition</th>
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<td>Total Phosphorus (µg/L)</td>
<td>180</td>
<td>10-62.5</td>
</tr>
<tr>
<td>Total Nitrogen (mg/L)</td>
<td>0.106 (NH₃-N) &amp; 0.32 (NO₂-N + NO₃-N)</td>
<td>0.30-0.96</td>
</tr>
<tr>
<td>Chlorophyll a(µg/L)</td>
<td>19.2</td>
<td>1.87-12.95</td>
</tr>
<tr>
<td>Secchi Depth (m)</td>
<td>-</td>
<td>0.46-2.04</td>
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High temperatures are of concern in the upper portion of Segment 1206 as well as public concerns for elevated suspended solids (TSS) from rock quarry operations. In the fall of 2004 a special study began to evaluate total suspended solids (TSS) in Segment 1206 and included routine sampling, storm water sampling, and biological assessment data collections. Decreasing trends for conductivity, total dissolved solids (TDS), chlorides, sulfates, and TSS were identified in Palo Pinto Creek, a tributary to the Brazos River below Possum Kingdom. A recent water quality analysis of long term monitoring locations on the main body of Lake Granbury, Segment 1205, yielded supporting water quality conditions; however, trend analysis shows an increasing trend in conductivity, TDS, chloride, and TSS. In May 2002, the Lake Granbury Escherichia coli (E. coli) Study began to assess the water quality in coves and canals and the potential impacts of on-site sewage facilities in these areas (BRA 2006).
2.3 HISTORICAL LAKE LEVELS, WATER QUALITY TRENDS AND WATER BALANCE

Historically, the water surface elevation has been maintained at or near CPE (Figure 2.1). Compared to the period of 1970 through 1998, inflows have reduced during the period 1998 to 2006 (Figure 2.2). For the period 1985 through 1997, volume of water releases were equivalent to 110.5 lake capacities; average residence time was 1.4 months (Figure 2.2). For the period 1998 through April 2006, volume of water releases were equivalent to 21.5 lake capacities; average residence time was 4.6 months (Figure 2.2).

Lake-wide increases in the concentration of chlorides, TDS (Figure 2.3) and specific conductance (Figure 2.4) were observed at the long-term Lake Granbury monitoring station near DeCordova Bend Dam (station 11860). Similar increases in specific conductance were observed at the Brazos River long-term monitoring station upstream of Lake Granbury (Figure 2.5) (station 11863); increases within the lake appear to be affected most strongly by concentration in inflows rather than an in-lake process. Compared to historical conditions, drought conditions have potential to affect higher evaporation rates, lower inflow volumes and/or higher concentrations of TDS in inflows; therefore, drought conditions have potential to increase TDS concentration in Lake Granbury. The magnitude of potential change in TDS concentration was not determined as part of this study.

![Lake Granbury Historical Lake Levels](image-url)
Figure 2.2: Lake Granbury – Release on the Basis of Total Lake Capacity

Figure 2.3: Lake Granbury Concentration of Chloride and Total Dissolved Solids at Long-Term Monitoring Station Near DeCordova Bend Dam.
Figure 2.4: Lake Granbury Concentration of Specific Conductance at Long-Term Monitoring Station Near DeCordova Bend Dam.

Figure 2.5 – Brazos River Segment 1206, Concentration of Specific Conductance at Long-Term Monitoring Station 11863 South of Mineral Wells.
2.4 LAKE GRANBURY HISTORICAL STUDIES

2.4.1 1982 Nutrient Study

Sponsored by the Texas Department of Water Resources (TDWR), the BRA and Alan Plummer and Associates, Inc. (APAI), conducted the Lake Granbury Septic Tank Evaluation Study in 1981 (APAI 1982a). The report describes the main lake body as either nitrogen or phosphorus limited with respect to algal growth based upon season and location. Nitrogen levels appeared at that time to be increasing and the potential was reported for a shift of the lake to Phosphorus-limited (APAI 1982b). EC analysis of more recent data (1980 through 2006) does not indicate inorganic Nitrogen concentrations approaching the 0.55 mg/L level predicted in the 1982 study.

Near-shore nutrient concentrations were reported to have potential to be influenced by septic tank/absorption systems because of rapid passage of tracers through soil to lake; the full nitrogen load from septic systems was estimated to enter the lake (APAI 1982b). While load contributed from septic systems to the main body of the lake was very small or insignificant compared to load contributed by inflows, erosion and wastewater treatment plants, the load from septic systems has potential to increase nitrogen concentrations locally, e.g. within the canals near the source, rather than within the main lake body.

Loading of total phosphorus from all sources between 1971 and 1980 were estimated to be 67,000 to 96,000 pounds per year (82,877 lbs/yr average) and total nitrogen loadings were estimated between 1,102,000 and 1,915,000 pounds per year (1,770,000 lbs/year average) (APAI 1982b). Brazos River inflows, erosion and the Mineral Wells WWTP were listed as primary sources of nutrients (APAI 1982b).

Water quality modeling, performed with a completely mixed, steady-state mass balance of nitrogen and phosphorus loads indicated that phosphorus concentrations in the lake would increase by 30% if all septic systems were rerouted to a treatment facility that discharged to the lake (APAI 1982b). The APAI report indicates that the increase in phosphorus is primarily driven by the fact that there is no phosphorus removal in the wastewater treatment facility. No phosphorus limits were placed on wastewater discharges evaluated in the Hood County Regional Sewerage System study (BRA et al. 2000).

2.4.2 1982 Near-Shore Tracer Studies

Tracer tests and ambient water quality monitoring were conducted as a component of that study in the subdivisions of Oak Trail Shores, Comanche Harbor, Ports O’ Call, Indian Harbor, Sandy Beach and Port Ridglea East (west canal).

The tracer tests were conducted by injecting lithium chloride into new shallow wells (5’ to 9’ deep) located 5’ to 104’ from nearest septic drain field and 23’ to 59’ from lake shore; potentiometric surface ranged from 0.10’ to 0.50’ above lake water surface at the time of survey. A second well was installed at each location between the injection well and the lake shore. Four sets of two wells were constructed. Water quality samples were collected on four dates in each monitoring well and in lake waters adjacent to the wells. No data indicated that fecal coliforms from septic systems were entering the lake waters (APAI 1982a). Nutrient concentrations decreased from injection wells down-gradient to intermediate wells and down-gradient to lake waters indicating treatment within the soil (APAI 1982a). The tracer tests indicated hydraulic travel times to be between 0.2 and 2.0 feet per day (APAI 1982a).
2.4.3 BRA Lake Granbury Septic System Clean River Program Pilot Project

In 1995, the BRA initiated a survey of conditions and potential for impact of septic tank pollution on water quality of Lake Granbury. The report, Lake Granbury Septic System Clean River Program Pilot Project, summarizes a review of potential for septic problems and classifies some areas as having increased potential for problems (BRA 1995).

Review of over 7,400 Hood County Health Unit septic system permit records showed 75% of systems in areas with “severe” soils, and existing inadequacies (by 1995 TNRCC standards) in 27% of systems because of existing tank volumes and 99% because of inadequate drainfield areas. A door-to-door survey was conducted, indicating 7.5% of respondents have problems and less than 9% had ever performed service on the systems. Areas with water quality problems did not appear to correlate to highest levels of system inadequacy.

An intensive WQ sampling effort is summarized and a review of older samples conducted and lake sediments were analyzed at five main lake sites. A listing of coves with problems is included: Oak Trail Shores, Sky Harbor, Holiday Estates, Port Ridglea West, Port Ridglea East, DeCordova Bend on Walnut Creek and Strouds Creek.

Tables 2-3 and 2-4 include summaries of mean and median constituent concentrations sourced from studies (BRA 1995) as well as from more recent TCEQ data. The Clean River Program pilot project reported similar water quality in coves in 1995 compared to 1980 data, except for mean total Kjeldahl nitrogen (TKN) concentration that was 49% higher than mean reported in the 1982 study (BRA 1995). More recent data, for the period 1997 through 2006, indicates little change on the basis of median and average constituent concentrations.

Table 2-3: Mean Water Quality Concentrations

<table>
<thead>
<tr>
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<tr>
<td>Total Phosphate (mg/l)</td>
<td>1.41</td>
<td>0.36</td>
<td></td>
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<tr>
<td>Ortho-Phosphate (mg/l)</td>
<td>5.49</td>
<td>0.12</td>
<td>0.11</td>
<td>0.08</td>
<td>0.025/0.02</td>
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<tr>
<td>Total Phosphorus (mg/l)</td>
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<td>0.12</td>
<td>0.14</td>
<td>0.18</td>
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<td>0.1</td>
<td>0.04</td>
<td>0.12</td>
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<tr>
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<td>0.1</td>
<td>0.69</td>
<td></td>
<td>0.051</td>
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<td>Nitrite Nitrogen (mg/l)</td>
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<tr>
<td>Nitrate-Nitrogen Nitrogen (mg/l)</td>
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<tr>
<td>Total Inorganic (mg/l)</td>
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<td>1.6</td>
<td>1.4</td>
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<tr>
<td>TKN (mg/l)</td>
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<tr>
<td>TSS (mg/l)</td>
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<td>6.2</td>
<td>13.2</td>
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<td>VSS (mg/l)</td>
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<td>8.5</td>
<td>18.4</td>
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<td></td>
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<tr>
<td>TOC (mg/l)</td>
<td>5.3</td>
<td>5.71</td>
<td>5.6</td>
<td>6</td>
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<td>Chlorophyll a (ug/l)</td>
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<td>29.6</td>
<td>18.5</td>
<td>12.13</td>
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<td>Phaeophtyn a (ug/l)</td>
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<td>4.3</td>
<td>4.2</td>
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<td>Fecal Coliform (cfu/100ml)</td>
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<td>Oil and Grease (mg/l)</td>
<td>8.82</td>
<td>9.7</td>
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Table 2-4: Median Water Quality Concentrations

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<td><strong>Ortho-Phosphate (mg/l)</strong></td>
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<tr>
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<td><strong>TOC (mg/l)</strong></td>
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<tr>
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<tr>
<td><strong>Fecal Coliform (cfu/100ml)</strong></td>
<td>8.5</td>
<td>median</td>
<td>median</td>
<td>median</td>
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</tr>
<tr>
<td><strong>Oil and Grease (mg/l)</strong></td>
<td>8.7</td>
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<td>median</td>
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</tbody>
</table>

2.4.4 Canal Dye Studies

Canal dye studies were performed in 1997 in seven canal developments in Lake Granbury (conducted with a boat-mounted Turner Designs Model 10 Field Fluorometer). Fluorescence measurements indicated that the dye (Rhodamine WT) plume moved predominantly in the direction of the prevailing wind and not necessarily with the circulation of the canals (Miertschin 1997). Wind conditions were 10 to 18 mph (high winds) during the first round of sampling, and calm to 8 mph during the second round of sampling.

Calculation of diffusion coefficient describing overall exchange with lake waters is difficult. Assuming the field measurement was taken approximately 1 foot below the surface, the reported plume describes near-surface water movement corresponding to wind direction. However, flow near the bottom may circulate back to lake. Additional study is recommended using dye releases and drogues to characterize surface and below-surface water movements.

2.5 EXISTING DISCHARGE PERMITS

There are currently nine permitted wastewater discharges into Lake Granbury. The two most significant in terms of water quality are the City of Granbury waste water treatment plant which is permitted to discharge 2.0 million gallons per day (MGD) and Acton MUD (0.6 MGD). Texas Utilities (TXU) discharges cooling waters from a natural gas power plant (currently not generating); anecdotal reports indicate that the discharge canal is long enough to prevent warm waters from entering the lake body. BRA is authorized to discharge up to 2 MGD of brine effluent from a reverse osmosis water treatment plant. The remaining discharges are all package plant wastewater treatment facilities authorized for less than 0.1 MGD.
The City of Granbury, under TPDES Permit No. WQ0010178002, is authorized to discharge wastewater from the City of Granbury Southeast Wastewater Treatment Facility via pipeline into Lake Granbury. The Southeast Wastewater Treatment Facility is located on the east bank of Lake Granbury, approximately 0.9 miles south of the intersection of U.S. Highway 377 and Old Cleburne Road. The annual average flow of effluent shall not exceed 2.0 MGD and is limited to an average daily CBOD$_5$ of 10 mg/L, TSS of 15 mg/L, ammonia nitrogen of 3 mg/L, and fecal coliform bacteria of 400 mg/L. The effluent shall have a pH not less than 6.0 standard units or greater than 9.0 standard units and a minimum DO of 4.0 mg/L. The City of Granbury has had the following four unauthorized discharges: 1) 500 gallons on February 28, 2005 from the manhole at Spring and Crites Streets, 2) approximately 100 gallons on May 11, 2005 from the manhole in front of 1701 W. Pearl, 3) approximately 1,000 gallons on May 11, 2005 from the manhole at Plaza Drive and Southtown Drive to the alley way, and 4) approximately 500 gallons on May 13, 2005 from the manhole at Plaza and Southtown Drive.

Acton Municipal Utility, under TPDES Permit No. WQ0014211001, is authorized to discharge wastewater from the Decordova Bend Wastewater Treatment Facility into McCarty Branch to a cove of Lake Granbury. The Decordova Bend Wastewater Treatment Facility is located on the west bank of McCarty Branch, approximately 2.6 miles south of the intersection of U.S. Highway 377 and Farm to Market road 167. The daily average flow of effluent shall not exceed 0.6 MGD. The effluent is limited to an average daily CBOD$_5$ of 7 mg/L, TSS of 15 mg/L and ammonia nitrogen of 2 mg/L. The effluent shall contain a chlorine residual of at least 1.0 mg/l, a minimum DO of 6.0 mg/L, and the pH shall not be less than 6.0 standard units or greater than 9.0 standard units. Acton Municipal Utility had an unauthorized discharge of wastewater in the amount of approximately 7,200 gallons on June 9, 2004 from manhole #2 tee box at Decordova off Fairway Drive, on August 25, 2004 at 4905 Rio Vista Street Decordova Bend, on August 1, 2004 of approximately 1,200 gallons from a manhole at 4605 Aqua Court, and on August 25, 2004 of 5,700 gallons at 4905 Rio Vista Street Decordova Bend.

The TXU DeCordova Company LP & TXU Generation Company LP, under TPDES Permit No. WQ0001481000, is authorized to discharge cooling water from the DeCordova Steam Electric Station to Lake Granbury. The DeCordova Steam Electric Station is located on the southwest shore of Lake Granbury along County Road 312, approximately seven miles southeast of the intersection of U.S. Highway 377 and State Highway 144, in the City of Granbury. The daily average flow of the once-through cooling water discharge shall not exceed 1,041.48 MGD and is limited to a daily average of 105 °F and a daily maximum of 0.2 mg/L of residual chlorine. Low volume wastes and storm water runoff from yard drains and diked oil storage areas shall not exceed 30 mg/l of TSS and 15 mg/L of oil and grease on a daily average and the pH shall not be less than 6.0 standard units nor greater than 9.0 standard units. Metal cleaning wastes and/or low volume wastes shall not exceed a daily average of 1.0 mg/L of total iron and 0.5 mg/L of total copper and the pH shall not be less than 6.0 standard units nor greater than 9.0 standard units.

The Brazos River Authority, under TPDES Permit No. WQ0002889000, is authorized to discharge brine from the reverse osmosis treatment system of the Lake Granbury Surface Water and Treatment System Facility. The wastewater is permitted to be discharged into Lake Granbury via a submerged pipe in the Lake. The Lake Granbury Surface Water and Treatment System Facilities are located southeast of the City of Granbury, approximately 5 miles southeast of the intersection of Farm to Market Road 167 and U.S. Highway 377, and approximately 0.5 miles southeast of the intersection of Farm to Market Road 167 and County Road 308. The daily average flow of effluent shall not exceed 2.5 MGD and is limited to a daily average 9,900 mg/L of chlorides and 4,700 mg/L sulfates. The pH shall not be less than 6.0 standard units or greater than 9.0 standard units.
Hood County Utilities, Inc., under TPDES Permit No. WQ0013022001, is authorized to discharge wastewater from the Hood County Utilities, Inc. wastewater treatment facility via pipeline to Lake Granbury. The Hood County Utilities, Inc. wastewater treatment facility is located at 4704 Blue Water Circle, on the north shore of Lake Granbury, approximately 2 miles from the Lake Granbury Dam and south of Hood County Road No. 309. The daily average flow of effluent shall not exceed 0.088 MGD and is limited to a daily average of 10 mg/L of BOD₅ and 15 mg/L of TSS. The effluent shall have a pH not be less than 6.0 standard units or greater than 9.0 standard units, a minimum dissolved oxygen (DO) of 4 mg/L, and at least a 1.0 mg/L chlorine residual.

EDR, Inc., under TPDES Permit No. WQ0002678000, is authorized to discharge wastewater from the Oak Hills electrode dialysis reversal surface water treatment facility into Lake Granbury. The Oak Hills facility is located approximately three miles northwest (via Farm to Market Road 2580) of the Town of Thorp Spring. The daily average flow of effluent from the electrode dialysis reversal unit reject water and filter backwash shall not exceed 0.16 MGD, is limited to a daily average of 4,500 mg/L of TDS, and the pH shall not be less than 6.0 standard units nor greater than 9.0 standard units.

Ridge Utilities, Inc., under TPDES Permit No. WQ0013025001, is authorized to discharge wastewater from the Ridge Utilities, Inc. Wastewater Treatment Plant to Lake Granbury. The wastewater treatment plant is located approximately 1,700 feet northeast of the intersection of Hood County Road 311-A and Farm to Market Road 3210 southeast of the City of Granbury. The effluent is limited to an average daily BOD₅ of 10 mg/L and TSS of 15 mg/L. The effluent shall contain a chlorine residual of at least 1.0 mg/L, a minimum DO of 4.0 mg/L, and the pH shall not be less than 6.0 standard units or greater than 9.0 standard units. The facility has different flow restrictions based on the status and size of the facility. During the period beginning upon the date of issuance and lasting through the completion of expansion of the facilities to 0.06 MGD, the permittee is authorized to discharge a daily average flow of effluent not to exceed 0.035 MGD. During the period upon the completion of expansion of the facilities to 0.06 MGD and lasting through the date of expiration, the permittee is authorized to discharge a daily average flow of effluent not to exceed 0.06 MGD.

Texas H₂O, Inc., under TPDES Permit No. WQ0013786001, is authorized to discharge wastewater from the Canyon Creek Wastewater Treatment Facility to Lake Granbury. The Canyon Creek Wastewater Treatment Facility is located adjacent to Lake Granbury approximately 2 miles north of the intersection of Farm to Market Road 2425 and 3210 in Walters Bend. The daily average flow of effluent shall not exceed 0.042 MGD and is limited to an average daily BOD₅ of 10 mg/L and TSS of 15 mg/L. The effluent shall have a pH not less than 6.0 standard units or greater than 9.0 standard units, a minimum DO of 4.0 mg/L, and a chlorine residual of at least 1.0 mg/L.

Lake Trails Properties, Inc., under TPDES Permit No. WQ0014162001, is authorized to discharge wastewater from the Lake Trails WWTP No. 1 Wastewater Treatment Facility to an unnamed tributary of South Fork Strouds Creek; thence Strouds Creek; thence to Lake Granbury. The Lake Trails WWTP No. 1 facility is located approximately 1,600 feet north of the intersection of U.S. Highway 377 and County Road 102 (Cokes Ct.). The effluent is limited to an average daily BOD₅ of 10 mg/L and TSS of 15 mg/L. The effluent shall contain a chlorine residual of at least 1.0 mg/L, a minimum DO of 4.0 mg/L, and the pH shall not be less than 6.0 standard units or greater than 9.0 standard units. The facility has different flow restrictions based on the status and size of the facility. During the period beginning upon the date of issuance and lasting through the completion of expansion of the facilities to 0.025 MGD, the permittee is authorized to discharge a daily average flow of effluent not to exceed 0.01 MGD. During the period beginning upon the completion of expansion of the facilities to 0.025 MGD and lasting through the date of expiration, the permittee is authorized to discharge a daily average flow of effluent not to exceed 0.025 MGD.
3.0 WATER QUALITY DATA ANALYSIS

3.1 PURPOSE

Water quality data obtained for this project was analyzed to determine potential water quality trends in Lake Granbury. These trends are evaluated for nutrients and bacteria in both the main lake body and each canal system of Lake Granbury where monitoring data are available. One objective of this analysis, which will be investigated in more detail during the subsequent Phase 2 modeling task, is to separate influence of background lake conditions from local influence inside each canal. A secondary objective is to determine the status of the lake with respect to nutrients. Since a potential outcome of this project is construction of new waste collection and treatment facilities, the current nutrient status of the lake needs to be determined so that potential wastewater discharges into the lake can be evaluated.

3.2 LAKE GRANBURY DATA ANALYSIS

Lake segmentation for this preliminary analysis is shown in Figure 1. TCEQ Surface Water Quality Monitoring (SWQM) data available from 1972 to present was analyzed for identification of trends. Three long-term water quality monitoring stations exist in the main body of the lake; each preliminary lake segment contains one of these long-term monitoring stations. Water quality parameters included in this analysis are total phosphorus, total nitrogen, Nitrate + Nitrate (NOx), turbidity (secchi depth), dissolved oxygen (DO), chlorophyll-a and bacteria. Analysis of a derivative dataset including DO deficit is also presented. The main body of Lake Granbury is divided into three segments and the trend analysis was completed utilizing data obtained in those three segments. Preliminary segmentation is shown in Figure 3.1.
3.2.1 Vertical profiles

Vertical variation in temperature and dissolved oxygen (DO) are evident in historical data; data for the period February 1972 through March 2006 were analyzed. Temperature stratification is common April through August, with average temperature difference being greater than 5°C (Figure 3.2). Min and max temperature for each measurement where profiles were taken are shown in Figure 3.3. Depth to greatest change in temperature (approximation of thermocline depth) is generally 11m near the dam (Segment 1) in May, followed by either greater or lesser depths through September. Few measurements show stratification near the dam October, November, December, January or February (Figure 3.4). Thermocline depth at Segments 2 and 3 are shown on Figure 3.4.
Figure 3.2 - Segment 1 - Average Temperature Profile by Month

Figure 3.3 - Segment 1 - Temperature Profiles, Discrete Readings (1998-2006)
Figure 3.4 – Depth to Thermocline, by Month (1998-2006)

Figure 3.4b – Average DO profile characteristics, by month
3.2.2 Lake Granbury – Chlorophyll-a, Nutrient, DO and Secchi Depth Spatial and Temporal Trends

3.2.2.1 Nitrate + Nitrite (NOx)

Nitrogen series data sets existed from 1970 through 2006. The confidence level for the early part of this historical record is low. The number of nitrogen samples was small prior to 1999. Detection limits were also different and nitrogen values were sometimes reported as the detection limit. Therefore, only recent nitrogen data was used in the evaluation of a nitrogen trend in the main body of Lake Granbury. No trends in NOx concentration were observed due to the small period of record (Figures 3.5 to 3.7). Nitrogen levels in Lake Granbury are sufficient to provide enough substrate for algae.

Figure 3.5: Segment 1, NOx
Lake Grandbury Segment 2 - 11861

Figure 3.6: Segment 2, NOx

Lake Grandbury Segment 3 - 11862

Figure 3.7: Segment 3, NOx
3.2.2.2 Total Phosphorus

Trends were seen in total phosphorus (Figures 3.8 to 3.10). Sample concentrations for total phosphorus that were reported at the reporting limit during the period 2001 to 2006 were replaced by either the actual machine output value or the method detection limit (0.005 mg/L), whichever was higher. The trend line from Figure 3.8 for Segment 1 shows an overall increase from 0.02 mg/L in the early 1970s to values of 0.05 mg/L and higher. Likewise, Segment 2 trends also increase from 0.02 to 0.05 mg/L and higher over the 30 year period. Segment 3 (Figure 3.10) also has a slightly increasing trend; however, the trend is not as dramatic as in the lower two reaches of the lake.

These trends need to be evaluated more closely and monitored to determine if the increasing trend is continuing. The figures show a linear regression trend line as well as lines representing the 95% confidence limits. The regression line should not be construed as a predictive tool for trends; rather, trends were evaluated using the confidence bound lines. Using Figure 3.8 as an example, the possibility of exists of a linear trend line having zero slope (i.e. there is no trend) or increasing slope; however, no possibility exists of a decreasing linear trend over time. Therefore, we are 95% confident that the trend in total phosphorus concentration has not been decreasing in Segment 1.

Differences in analytical methods for testing, in detection limits for the methods and in reporting of values at or below detection limits need to be considered when evaluating these nutrient results. If this trend continues additional analysis for phosphorus sources will need to be performed to quantify the source and amounts of nutrients to allow BRA to minimize the amount of phosphorus coming into Lake Granbury. Phosphorus levels in Lake Granbury are sufficient to provide enough substrate for algae.
Temporal Trend with 95% confidence limits - Lake Granbury Segment 2 - 11861

Figure 3.9: Segment 2, Total Phosphorus

Temporal Trend with 95% confidence limits - Lake Granbury Segment 3 - 11862

Not shown:
11/20/2002 0.87 mg/L
09/09/2004 0.76 mg/L

Figure 3.10: Segment 3, Total Phosphorus
3.2.2.3 Chlorophyll-a

Chlorophyll-a is a measure of the presence of algae (phytoplankton) in a body of water. The first trend analysis performed for this study was for chlorophyll-a in the main body of Lake Granbury. Figures 3.11 through 3.13 provide the chlorophyll-a data for the three main body segments. Within the main lake body within all segments, increases were observed in chlorophyll-a concentration within 95% confidence limits of the linear trend (Figures 3.11 to 3.13). The trend line from Figure 3.5 for Segment 1 shows an overall increase from low values in the early 1970s to values of 20 µg/L in the 2000s. Likewise, Segment 2 trends also increase from 10 to 20 µg/L over the 30 year period. Segment 3 (Figure 3.13) also has an increasing trend; however, the trend is not as dramatic as in the lower two reaches of the lake. These trends need to be evaluated more closely and monitored to determine if the increasing trend is continuing. If this trend continues additional analysis for nutrient sources will need to be performed to quantify the source and amounts of nutrients to allow BRA to minimize the amount of nutrients coming into Lake Granbury.

![Temporal Trend with 95% confidence limits - Lake Grandbury Segment 1 - 11860](image)

**Figure 3.11: Segment 1, Chlorophyll-a**
Figure 3.12: Segment 2, Chlorophyll-a

Figure 3.13: Segment 3, Chlorophyll-a
Chlorophyll-a exhibited a range of concentrations during every month of the year. Common to all three stations was a weak trend where minimum concentrations in March and April were slightly elevated. Minimum concentrations in September, October and November were also slightly elevated.

3.2.2.4 DO and Secchi

Trend analysis performed was for DO and secchi depth in the main body of Lake Granbury. Within Segment 1 near the dam, DO measurements have decreased slightly (Figure 3.14). Slight increases in the DO deficit (Figure 3.15) and decreases in secchi depth readings (Figure 3.16) were also observed but no significant trend was shown within 95% confidence in either case. DO deficit was determined by subtracting measured DO from saturation DO. Theoretical saturation concentration for DO was calculated using corrections for temperature and salinity.
Temporal Trend with 95% confidence limits - Lake Granbury Segment 1 - 11860

Figure 3.14: Segment 1, DO Measurements

Temporal Trend with 95% confidence limits - Lake Granbury Segment 1 - 11860

Figure 3.15: Segment 1, DO Deficit
DO measurements for Segment 2 of the main body of Lake Granbury are shown in Figure 3.17. Slight decreases in DO measurements are also seen in Segment 2. However, no significant trend was observed for DO deficit (Figure 3.18). Within Segment 2 near the City of Granbury, scatter within secchi depth data prevented evaluation of a trend (Figure 3.19) but an increase was shown between 95% confidence limits.
Figure 3.17: Segment 2, DO Measurements

Figure 3.18: Segment 2, DO Deficit
DO measurements for Segment 3 of the main body of Lake Granbury are shown in Figure 3.20. A slight decrease can be observed in the DO measurements. Within Segment 3 near the headwaters, an increase in DO deficit was observed within 95% confidence limits (Figure 3.21). No significant trend in secchi depth readings was observed (Figure 3.22).

While trends in DO have not been significant enough to cause concern that the DO standard could be violated, DO deficit values exhibit a significant fraction of samples that are supersaturated by 2 mg/L or more. Considering samples are collected during daylight hours, the persistent supersaturation may be cause for concern that algal activity, i.e., photosynthesis, may be inflating DO concentrations. This observation, coupled with a general decrease in secchi depth, and increases in total phosphorus and chlorophyll-a concentrations, may indicate a trend towards eutrophication. To determine significant sources of nutrients, a careful nutrient budget is recommended as well as additional monitoring of phosphorus concentrations to detection limits below the existing reporting limit.
Temporal Trend with 95% confidence limits - Lake Granbury Segment 3 - 11862

Figure 3.20: Segment 3, DO Measurements

Temporal Trend with 95% confidence limits - Lake Granbury Segment 3 - 11862

Figure 3.21: Segment 3, DO Deficit
3.2.3 Lake Granbury – Nutrient Trends With Flow and Precipitation

Nutrient concentrations were analyzed with regard to inflows into Lake Granbury. This analysis was performed in Segment 3 (upstream segment) to determine trends in nutrient concentrations related to high or low flows into Lake Granbury. As can be seen in Figure 3.23 nitrate concentrations greater than 0.05 mg/L near the dam occurred during low and high inflows (USGS Dennis gauge). Similar trends were evaluated for total and orthophosphorus. Orthophosphorus is the soluble form of phosphorus that is readily utilized by biological organisms such as algae. Orthophosphorus measurements greater than 0.05 mg/L were also found during low and high flow events (Figure 3.25). Total phosphorus above 0.05 mg/L was found in flows over 100 cfs.

Additional analyses were performed to determine if nutrient concentrations were related to precipitation events. Nitrate concentrations greater that 0.05 mg/l occurred during both low or high rainfall events (Figure 3.24); nitrogen concentrations in the main body of Lake Granbury do not illustrate a trend related to inflow or rainfall. Orthophosphorus measurements greater than 0.05 mg/L were also found during low and high precipitation events (Figure 3.26). Total phosphorus also does not have a relationship to precipitation events.
Figure 3.23: Segment 3, NOx vs. Lake Inflow

Figure 3.24: Segment 3, NOx vs. 5-day Precipitation
Figure 3.25: Segment 3, TP vs. Lake Inflow

Figure 3.26: Segment 3, TP vs. 5-Day Precipitation
3.2.4 Lake Granbury - Carlson’s Trophic State Index

The Carlson’s Trophic State Index (TSI) is an index developed for nutrient levels, algae growth, and secchi depths to allow reservoirs to be compared on a common basis. For the station located nearest the dam, the TSI was determined using data for the period 1993 to 2003 (TCEQ 2005).

TSI (chlorophyll-a) is 57.4 for average surface chlorophyll-a concentration of 15.4 mg per cubic meter for all records (N=21). Lakes with TSI chlorophyll-a > 55 are assigned a Trophic Class of Hypereutrophic. Lake Granbury would rank between Lake Tawakoni (TSI chlorophyll-a = 56.61) and Fayette Reservoir (TSI chlorophyll-a = 58.24), with only 9 of 94 classified Texas lakes having higher TSI chlorophyll-a values. Other lakes with TSI chlorophyll-a between 55.70 and 60.98 that rank between #83 and #88 include Lake Livingston, Lake Tanglewood, Springfield Lake and Eagle Mountain Reservoir.

TSI (total phosphorus) is 58.8 for average surface total phosphorus concentration of 46.0 mg per cubic meter for all records (N=18). Lakes with TSI total phosphorus between 58.63 and 59.03 that rank between #47 and #51 on an increasing scale out of 94 classified Texas lakes include Lake Cypress Springs, Lake Lavon, Lake Waxahachie, Lake Buchanan and Lake O’ the Pines.

TSI (secchi disk) is 56.9 for average secchi depth of 1.24 m for all records (N=46). Lakes with TSI secchi between 56.5 and 57.21 that rank between #29 and #33 on an increasing scale out of 94 classified Texas lakes include Lake Lyndon B. Johnson, Lake O’ the Pines, Richland-Chambers Reservoir, Joe Pool Lake and Fayette Reservoir.

3.2.5 Lake Granbury – Bacteria

Between 1972 and 2004, fecal coliform and E. coliform concentrations have historically been below 15 or 20 colonies per 100mL with spikes generally less than 70 colonies per 100 mL (Figures 3.27 to 3.36). Three fecal coliform samples are reported between 150 and 300 colonies per 100 mL in Segment 3 (lake headwaters) (Figure 3.33). One occurred in January and two in March which may correspond to periods that waterfowl migration, utilizing the shallow headwater areas. High concentrations of coliform occurred when rainfall had occurred within the 5 days preceding the sampling event (Figure 3.36); however, no relationship with precipitation is indicated. No strong relationship of concentration to lake inflow was evident (Figure 3.35).
Lake Granbury Segment 1 - 11860

Not shown:
1/12/98  1,200 #/100mL

Figure 3.27: Segment 1, Fecal Coliform

Figure 3.28: Segment 1, E. coli
Figure 3.29 - Bacteria vs. Precipitation at the Dam

Figure 3.30: Segment 2, Fecal Coliform
Lake Granbury Segment 2 - 11861

Not shown: 03/26/2002 62 MPN/100mL

Figure 3.31: Segment 2, E. coli

Figure 3.32 - Segment 2, Bacteria vs. 5-Day Precipitation at the Dam
Lake Granbury Segment 3 - 11862

**Figure 3.33:** Segment 3, Fecal Coliform

Lake Granbury Segment 3 - 11862

**Figure 3.34:** Segment 3, E. coli
Figure 3.35: Segment 3, Bacteria vs. Lake Inflow

Figure 3.36: Segment 3, Bacteria vs. 5-Day Precipitation at Dam
3.3 WATERSHED

3.3.1 Spatial Data Sources

Data for this analysis were collected from a wide variety of sources and processed to match the extent and coordinate system for the study area (Table 3.1). The study area includes the USGS 12-digit hydrologic unit code (HUC) boundaries adjacent to Lake Granbury as well as a subset of the area covered by microwatersheds created by BRA. The coordinate system used in this study was Universal Transverse Mercator (UTM) Zone 14N, North American Datum 1983 (NAD83), with linear units in meters.

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<th>Base Data</th>
<th>Cities – ESRI StreetMap Data, representing cities with populations of 10,000 or greater.</th>
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<td>Digital Elevation Model (DEM) – USGS 30 m National Elevation Data (NED)</td>
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<td>Slope – degree slope derived from 30 m NED data</td>
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<td>Hood County Appraisal District septic system permit records</td>
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<td>USGS 1992 National Land Cover Data (NLCD)</td>
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<td></td>
<td>Brazos River Authority (BRA) 2003-2005 land use/land cover</td>
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<td>Farm Service Agency 2004 NAIP imagery</td>
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<td>National Hydrography Data (NHD) Plus flowline data</td>
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<td>NRCS SSURGO soils data</td>
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<td>BRA delineated microwatershed boundaries</td>
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3.3.2 SPATIAL TRENDS

Trends were analyzed for both land use change and septic system use in the study area.

3.3.2.1 Land Use Change
Land use data was obtained from the 1984 GIRAS, 1992 NLCD, and 2004 BRA digitized land use datasets. Data was aggregated for each dataset in order to address issues with classification codes for each dataset (Table 3.2).

The Tabulate Area tool in ESRI's ArcGIS software was used to determine the total area of each land use type associated with the GIRAS and NLCD datasets in the cove (12-digit) watersheds. From this, the percent area was calculated (Tables 3.3 and 3.4). This process was repeated for the GIRAS, NLCD, and BRA land use datasets using the BRA microwatersheds. Finally, the percent area for commercial and residential land use types for the three datasets was joined to the microwatershed boundaries for comparison (Figure 3.37).

In general, there was a decrease in agricultural land and increase in rangeland, with a slight increase in commercial areas and only negligible changes in residential areas for the cove watersheds from 1984 (GIRAS)-1992 (NLCD). However, there was a significant increase in residential areas of many microwatersheds around the lake between the 1992 (NLCD) and 2003 (BRA) time periods (Figure 3.37).

3.3.2.2 Septic System Use

Two datasets were used in the septic trend analysis for the subdivisions near Lake Granbury, subdivision age and the SCS (Soil Conservation Service) Limitation Classes for Septic Tank Soil Absorption Suitability. Subdivision age was obtained by BRA from the Hood County Appraisal District. The data was then broken into four risk classes (Table 3.5) based on similar work by Tyson (2003).

In addition to the subdivision age, the SCS Limitation Classes for Septic Tank Soil Absorption Suitability were used to further identify areas at risk. The data used in this analysis were gathered from the Hood and Parker County Soil Surveys. The parameters used in this classification (Table 3.6) are outlined in the SCS Soil Survey Manual Chapter 6 (SCS, 1993).

The septic tank suitability ratings were joined to the corresponding SSURGO soil polygons and the majority rating for each subdivision was used for further analysis.

Once the age and septic tank suitability ratings were calculated for each subdivision, they were weighted based on survey responses summarized in Reed et al. (2001). The weighting factors for Region 1 of the On-site Waste Water Regions of Texas were 51% for age of the system and 20% for soil suitability (17% for soil properties and 3% for water table depth). These values were normalized and age was weighted at 71%, whereas soils were weighted at 29%.

The final combination of these weighted rankings resulted in a range of values between 1 and 3, which were classified into the three groups, slight (1), moderate (2), and severe (3). This risk refers both to the risk of septic system failure (age) and the risk that contaminants will runoff into the environment rather than being absorbed into the soil (septic tank suitability). A class 4 rating identifies subdivisions that are not currently using septic systems. Additionally, any subdivision missing either age or septic tank suitability ratings was removed from further analysis and assigned a value of -99 (Figure 3.39).
### Table 3-2: Land Use Groupings for Trend Analysis

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<th>NLCD 1992</th>
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Figure 3.37: Microwatersheds and Change in Percent Residential Area 1984 to 2003

Legend

Percent Residential Area

51

Giras Residential (1984)
NLCD Residential (1992)
BRA Residential (2003)
### Table 3.5 - Age Based Classification of Granbury Subdivisions.

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<thead>
<tr>
<th>Subdivision/Septic System Age</th>
<th>Failure Risk Rating</th>
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<tr>
<td>0-10 years old</td>
<td>Low Risk</td>
</tr>
<tr>
<td>11-20 years old</td>
<td>Low – Mod Risk</td>
</tr>
<tr>
<td>21-30 years old</td>
<td>Mod – High Risk</td>
</tr>
<tr>
<td>&gt;30 years old</td>
<td>High Risk</td>
</tr>
</tbody>
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### Table 3.6 - Interpretative Soil Properties and Limitation Classes for Septic Tank Soil Absorption Suitability (Source: SCS, 1993).

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<th>Limitation Class</th>
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<td></td>
<td>Slight</td>
</tr>
<tr>
<td>Total Subsidence (cm)</td>
<td>--</td>
</tr>
<tr>
<td>Flooding</td>
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</tr>
<tr>
<td>Bedrock Depth (m)</td>
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</tr>
<tr>
<td>Cemented Pan Depth (m)</td>
<td>&gt; 1.8</td>
</tr>
<tr>
<td>Free Water Occurrence (m)</td>
<td>&gt; 1.8</td>
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<td>Saturated Hydraulic Conductivity (µm/s)</td>
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<tr>
<td></td>
<td>Maximum 0.6 to 1 m²</td>
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<tr>
<td>Slope (Pct)</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>Free Water Occurrence (m)</td>
<td>&lt; 1.8</td>
</tr>
<tr>
<td>Saturated Hydraulic Conductivity (µm/s)</td>
<td>&lt; 10-40</td>
</tr>
<tr>
<td></td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Ice Melt Pitting</td>
<td>c</td>
</tr>
<tr>
<td>Permafrost</td>
<td>d</td>
</tr>
</tbody>
</table>

a. 0.6 to 1.5 m pertains to percolation rate; 0.6 to 1 m pertains to filtration capacity
b. Weighted average to 1 m.
c. Rate severe if occurs.
d. Rate severe if occurs above a variable critical depth (see discussion of the interpretive soil property).
Figure 3.38 - Septic Index
Aerial Photo and Subdivision Map With Septic Index

Lake Granbury, Texas

Legend

- Septic Index
  - 0: no data
  - 1: slight risk
  - 2: moderate risk
  - 3: high risk
  - 4: collection sys

- Sites
  - Rollinghills Shores
  - Arrowhead Shores
  - Oak Trail Shores
  - Sunrise Bay
  - City of Granbury, Lambert Branch
  - Lake Granbury Marina Addition
    - JJ. Mathis
    - South Harbor
    - Rough Creek
    - Rock Harbor
    - Scenic View
  - Comanche Harbor
  - Comanche Point
  - Island Village
  - Ports O' Call
  - Indian Harbor
  - Canyon Creek
  - Texas Utilities
  - Laguna Tres
  - Sky Harbor
  - Alta Vista
  - Hideaway Bay
  - Mallard Pointe
  - Lakewood Hills
  - The Shores
  - Catalina Bay II
  - Western Hills Harbor
  - Harbor Lakes
  - Waters Edge
  - Grand Harbor
  - Sandy Cove
  - Nassau Bay
  - DeCordova Bend Estates
  - Timber Cove
  - Montego Bay
  - Port Ridglea East
  - Port Ridglea
  - Holiday Estates
  - Nassau Bay II
  - Ray Lynn
  - Jackson Heights
  - Jackson Estates
  - Blue Water Shores
3.4 COVES AND MAN-MADE CANALS ANALYSIS

Lake Granbury has numerous coves and man-made canals that have been impacted by high levels of bacteria. BRA has developed a monitoring program to assist in the data collection to obtain the data needed to identify which of the coves or canals has a bacteria problem and which cove or canal has the most significant problem. These data sets (along with others developed in this report) will provide the information needed to perform water quality analysis and modeling to improve these troubled areas.

3.4.1 Rolling Hills Shores

The Rolling Hills Shores subdivision is located at the north end of Lake Granbury is a cove/canal area. Rolling Hills Shores was developed in the early 1970s and is surrounded by a large lagoon area. Since the subdivision is located in a large lagoon area it is not on the deeper channel of the Lake. The subdivision is not located on the The subdivision was originally approved as a vacation community with septic systems without leachfields or drainfields. The septic systems were simple holding tanks that require pumping and disposal of waste. However, since most current residents live at the properties year-round the need to pump the septic systems has increased dramatically. Significant amounts of sewage ends up in the lagoon either from direct application (illegal pump-out of holding tanks directly into the water) or from damaged holding tanks (bottoms fractured or removed). BRA Ranger Lewis described multiple enforcement actions in this area. Bathymetry and sedimentation is unknown in this area and neither the TWDB 1993 or 2003 hydrographic surveys report data in this part of Lake Granbury.

With the exception of one measurement, all orthophosphate and NOx concentration measurements were reported at the reporting limits, so no trends were indicated. The geometric mean E. coli. concentration was 13.9 MPN per 100 mL and the 75th percentile was 40.25 MPN per 100 mL. Twelve samples exhibited concentrations greater than 126 MPN per 100 mL with the maximum concentration reported at 812 MPN per 100 mL (Figure 3.41). DO measurements are shown in Figure 3.43 and indicate low DO in 2004 with an increasing trend to 2006 (median 5.64 mg/L; 25th percentile 2.1 mg/L) and DO deficit was high in 2004 but showed a decreasing trend to 2006 (Figures 3.44).
Figure 3.40: Rolling Hills Shores Septic Index
Figure 3.41: Rolling Hills Shores, E. Coli Bacteria

Figure 3.42 - Rolling Hills Shores, Bacteria vs. 1-Day Precipitation at Dam
Figure 3.43: Rolling Hills Shores, DO Measurements

Figure 3.44: Rolling Hills Shores, DO Deficit
3.4.2 Arrowhead Shores

Arrowhead Shores is a man-made “T” canal with one inlet from the main body of the lake in the middle of the canal (Figure 3.45). The subdivision is not on the river channel side of the lake. TWDB 2003 hydrosurvey indicates elevations of 685’ to 687’ inside the canal (5’ to 7’ depth from CPE); however, depths at the lake interface are reduced to 3’ to 3.5’ (689.5’ to 690’). DO measurements indicate seasonal cycling between 2004 and 2006 with summertime DO concentrations lower than 5.0 mg/L and as low as 3 mg/L. This canal system has had high concentrations of E. coli over 500 and 600 MPN per 100 mL. Two high bacteria concentrations were evident with antecedent rainfall but the trend is unclear.

Figure 3.45: Arrowhead Shores Septic Index
Arrowhead Shores

Station IDs: 18006, 18007

Figure 3.46: Arrowhead Shores, DO Measurements

Figure 3.47: Arrowhead Shores, DO Deficit
Figure 3.48: Arrowhead Shores, Bacteria vs. 1-Day Precipitation
3.4.3 Oak Trail Shores

Oak Trail Shores is a densely populated subdivision developed in the early 1970’s. As can be seen in Figure 3-49, the subdivision is not on the river channel side of the lake. The north end of the north arm of the man-made T-canal collects and holds debris and floating vegetation (winds generally hail out of south). Ranger Lewis described a developer’s proposal to collect stormwater runoff from higher surrounding elevations and discharge into north end of north arm to provide circulation and dilution.

The 2003 TWDB hydrosurvey indicate elevations are near 689’ (4’ deep at CPE) and uniform from the entrance to the ends of canals.

Orthophosphous concentrations were reported at the reporting limits for all samples. Nitrate plus nitrite (NOx) concentration exhibited several high samples, but no high concentrations were measured after...
September 2005 (Figure 3.50). Nitrate concentration was generally lower for station 18008 (north end of north canal) and exhibited highest concentrations in the south end of the south canal (18010); concentrations at the “T” part of the canal (18009) generally tracked slightly lower than concentrations to the south. No trend in nitrate concentration with precipitation was evident.

Peak bacteria concentrations at each station did not correspond temporally to peaks at other stations, i.e., peak concentrations for a sampling day alternated among all three stations indicating that a single source is likely not causing all bacteria problems. There were numerous high E. coli measurements over the data collection period (Figure 3.51) but no trend was apparent from 2004 through 2006. E. coli concentrations also did not relate to precipitation events (Figure 3.52). DO measurements from 2004 to 2006 indicate seasonal cycling with summertime DO concentrations lower than 5.0 mg/L and as low as 2 mg/L (Figure 3.50). This canal system has exhibited baseline concentrations of E. coli between 200 and 300 MPN per 100 mL (Figure 3.50). Four of six samples exhibiting higher concentration (400 to 1800 MPN/100mL) occurred after a rainfall event; however, 23 samples exhibited baseline concentrations so a trend with rainfall is not evident (Figure 3.51). The DO deficit exhibited an increasing trend during that time period (Figure 3.54).
Figure 3.51: Oak Trail Shores, E. Coli

Figure 3.52: Oak Trail Shores, Bacteria vs. 1-Day Precipitation
Figure 3.53: Oak Trail Shores, DO Measurements

Figure 3.54: Oak Trail Shores, DO Deficit
3.4.4 Sky Harbor

Sky Harbor is a development constructed in the early 1970s. The development has houses with septic systems with drainfields located on terraces immediately adjacent to the canal system. Upper reaches of the canal had a layer of debris visible on the surface of the water. The subdivision is on the river channel side of the lake. The 2003 TWDB hydrosurvey ranged from 675’ in the deepest part of the main cove waters to uniform bottom elevations of 686.5’ and 689’ in two of the canals (5.5’ to 4’ depth from CPE).

An impoundment on Bee Creek, a tributary providing inflow to one arm of the cove, was visually inspected by land. The pond was nearly dry at the time of site visit (June 16, 2006). A fountain system was visible and consisted of a pump drawing water from lake (downstream, below culverts); BRA noted it is permitted to withdraw 15 ac-ft/year from the lake. Resident anecdotes report that problems have decreased since installation of the fountain system. Bacterial issues could be reduced with the addition of lake water due to dilution; the fountain system promotes circulation and aeration thereby potentially reducing odors.

Orthophosphous concentrations were reported at the reporting limits for all samples. Nitrate plus nitrite (NOx) concentration exhibited several high samples coincident with high values in the lake (Figure 3.56).

There were numerous high E. coli measurements over the data collection period (Figure 3.57) with a slightly decreasing trend. Many of the values are in excess of 400 MPN per 100 mL (Figure 3.57). The relationship of E. coli concentrations to precipitation events was not clear (Figure 3.58). Careful station-by-station analysis of concentration peaks revealed the potential for multiple bacteria sources, none of them individually trending with precipitation. DO measurements from 2004 to 2006 exhibited a seasonal trend with DO levels falling below 5.0 mg/L in summer months, falling near 2.0 mg/L in some areas (Figure 3.59). The DO deficit exhibited springtime periods of supersaturation indicative of algal growth (Figure 3.60).
Figure 3.55: Sky Harbor Septic Index
Figure 3.56: Sky Harbor, NOx Measurements

Figure 3.57: Sky Harbor, E. Coli Measurements
Figure 3.58: Sky Harbor, Bacteria vs. 1-Day Precipitation

Figure 3.59: Sky Harbor, DO Measurements
Figure 3.60: Sky Harbor, DO Deficit
3.4.5 Subdivisions near Granbury, TX, including Waters Edge

A number of subdivisions near the City of Granbury that are not connected to the collection system have a septic index indicating risk for system failure (Figures 3.61 and 3.62). Water’s Edge, which is connected to the City’s wastewater collection system, was the only subdivision in this area where monitoring data was collected. E. coli concentrations were only slightly elevated compared to lake concentrations, except for two isolated events when concentrations at station 18018 were higher than 200 MPN/100ml (Figure 3.63).
Figure 3.62: Septic Index for areas south of Granbury, TX
Figure 3.63: Waters Edge, E. Coli vs. 1 day Precipitation

Station IDs: 18018, 18019, 18020
3.4.6 Ports O’ Call and Indian Harbor

Baseline concentrations of E. coli in both Ports O’ Call and Indian Harbor subdivisions were elevated above lake levels; four measurements (two each from 18021 and 18022) exhibited concentrations above 100 MPN/100mL. These subdivisions are not on the river channel side of the lake. Compared to other canals, these canals are larger and deeper so therefore likely benefit from more exchange with lake waters. Lower bacteria levels may be the result of dilution rather than lower load.

Figure 3.64: Ports O’ Call and Indian Harbor Septic Index
Figure 3.65: Ports O’ Call and Indian Harbor, Bacteria vs. 1-Day Precipitation
3.4.7 Canyon Creek Cove

Based on less than one year of monitoring data, bacteria concentrations within Canyon Creek cove were not higher than lake-wide background concentrations (Figure 3.67). Canyon Creek subdivision is not on the river channel side of the lake.
Figure 3.67: Canyon Creek Cove, Bacteria vs. 1-Day Precipitation
3.4.8 Holiday Estates

Holiday Estates is on the channel side of the lake. Orthophosphorous concentration was reported at the reporting limits for all samples. Nitrate plus nitrite (NOx) concentration exhibited three events with concentrations above the reporting limits but these correspond to similar Nitrate concentrations in segment 1 measured on December 21, 2004. A slight decreasing trend in NOx concentration was observed from 2004 to 2006.

Peak bacteria concentrations did not occur consistently near any one station. The 75th percentile E. coli. concentration in this subdivision is 127 MPN per 100 mL and the maximum was 2,419 MPN per 100 mL (Figure 3.69) with a slightly decreasing trend. The DO measurements did not show a trend between 2004 to 2006. The lowest DO measured for all samples was 5.95 mg/L (Figure 3.70). E. coli concentrations also did not relate to precipitation events (Figure 3.71 - 73).
Figure 3.69: Holiday Estates, Nassau Bay and Sandy Beach E. Coli Measurements

Figure 3.70: Holiday Estates, Nassau Bay and Sandy Beach, DO Measurements
Figure 3.71: Holiday Estates - Station 18025, Bacteria vs. 1-Day Precipitation

Figure 3.72: Nassau Bay II - Stations 18026, 18027, and 18028, Bacteria vs. 1-Day Precipitation
Figure 3.73: Sandy Beach/Nassau Bay - Stations 18029, 18030, Bacteria vs. 1-Day Precipitation
3.4.9 Port Ridglea East, West Canal

Port Ridglea East, West Canal is not located on the channel side of the lake (the channel is located in the middle of the lake in this area. Orthophosphorous concentrations were reported at the reporting limits for all samples. Orthophosphorous was measured in Lake Segments 1 and 2 on the same date at 0.2 mg/L. Nitrate plus nitrite (NOx) concentration exhibited four events with concentrations above the reporting limits (Figure 3.75) but these correspond to similar Nitrate concentrations in lake Segment 1 measured on December 21, 2004.

Peak bacteria concentrations were consistently high at station 18033. The 75th percentile E. coli. concentration in this subdivision is 140 MPN per 100 mL (Figure 3.76). Four measurements were over 1000 MPN per 100 mL and many others are between 200 and 400 MPN per 100 mL. DO exhibited a
cyclical trend, with lower levels in summer months but no measurements below 4 mg/L (Figure 3.78); DO deficit exhibited a decreasing trend towards supersaturation.

Figure 3.75: Port Ridglea West, NOx Measurements

Temporal Trend with 95% confidence limits - Port Ridglea West

Figure 3.76: Port Ridglea West, E. Coli Measurements
Figure 3.77: Port Ridglea West, DO Measurements

Figure 3.78: Port Ridglea West, DO Deficit
3.4.10 Port Ridglea East, East Canal

Orthophosphorus concentrations were reported at the reporting limits for all samples. Nitrate plus nitrite (NOx) concentration exhibited two elevated samples; one high concentration was consistent with similar concentrations in both Port Ridglea West and Segment 1 of the lake. The one other high nitrogen event corresponded to high orthophosphorus levels in the lake segment 2 (Figure 3.80); however, orthophosphorus was below detection limits within Port Ridglea East. Concentrations of E. coli were consistently high at station 18038; no trend with precipitation was evident (Figure 3.82).
Figure 3.80 – Port Ridglea East, east canal, NOx

Figure 3.81 – Port Ridglea East, east canal, E. coli
Figure 3.82 – Port Ridglea East, east canal, E. coli vs. 1-day antecedent rainfall

Figure 3.83– Port Ridglea East, east canal, DO concentration
Figure 3.84– Port Ridglea East, east canal, DO deficit
3.4.11 DeCordova Bend

A cove located on the east side of DeCordova Estates subdivision was monitored. DeCordova Estates is located close to the channel of the lake. Two periods of elevated bacteria concentrations were observed; one period after a rainfall event and one with no antecedent precipitation (Figure 3.86). Higher concentrations were observed at station 18042 located farther from the lake; deeper waters (8’ to 10’ deep) and wide connection with the lake facilitate increased water exchange at station 18041.
Figure 3.86 – 18041 and 18042, E.coli concentration vs. 1-day antecedent precipitation
3.4.12 Blue Water Shores North

Blue Water Shores subdivision is not located on the channel side of the lake. Orthophosphorous concentrations were reported at the reporting limits for all samples. Nitrate plus nitrite (NOx) concentration exhibited one elevated sample coincident within Blue Water Shores North and Segment 1 of the lake.

E. coli concentrations were frequently above 200 MPN per 100 mL, with a maximum of 2,420 MPN per 100 mL. The lowest DO measured for all samples was 5.76 mg/L. Stations 18044 and 18741 exhibited consistently high E. coli concentrations. The existence of a collection system for this subdivision calls to question whether the treatment facility is operating optimally or whether there exists a local watershed source.

![Figure 3.87: Blue Water Shores North Septic Index](gran03_gen.txt Events)
Station IDs: 18043, 18044, 18045, 18738, 18740, 18741, 18742

Figure 3.88 – Blue Water Shores, E. coli concentration

Figure 3.89 – Blue Water Shores, Stations 18043 and 18044, E. coli vs. 1-day Precipitation
Figure 3.90 – Blue Water Shores, Station 18738, E. coli vs. 1-day Precipitation

Figure 3.91 – Blue Water Shores, Stations 18740 to 18742, E. coli vs. 1-day Precipitations
Figure 3.92: Blue Water Shores, DO Measurements
4.0 WATER QUALITY MODELING

4.1 WATERSHED MODELING

4.1.1 Overview of Available Watershed Models

In order to accurately develop a watershed assessment model, it is essential to investigate the various available tools to determine the most applicable for the watershed of interest. The parameters to compare are the model developer, inputs, outputs, reliability, limitations, and applicability to Texas watersheds. It is important to consider the various runoff, erosion/sediment, and contaminant load computations. This literature review focuses on surface water quantity/quality assessment tools. The most common models in practice today are SWAT and HSPF. There is an extensive amount of information available for these models and thus they make up the bulk of this review. Some lesser known models included in this evaluation are PRMS, WEPP, and SWMM. Unless otherwise noted the information for this review can be found in the relative product documentation for each model.

4.1.1.1 SWAT

The Soil and Water Assessment Tool, better known as SWAT, was co-developed by the Grassland, Soil, and Water Research Laboratory of the Agricultural Research Service (ARS), and the Blackland Research Center ran by the Texas Agricultural Experiment Station, both located in Temple, Texas. These research centers are funded and governed by the United States Department of Agriculture (USDA). These research organizations are well known for their work and progress in the area of water resource management in Texas. It can be assumed the model was designed especially for use in Texas, though it certainly can be used for watershed assessment outside of the state. The software, documentation, and support for this model can be found at http://www.brc.tamus.edu/swat/index.html (USDA Agricultural Research Service - Grassland).

SWAT is a watershed scale model capable of describing pollutant transport in a field and between fields and their receiving waters. SWAT uses algorithms that simulate physical processes governing the movement of water, nutrients and pesticides within a watershed. For this to be feasible, input is defined at various levels of detail: watershed, subbasin, or HRU (hydrologic response unit). Features such as point sources and water reservoirs must have include data for each individual feature in the watershed simulation.

Watershed level inputs are used to model processes throughout the watershed. Within the watershed configuration are subbasins with an unlimited number of HRU’s and an optional pond and/or wetland, reach/main channel segments, optional impoundments on the main channel network, and optional point sources. Input files include the watershed configuration file, a basin file to model physical processes uniformly over the entire watershed, various weather information files, calibration files, a land cover/plant growth file, land use and application files for tillage, pesticides, fertilizers, etc., subbasin and water use files, and finally an optional water quality file.

The output summary file yields average loadings from the HRUs to the streams within the watershed. The model output also includes tables that present average annual HRU and subbasin values for a few parameters. The HRU output file provides summary information for each of the hydrologic response units in the watershed. The subbasin output file contains summary information for each subbasin within the watershed. The reported values for the variables are the total amount or weighted average of all HRUs within the subbasin. The main channel output file written in includes summary information for each routing reach in the watershed. The HRU impoundment output file consists of information for depressional/impoundment areas, ponds, and wetlands in the HRUs. The reservoir output file contains...
summary information for all reservoirs in the watershed. All the output files are written in spreadsheet format.

A report entitled A Survey and Review of Modeling for TMDL Application in Texas Watercourses (1999) was submitted to the Texas Natural Resource Conservation Commission (TNRCC) predecessor to the TCEQ. According to this report the main purpose of SWAT is computation of runoff and loadings from rural, agriculture-dominated, watersheds. The model has subbasin spatial units assumed to be homogenous in all watershed parameters. It allows up to 10,000 subbasins permitting more spatial resolution and is capable of addressing large watersheds. The hydrologic component of SWAT is the SCS Curve Number in a computerized version. Sediment/erosion transport is computed by USLE methods in digital versions. The greatest advantage of SWAT is its capability to apply a wide variety of surface agriculture treatments. This provides the user with alternative strategies for runoff control with the evaluation of many BMP’s, both structural and non-structural. According to the TNRCC report, the greatest weakness of SWAT is “its reliance upon the empirical formulations of the CN and USLE methods.” A water management assessment that is more deterministic in concept but not currently as well developed is WEPP (this model is discussed in a later section of this paper).

4.1.1.2 HSPF

The U.S. Geologic Survey developed the general purpose watershed model named Hydrologic Simulation Program – Fortran (HSPF). HSPF simulates the hydrologic and associated water quality processes on pervious and impervious land surfaces, in streams, and well-mixed impoundments for extended periods of time. The original model was based on the concepts of the Stanford Watershed Model. Separately available programs support data processing for statistical and graphical analysis which is then saved to the Watershed Data Management (WDM) file. The programming is in Fortran 77 and the model includes numerous process algorithms developed from theory, empirical relations, and lab experiments. The model simulations can be developed for both pervious and impervious areas discharging to one or many river reaches or reservoirs. HSPF is generally used to assess the effects of reservoir operations, point or non-point source treatment options, flow diversions, land-use change, etc (USGS).

HSPF uses continuous rainfall and other meteorologic records to compute pollutographs and hydrographs. Records of precipitation and estimates for evapotranspiration are required for watershed simulation. For water quality simulation air temperature, wind, solar radiation, humidity, tillage practices, point sources and pesticide applications may be required. Physical descriptions of the land area, channel reaches, and reservoirs are required (USGS).

This dynamic model simulates surface runoff, interception, interflow, baseflow, evapotranspiration, groundwater recharge, snowmelt, DO, BOD, pesticides, fecal coliform, sediment mobilization, and nutrient loading. The output can be in table format at any time step, a flat file, or the WDM file (USGS). The watershed is subdivided into computational catchments based upon meteorological station distributions and soil types. These sub-catchments are assumed homogeneous in climate and soil type. Each of these groups are further divided according to land use. These segments then define the reaches of the receiving waters. This leads to a great complexity of input file structure that increases with each segment. In addition, this resolution is inadequate for illustrating water quality variation in a stream. According to the report (George H. Ward and Benaman 1999) operation of the model is complicated. There is a “bewildering array of options for the user” which requires specifying coefficients in process equations which have limited relation to traditional formulations of the processes. This can frustrate the user as well as introduce a large range of error with incorrect specification of parameters. There is little guidance from the program literature and all this can combine to give unrealistic results. For these reasons the CRWR report does not recommend the use of HSPF for TMDL development in Texas until
the model is revised and even suggests the TCEQ develops their own “Texas” version of HSPF more appropriate to the states applications and environment (George H. Ward and Benaman 1999).

4.1.1.3 PRMS

The USGS developed and supports the Precipitation-Runoff Modeling System (PRMS). This model is a modular-design, distributed-parameter modeling system. PRMS evaluates the impacts of various combinations of precipitation, land use, and climate on streamflow, sediment yields, and general basin hydrology. The basin response to rainfall events can be simulated to evaluate changes in water balance relationships, flow patterns, flood peaks and volumes, soil-water relationships, sediment yields, and groundwater recharge. The evaluation method for the model divides the watershed into subunits based on basin characteristics. The partitioning can be done on two levels. The first divides the basin into hydrologic response units (HRUs). Daily water and energy balances are computed for each HRU to develop daily system response and streamflow for the basin. The second level of division is for storm hydrograph simulation (USGS).

A minimum of daily precipitation and daily minimum and maximum air temperatures are required for daily streamflow computations. Daily solar radiation data is recommended for snowmelt calculations. Daily evaporation data can be substituted in areas without snowmelt. For storm hydrograph and sediment computations, short time-interval precipitation, streamflow, and sediment data are needed. Physical descriptions of topography, soils, and vegetation are needed for input for each watershed subunit. The spatial and temporal data for precipitation, temperature, and solar radiation are also needed (USGS).

Output for the mean daily discharge (observed and predicted) for the basin is in tabular format. Annual and monthly summaries of precipitation, interception, evapotranspiration, and inflows/outflows of the groundwater and subsurface reservoirs are available. Times series at various time steps are available. All this information is also available for the individual HRUs. Observed and predicted peak flows and runoff volumes for each storm period is output in a summary tabular form. User selected flow planes and channel segments outflows and inflows can be output in tabular form, as printer plots, or to the WDM file (USGS).

The number of parameters is large for PRMS, though not as many as required for HSPF. This makes PRMS easier to use but less general than the HSPF model. A significant limitation of PRMS is it does not contain any water quality capabilities. USGS is currently developing a Modular Modeling System, MMS, which includes a PRMS component. MMS uses a library of compatible modules for simulating water, energy, and biochemical processes. A GIS interface is being developed to aid in the use of MMS. Neither PRMs or MMS can be considered for Texas TMDL development at this time. The PRMS model has potential that advances HSPF and SWAT in hydrological simulation. The model should be monitored for future developments in order to be a viable candidate for Texas TMDL applications (George H. Ward and Benaman 1999).

4.1.1.4 WEPP

The Water Erosion Prediction Project (WEPP) is a continuous simulation computer program developed by the USDA-Natural Resources Conservation Service, USDA-Forest Service, and the USDI-Bureau of Land Management for improved soil erosion prediction technology based on modern hydrologic and erosion science. Its application is for small watersheds and hillside profiles within these watersheds. While the program is primarily for soil erosion prediction it has extensive hydrologic capabilities. This model computes spatial and temporal distributions of soil loss and deposition and provides explicit estimates of where and when erosion occurs (USGS).
The model includes a climate component which uses a stochastic generator to provide daily weather information. This includes mean daily precipitation, daily maximum and minimum temperature, mean daily solar radiation, and mean daily wind direction and speed. A disaggregation model within the climate component generates time-rainfall intensity data from daily rainfall amounts to derive a rainfall intensity pattern for the watershed. This climate and rainfall intensity data is utilized by the infiltration component to compute runoff. Other components within the model are a winter processes component, irrigation component, overland flow hydraulics, water balance, plant growth, residue decomposition, soil parameters, hillslope erosion and deposition, watershed channel hydrology and erosion processes, and a watershed impoundment component. These components combine to yield a comprehensive erosion prediction model complete with a hydrologic assessment. Also included as part of the WEPP model are user interface programs, input file building programs, a climate database, a soil database, a crop parameter database, and a tillage implement database (USGS).

An apparent limitation is its lack of water quality assessment capabilities. It also appears to focus on small agricultural watersheds and does not address applications to larger watersheds or urban areas.

4.1.1.5 SWMM 5

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulations model used for single event or continuous simulation of runoff quantity and quality primarily from urban areas. The latest version of SWMM was produced by the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency’s National Risk Management Research Laboratory in a joint development effort with CDM, Inc.

The runoff component within SWMM utilizes a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing component transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. During a simulation period comprised of multiple time steps, the model traces the quantity and quality of runoff produced within each subcatchment, as well as the flow rate, flow depth, and quality of water in each pipe and channel (EPA).

SWMM 5 integrates input data to produce hydrologic, hydraulic, and water quality simulations with results in a variety of formats. These include color-coded drainage area and conveyance system maps, time series graphs and tables, profile plots, and statistical frequency analyses. The hydrologic processes SWMM accounts for include:

- Time-varying precipitation
- Evaporation of standing surface water
- Snow accumulation and melting
- Rainfall interception from depression storage
- Infiltration of rainfall into unsaturated soil layers
- Percolation into groundwater
- Interflow between groundwater and the drainage system
- Nonlinear reservoir routing of overland flow

Dividing a study area into smaller, homogeneous subcatchment areas achieves spatial variability. Overland flow can be routed between subcatchments, sub-areas, or entry points of a drainage system. SWMM also contains hydraulic modeling capabilities to route runoff and external inflows through the drainage system and diversion structures. The SWMM model can also estimate pollutant loads associated
with this runoff. Any number of user-defined water quality constituents can be modeled by the following processes (EPA):

- Dry-weather pollutant buildup over different land uses
- Pollutant washoff from specific land uses during storm events
- Direct contribution of rainfall deposition
- Reduction in washoff load due to BMPs
- Routing of water quality constituents through the drainage system
- Reduction in constituent concentration through treatment in storage units or by natural processes in pipes or channels

Typical applications of SWMM include (EPA):

- Design of sizing of drainage system components and detention facilities for flood control
- Flood plain mapping of natural channel systems
- Designing control strategies for minimizing sewer overflows
- Evaluating the impact of inflow and infiltration on sanitary sewer overflows
- Non-point source pollutant loadings for waste load allocation studies
- Evaluating the effectiveness of BMPs for reducing wet weather pollutant loadings

Unfortunately, there is no formal support offered for EPA SWMM. This is a specialized model dealing with the complexities of urban drainage and plumbing, and in general is too detailed for the strategic-level evaluations of a TMDL. There may be isolated problems in urban areas that would require the level of detail provided by SWMM (George H. Ward and Benaman 1999).

4.1.1.6 Load Duration Curve Models

Load Duration Curve (LDC) models can be utilized to address bacteria impairments in watersheds and are easy to understand, produce reasonable results and have minimal data requirements (Cleland 2002 and 2003). LDCs depict pollutant loadings graphically utilizing streamflow data. The LDC begins with a flow duration curve. In a flow duration curve the x-axis is based on the frequency of exceedance of specific flows (y-axis) during the entire period of record represented in the data. The flow duration curve is then converted to a LDC by multiplying the flow by the water quality criterion. The resulting plot represents the maximum pollutant load for each flow value. Therefore the LDC has the pollutant load (bacteria) on the y-axis and the flow exceedance on the x-axis. Monitoring data can then be added to the LDC and evaluated against the curve (TCEQ, 2007).

4.1.1.7 Summary

The models described above can be lumped into categories of standard and comprehensive, where standard models are simple steady-state models based upon empirical relationships (Table 4-1). Standard models are empirical and require less data to implement than comprehensive models (Table 4-2).
Table 4-1 - Watershed Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Category</th>
</tr>
</thead>
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<tr>
<td>SWAT</td>
<td>Comprehensive runoff and constituent model, process-based Agricultural</td>
</tr>
<tr>
<td>HSPF</td>
<td>Comprehensive runoff and constituent model, process-based Sediment</td>
</tr>
<tr>
<td>SWMM5</td>
<td>Comprehensive runoff and constituent model, process-based Urban</td>
</tr>
<tr>
<td>PRMS</td>
<td>Comprehensive runoff-only</td>
</tr>
<tr>
<td>WEPP</td>
<td>Comprehensive runoff-only</td>
</tr>
<tr>
<td>Soil Conservation Service Curve Numbers</td>
<td>Standard runoff-only</td>
</tr>
<tr>
<td>Load Duration Curves</td>
<td>Statistical characterization of bacteria concentration</td>
</tr>
</tbody>
</table>

Table 4-2 - Watershed Model Data Requirements

**INPUT DATA REQUIREMENTS**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Standard</th>
<th>Comprehensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage area</td>
<td></td>
<td>Rainfall time-series</td>
</tr>
<tr>
<td>Topography/drainage patterns</td>
<td></td>
<td>Infiltration</td>
</tr>
<tr>
<td>Soil characteristics</td>
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<td>Evapotranspiration</td>
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<td>Rainfall</td>
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<td>Wind</td>
</tr>
<tr>
<td>Pollutant source and concentration</td>
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<td>Temperature</td>
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<tr>
<td></td>
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<td>Tillage</td>
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<tr>
<td></td>
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<td>Erosion/deposition</td>
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**CALIBRATION AND VALIDATION DATA**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Standard</th>
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</tr>
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<td>Flow</td>
<td></td>
<td>Flow time-series</td>
</tr>
<tr>
<td>Concentration</td>
<td></td>
<td>Concentration time-series</td>
</tr>
</tbody>
</table>

4.1.2 Watershed Models Used for Watershed Protection Plans

Most WPPs completed for lake watersheds both nationally and in Texas have addressed actual or potential nutrient problems, actual sediment problems or a combination (EPA 2007; TSSWCB 2007). Fewer WPPs use models to address either toxics or bacteria contamination.

Non-point source nutrient or toxic loading can be developed using models like HSPF and SWAT or with other ad hoc methods that consider rainfall-runoff, land use and land properties. Choosing the best method or model depends upon the size and complexity of the watershed system as well as the data available to quantify model inputs.

WPPs addressing coliform contamination have utilized a number of different models including HSPF (San Antonio River and Salado Creek, TX) and simpler statistical characterizations by load-duration curves (Plum Creek, TX).

4.1.3 Recommendation for Watershed Model

Based upon existing available data, a simple watershed modeling approach is recommended to estimate bacterial loading to each canal system. Peak inflow to each canal system will be estimated for a range of
rainfall events using a standard approach where a Soil Conservation Service (SCS) Curve Number (CN) is assigned to each drainage area based upon unique characteristics including impervious cover, soils and slope. A load-duration curve will be developed using existing data on bacteria concentration and inflow volume based upon antecedent rainfall data.

A nutrient budget will be developed for the lake as part of the lake modeling task. The immediate watershed around Lake Granbury is not, based upon preliminary analysis, considered to be a major contributor of nutrients to the lake. If, however, the results of the nutrient budget indicate the watershed is a significant source compared to point and upstream sources, additional modeling will be required to determine type and placement of best management practices to reduce loads from the watershed.

4.2 LAKE AND COVE MODELING

4.2.1 Objectives

Using inflows and loadings (determined during the watershed modeling process), the generalized objectives of the lake modeling task are to:

- Determine processes affecting the existing condition in the lake.
- Determine processes affecting the existing condition of selected coves and canals.
- Estimate expected changes over time for the “do nothing” alternative.
- Estimate expected changes over time for a series of action alternatives.

Two concerns are evident based upon data analysis: nutrient enrichment within the entire lake and elevated bacteria concentrations within the waters of some residential canal systems. To identify the major sources of nutrients, a comprehensive mass balance is recommended; potential sources include river inflows, treatment plant discharges and non-point sources within the watershed. To characterize bacteria concentrations within canal waters, modeling is recommended to characterize the relationships between loading, inflow and concentration.

4.2.2 Available Lake Models

Ward and Benaman (1999) provide an overview of available models and recommend those appropriate for TMDL determinations in Texas. Five off-the-shelf lake water quality models were identified, including BATHTUB, HSPF, QUAL2E/QUALTX, WASP and CE-QUAL-W2. An additional tool identified for lake water quality modeling was the continuously-stirred tank reactor (CSTR) approach to solving mass-balance problems in well-mixed waters.

4.2.2.1 BATHTUB

This is a segmented mass-balance model, based on statistical relationships developed from default USACE data or from site-specific data, used to predict lake eutrophication response to long-term changes in nutrient loadings. Ward and Benaman (1999) do not recommend this model for use in Texas since necessary modifications may more appropriately be incorporated into a simpler CSTR model.

4.2.2.2 HSPF

In addition to its utility for watershed modeling (see Section 3.1.1), HSPF can be used to model lakes where the entire lake is a single, well-mixed volume (CSTR), and the solution varies in time. Bacteria and other constituents could be modeled using the first-order decay module. Nutrients, DO and algae are modeled using 1st order rates or user-specified Michaelis-Menten coefficients. Because of the longitudinal
nature of Lake Granbury and each of the canals, HSPF is not recommended for lake modeling for this project since it does not account for intra-lake hydrodynamic exchanges.

4.2.2.3 QUALTX and QUAL2E

These similar models are steady-state, well-mixed, segmented, one-dimensional models most often applied to water quality problems in river segments. Bacteria could be modeled as a first order kinetic reaction whose rate coefficient considers temperature in assignment of the coliform die-off rate. To include settling (if sufficient data exists to describe that process), bacteria could be modeled as a non-conservative material. QUALTX and QUAL2E also include modeling algorithms for algal respiration, DO, nutrient cycles, BOD, DO, temperature, salinity and non-conservative constituents.

Since these models only consider steady-state problems, they are not suitable for time-varying analysis that is desired for coves on Lake Granbury.

4.2.2.4 WASP

Capable of modeling time-varying problems in three dimensions, the WASP model is the most comprehensive water quality model available. However, because of WASP’s comprehensive deterministic basis, site-specific data is rarely available to assign the large number input parameters. Using default parameters in lieu of site-derived parameters is possible; however, a model that more simply accounts for salient water quality processes is more desirable.

Unlike the models previously mentioned, WASP requires use of an external model to provide hydrodynamic forcing. DYNHYD5 and EFDC are two hydrodynamic models capable of generating appropriate WASP hydrodynamic input files, although a WASP input file could be generated from other models. DYNHYD5 is a one-dimensional link-node model suitable for systems having primarily longitudinal flow. EFDC is a fully three-dimensional finite-difference hydrodynamic model suitable for systems with lateral and/or vertical fluxes. Without easily available graphical user interfaces, setup of the hydrodynamic models requires some time and effort.

4.2.2.5 CE-QUAL-W2

Developed by the USACE, CE-QUAL-W2 is a two-dimensional (laterally-averaged), finite difference, hydrodynamic and water quality model. Water quality components are similar to WASP. Processing and visualizing input and output files is difficult since there is no GUI. Since stratification is not an issue for the problem of bacteria in shallow canals, CE-QUAL-W2 is not recommended for this project.

4.2.2.6 Mass balance methods

The mass balance method calculates a mass balance between bacteria loads entering the water body and the bacteria loads within the stream. Sources are identified and compared to existing in-stream loads at specified points in the stream. The mass balance approach requires more data than the LDC model. Mass balance methods can be utilized where there are potential point and non-point sources at low and high concentrations. This method is generally completed utilizing a spreadsheet approach. This analysis is a static representation of the system and does not account for temporal variations in loading. Output from this method can be utilized to develop a more complex mechanistic model if needed. There are several mass balance models currently available including the Bacteria Load Estimator Spreadsheet Tool (BLEST) and Bacteria Indicator Tool (BIT) from EPA.
Another common tool for water quality analysis is the continuously-stirred tank reactor (CSTR) model. For situations when a completely mixed control volume can be discretized, this simple model can be implemented within a spreadsheet. While the assumption of a completely mixed control volume may not be applicable to an entire lake (or cove or canal) volume, the lake can be partitioned into segments satisfying the assumption of complete mixing. The model can be set up to provide either a steady-state or dynamic answer. Kinetics for water quality processes or bacteria decay can be programmed to take advantage of available field data, without the need to use default values necessary in the case of an “overparameterized” model.

A completely-mixed mass balance model for nutrients (total phosphorus and total nitrogen) was developed as a part of the 1982 septic tank evaluation study (APAI 1982b). Assuming a completely mixed condition throughout the lake, and developing loadings based upon limited data, the model was used to estimate change in nutrient concentrations resulting from changes in loadings. Changes in loadings were developed to represent scenarios including addition of advanced treatment for existing treatment facilities discharging into the lake and transfer of all OSSF systems to a collection system and treatment (excluding and including advanced treatment).

4.2.2.7 Summary

As for watershed models, the lake models described above can be lumped into categories of standard and comprehensive (Table 4-3). Standard models are empirical and require less data to implement than comprehensive models (Table 4-4).

<table>
<thead>
<tr>
<th>Table 4-3 - Lake Models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BAYTUB</strong></td>
</tr>
<tr>
<td><strong>HSPF</strong></td>
</tr>
<tr>
<td>Hydrologic Simulation Program - FORTRAN</td>
</tr>
<tr>
<td><strong>QUALTX</strong></td>
</tr>
<tr>
<td><strong>WASP</strong></td>
</tr>
<tr>
<td>Water Analysis and Simulation Package</td>
</tr>
<tr>
<td><strong>CE-QUAL-W2</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>CSTR</strong></td>
</tr>
<tr>
<td>Continuously-stirred tank reactor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4-4 - Lake Modeling data requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT DATA REQUIREMENTS</strong></td>
</tr>
<tr>
<td>Standard</td>
</tr>
<tr>
<td>Inflow</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>Surface area</td>
</tr>
<tr>
<td>Water exchange</td>
</tr>
<tr>
<td>Segmentation</td>
</tr>
<tr>
<td>Pollutant concentration input</td>
</tr>
<tr>
<td>Pollutant change or decay</td>
</tr>
<tr>
<td>Pollutant concentration output</td>
</tr>
</tbody>
</table>
4.2.3 Lake Models Used in Watershed Protection Plans

A number of WPPs have been developed for lake watersheds across the country; however, few with similar problems to Lake Granbury have been developed. In Texas in the Brazos River basin, WPPs have targeted water quality in Aquilla Reservoir, Lake Waco, Belton Lake, Stillhouse Hollow Lake and Lake Granger. Subsequent to development of a WPP for Aquilla Reservoir, agricultural BMPs were implemented thus reducing atrazine concentrations 60%. To identify sources of bacteria within the Lake Waco and Belton Lake watersheds, a Bacterial Source Tracking has been completed. A Public Water Supply Protection Strategy has been developed for Stillhouse Hollow Lake which details all potential risks identifies measures taken to minimize those risks. A WPP for Lake Granger is under development and will recommend BMPs to reduce erosion and nutrient loading from the watershed, to reduce reservoir volume loss and keep water treatment costs low by reducing turbidity.

In the Trinity River watershed, methods to protect water quality are being studied for Lake Bridgeport, Eagle Mountain Lake, Lake Benbrook, Cedar Creek Reservoir and Richland-Chambers Reservoir. The major problems in these lakes are sediment and nutrient loading.

Few technical writeups of bacterial modeling in lakes were found and none in Texas. Lake Onondaga, near Syracuse, NY, employed a bacterial model to estimate concentrations before and after proposed eradication of Combined Sewer Overflows (CSOs) discharging in the watershed. The simple model discretizes the lake into eight surface cells and three deepwater cells, calculating the bacteria concentration in each cell based upon hourly inflows. Inflows were developed using SWMM to model storm events.

4.2.4 Recommended Lake Modeling Approach to Address Bacteria

Given the shallow depths (generally less than 6’ deep measured from CPE) in each of the canal systems, vertical stratification is not an issue.

A segmented well-mixed mass balance model is recommended for modeling of each canal system. The model will consider gradients of concentration from the lake boundary to the upper dead-end reaches of the canal system. The model will be executed for a series of steady-state conditions.

Assumptions:
- The simple segmented mass balance model applies to the coves; ie, cove waters are well-mixed and homogeneous within a given segment.
- Boundary conditions, ie, exchanges between the cove and the lake main body, can be suitably applied to each cove simple segmented mass balance model.
- Wave-induced circulation patterns in the coves are insignificant and resultant mixing could be modeled indirectly with diffusion (particle motion or turbulent mixing) or dispersion (variation in velocity) coefficients.

Required input data:
- Inflow
Depth
Surface area
Segmentation
Exchange between segments and boundary
Bacteria concentration/loading
Bacteria decay rates
5.0 FINDINGS AND RECOMMENDATIONS

5.1 LAKE NUTRIENTS

Additional investigation into nutrient concentrations through development of a nutrient budget is recommended. Existing nutrient concentrations exhibit increasing trends and a general trend towards eutrophication is exhibited. Decreasing trends in overall DO concentrations, daytime DO increases to super-saturation, decreasing trend in secchi depth and increasing trends in chlorophyll-a concentrations were also observed in this initial data review.

Investigation should include determination of nitrogen and phosphorus loads into the main lake body, particularly potential for increase in these loads associated with transition from on-site treatment facilities to regional treatment that discharges into the lake.

5.1.1 Additional Water Quality Monitoring (Task 6.1)

Additional monitoring is recommended for nutrients to evaluate potential trends exhibited by long-term monitoring data. Particularly, monitoring of phosphorus and orthophosphorus to low detection levels is recommended.

Locations:
Monitor at all three main lake stations; 11860 near Dam, 11861 mid-lake near Granbury, 11862 headwaters.

Interval and duration:
Monthly for one-year, re-evaluating need for continued monitoring.

5.2 CANAL NUTRIENTS

Nutrient concentrations (nitrogen and phosphorus) in the coves correspond to concentrations in the lake. The only canal development exhibiting significant concentrations of Nitrate + Nitrite was Oak Trail Shores where 25% of the samples exhibited NOx concentrations higher than 0.14 mg/L.

On site septic facilities likely provide adequate phosphorus treatment but little or no nitrogen treatment (APAI 1982b). High hydraulic conductivity in loose soils may allow pathways for nitrogen to enter canal waters. Determination of the source of nitrogen (whether from septic systems, greywater discharge or some other source) in Oak Trail Shores is recommended.

5.3 BACTERIA

5.3.1 Findings

Elevated bacteria concentrations in the lake do not occur regularly nor are periods of high concentration persistent. Background levels are less than 10 MPN per 100 mL. Bacteria concentrations are persistently higher within the canal systems.

Based on the GIS-based spatial trend analysis utilizing the septic index to identify subdivisions with characteristics (soils, geology, septic system age, etc.) with potential to exhibit bacterial problems, the following subdivisions are classified as high risk:

Rolling Hills Shores
Arrowhead Shores
Oak Trail Shores
Sunrise Bay
South Harbor
Rough Creek
Based on analysis of available monitoring data, bacteria levels in the following canals were found to be persistently elevated compared to background lake levels:

- Rollinghills Shores
- Arrowhead Shores
- Oak Trail Shores
- Ports O’ Call
- Indian Harbor (<100)
- Nassau Bay

Modeling is recommended for bacteria concentration in the following canal systems:

- Rolling Hills Shores: Restricted lagoon; unique
- Arrowhead Shores: T-canal
- Oak Trail Shores: T-canal
- Sky Harbor: Deep cove and canals with tributary inputs
- Nassau Bay: Deep cove and canals with tributary inputs
- Waters Edge: Finger canal, to validate model predictions at low concentrations
- Ports O’ Call: Deep finger canal
- Indian Harbor: Eastern-most lagoon
- Port Ridglea East: Shallow finger canals
- Blue Water Shores: Determine sources

These canal systems are recommended for modeling because they exhibit a range of conditions (length, width, orientation, and depth) that may allow inferences to be made on other canal systems with similar configurations. More practically, these subdivisions are chosen for modeling because they exhibit high bacteria concentrations and therefore have most potential for improvement. Waters Edge subdivision was chosen for modeling as a control, to show applicability of the model framework at low bacterial concentrations. Arrowhead Shores and Oak Trail Shores have similar configurations, as do Sky Harbor and Nassau Bay; modeling of one canal system may serve as a surrogate for the other canal systems with similar configuration.

5.3.2 Field Data Collection Recommendations

Data collection necessary for completion of this project are described below. Field collection should be conducted between August and October to allow analysis by end of year 2007.
5.3.3 Lake-to-Cove Exchange and In-Cove Circulation (Tasks 5.1, 6.2)

For modeling canal waters, data is required to quantify the exchange of water between the main lake body and each cove. Additionally, data is needed to quantify circulation within each cove to identify sources and movement of water and constituents. These data will include but may not be limited to estimated wind speeds, wind effects, level of downward mixing, stratified flow, convective flow, current patterns, specialized eddy flow, etc. The data collection period(s) would ideally occur during conditions exhibiting no antecedent rainfall, high temperatures, moderate wind conditions (7 to 10 knots), ordinary pool elevations (at or above 692’) and low lake inflows.

**Locations to collect data:**
- Port Ridglea East, east canal (fingers on north shore),
- Water’s Edge (long canal on east shore),
- Oak Trail shores (t-canal on south shore),
- Sky Harbor (deeper on north shore),
- Ports O’ Call (one finger canal),
- Indian Harbor (eastmost lagoon), and
- Rolling Hills Shores (lagoon near lake headwaters), if possible.

**Data to be collected in the field (for duration of field effort):**
- **Atmospheric:** wind speed and gusts near water surface (to be compared to NCDC and BRA station data for same period)
- **Dye release:** measure dye concentration (Rhodamine WT) using a fluorometer in real time; ensure careful release on surface and that vertical concentration profiles are measured to determine level of vertical mixing.
- **Drogue release:** Release a series of drogues in each canal system. Each drogue shall have vanes set at different levels, so that water velocity and direction at the surface and at depth can be quantified.
- **Grab samples:** (Task 6.2) Surface grab samples to be collected and analyzed according to usual SWQM/CRP protocol at each location. Additional mid-depth or near-bottom sample to be collected and analyzed for same parameters.
- **Sediment sample:** Within each canal, collect one or more sediment core samples. Analysis of sediment samples will be conducted only if needed based upon site conditions and circulations patterns.

5.3.4 Septic Tracer (Task 5.2)

To determine the sources of bacteria, or to validate the hypothesis that bacteria in canals is primarily from leaky septic systems, the injection of dye into existing septic systems is recommended. The canals with the highest and most persistent bacteria concentrations are Port Ridglea, Sky Harbor and Oak Trail Shores; therefore, these locations are recommended for testing. Rolling Hills Shores could also be tested if funds are available. The treatment facility Blue Water Shores should also be investigated if possible. This initiative should also coordinate with Bruce Lesikar (TAMU) for tracer scope and setup.
6.0 REFERENCES


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