STATEWIDE DECISION SUPPORT SYSTEM FOR POTENTIAL *E. coli* LOAD

MANAGEMENT IN TEXAS WATERSHEDS

A Thesis

by

SHUBHAM JAIN

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Raghavan Srinivasan
Committee Members,	Clyde Munster
	Virender K. Sharma
Head of Department,	John R. Giardino

December 2018

Major Subject: Water Management and Hydrological Science

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ABSTRACT

The Section 303(d) of the Federal Clean Water Act cites bacterial pathogens as one of the most common cause of impairment in the streams and other water bodies in the state of Texas and the number of bacteria impaired water bodies in Texas have been on the rise with a 57 percent increase in the number between 2004 and 2006. As development of Total Maximum Daily Loads (TMDLs) are mandatory to be prepared for each impaired water body by the United States Environmental Protection Agency (USEPA) regulations, the Texas Commission on Environmental Quality (TCEQ) and other institutions in Texas work together to develop TMDLs and Watershed Protection Plans (WPPs) for these impaired water bodies to identify potential sources of bacteria and provide strategies and best management practices to reduce bacterial pathogens in water.

The GIS based Spatially Explicit Load Enrichment Calculation Tool (SELECT) is used in most TMDL reports to identify potential sources of bacteria in a watershed and high priority areas affected by bacterial contamination. However, the tool requires tedious process of collecting data from various sources, developing model in ArcGIS and running the model several times during the development of TMDL reports and watershed protection plans. The process can be time consuming and requires sufficient knowledge of GIS software.

The Texas Watershed Characterization System (TWCS), a web-based user-friendly interface was developed using R Studio and R Shiny application, for estimation of potential sources of fecal coliform and develop management scenarios in Texas

watersheds through pre-loaded datasets and user-editable inputs. The tool allows users to work on three spatial resolutions (HUC 8, HUC 10, and HUC 12) to calculate total potential Escherichia coli in HUC 12 sub-watersheds within the selected watershed and produce interactive charts and maps within a few minutes. Along with the calculation of *E. coli* loads, users can also develop management scenarios to look at load reduction strategies in the high priority sub-watersheds.

This study was done to demonstrate the workflow of TWCS and estimate potential *E. coli* loads for the La Nana Bayou watershed in Texas using the TWCS web-interface.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Raghavan Srinivasan, and my committee members, Dr. Clyde Munster and Dr. Virender K. Sharma, for their guidance and support throughout the course of this research.

Thanks to Dr. Lucas Gregory, Michael Schramm, and Dr. Allen Berthold at Texas Water Resources Institute and Dr. Khedun C. Prakash at Department of Water Management and Hydrological Sciences for their guidance during my research.

Also, Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Finally, thanks to my mother and father for their encouragement and for their patience and love.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Raghavan Srinivasan and Dr. Clyde Munster of Biological and Agricultural Engineering Department and Dr. Virender K. Sharma of Department of Environmental and Occupational Health.

All work for the thesis was completed independently by the student under the advisement of Dr. Raghavan Srinivasan of Department of Biological and Agricultural Engineering.

Funding Sources

There are no outside funding contributions to acknowledge related to the research and compilation of this document.

NOMENCLATURE

E. coli	Escherichia coli
SELECT	Spatially Explicit Load Enrichment Calculation Tool
TWCS	Texas Watershed Characterization System
NLCD	National Land Cover Database
HUC	Hydrologic Unit Code
BMP	Best Management Practices
WPP	Watershed Protection Plan
TMDL	Total Maximum Daily Load

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1. INTRODUCTION

Pathogen contamination is the leading cause of water quality impairments in Rivers, Lakes, and Estuaries in Texas and the number of impaired water bodies has been on the rise. The number of bacteria impaired water bodies listed in the 303(d) list have increased from 197 in 2004 to 310 in 2006 accounting for about 57 percent of impaired water bodies in Texas (Christopher Pooley and Harris, 2007). The federal clean water act requires the development of Total Maximum Daily Loads (TMDL) reports for all impaired water bodies, monitoring of water quality and implementation of best management practices for the water segment to be classified as a not impaired water body (U.S. Environmental Protection Agency, 2001). Bacteria impairments are determined by measuring Escherichia coli and Enterococci for freshwater and saltwater bodies respectively. Thus Texas Commission on Environmental Quality (TCEQ) states a limit of *E. coli* geometric mean of 126 cfu/100ml and single grab sample of 394 cfu/100 ml (TCEQ, 2007).

While methods such as Bacterial Source Tracking (BST) assessments help identify and differentiate sources of fecal bacteria by DNA fingerprinting using collected soil and water samples from impaired sites (C. Baffaut and V. W. Benson, 2013), computer models such as Soil and Water Assessment Tool (SWAT) and Hydrological Simulation Program – FORTRAN (HSPF) have been increasing used to model these sources of bacteria and transport due to the costs incurred in collection and analysis of soil and water sample (Arnold et al., 2012; Benham et al., 2006; Douglas-Mankin et al., 2010). The complexity in the development of bacterial source tracking and transport modeling with these models prevent watershed managers from using these models in preparation of TMDL reports and watershed protection plans. More simplistic models such as the Spatially Explicit Load Enrichment Calculation Tool (SELECT) allow users to rank the potential sources of *E. coli* loads in the watershed by providing a snapshot of daily maximum bacteria load for each indicator. Even though SELECT may not represent actual scenario of *E. coli* loading in the watershed but its simplicity and ease in development of potential sources and identification of high priority areas has led to its use in most TMDL reports in Texas watersheds (Borel et al., 2012; Texas Water Resources Institute. et al., 2012).

The SELECT model is used to identify potential *E. coli* loads from point and non-point sources using an automated script developed in ArcGIS (Teague et al., 2009). Bacteria indicators such as livestock, wildlife, pets, wastewater treatment facilities and failing on-site sewage facilities are generally identified as potential bacteria sources and daily loads are estimated using SELECT.

Even though models such as SELECT and Spatially Explicit Delivery Model (SEDMOD) are simplistic models, it is still tedious to collect data inputs and perform analysis using these models and inputs from stakeholders are regularly updated of the model during the development of watershed protection plans and TMDLs. Also, these models require enough knowledge of GIS and other watershed modeling tools. Models such as the Hydrologic and Water Quality System have been introduced to develop watershed models based on a pre-loaded web-based interface (Yen et al., 2016). Therefore, a web-based statewide decision support system was developed using R and R

Shiny that provides a user-friendly interactive interface and pre-loaded data required to determine potential bacteria loads on Texas watersheds. TWCS can be used by watershed planners and stakeholders to collect watershed data and perform load estimation analysis using the Spatially Explicit approach and create management scenarios on three different spatial resolutions (HUC 8, HUC 10, HUC 12) within a few minutes.

This study introduces the workflow of TWCS for estimating *E. coli* loads and developing watershed management scenarios. Potential E coli loads for the La Nana Bayou watershed which is indicated as a bacteria impaired watershed in the 303(d) list were calculated using TWCS.

2. TWCS DEVELOPMENT

TWCS was developed using R programing language, and the Shiny package in R was used to build an interactive web app directly from R. R is a free programing language that is increasingly being used for statistical computing and building graphics by researchers and scientists (Muenchen, 2013). Numerous packages are available to add functionalities such as analyzing Raster and Spatial analysis and creating interactive maps such as the leaflet package allowing GIS developers to carry out spatial analysis in R due to its powerful statistical computing framework and enable users to view and analyze data outputs through interactive maps (Whateley et al., 2015).

The web tool was developed to allow users to carry out spatial and statistical computation on web servers and therefore not requiring any computational capacity or knowledge of GIS or statistical software. The workflow for the web-based DSS as shown in **Figure 1**, involves a step by step tabbed panel UI that begins with the user defining the watershed resolution and HUC number. Users are then allowed to view various selected watershed characteristics and input data based on tool suggestions and stakeholder inputs. Users can generate multiple scenarios to look at changes in *E. coli* loads by implementing Best Management Practices (BMPs) and compare these scenarios. Finally, users can view and download input/output files and save a project link for future development.

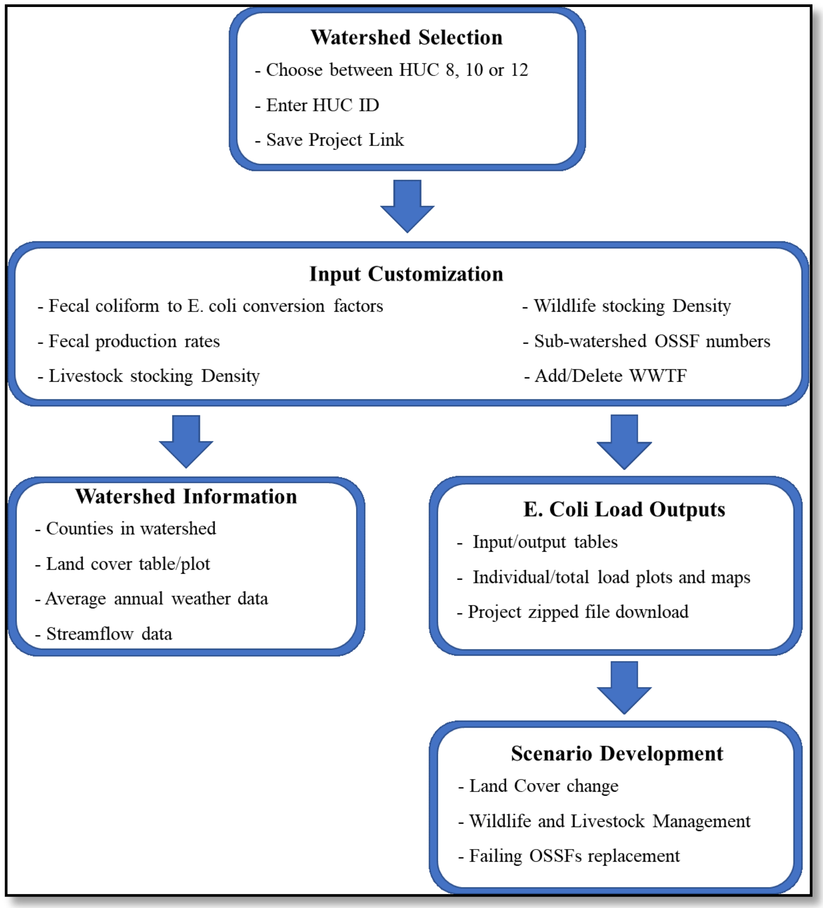

Figure 1. TWCS Workflow

The data inputs used in the development of the tool are listed below:

a) Watershed boundaries – Texas Natural Resources Information System (TWDB).

b) Land cover – National Land Cover Database (NLCD).

c) Weather – Parameter-elevation Regressions on Independent Slopes Model (PRISM).

d) Population and Households – United States Census Bureau (2010).

e) County livestock - National Agricultural Statistics Service (NASS).

f) 911 Address Points – State Council of Governments.

g) CCN Sewer areas – Public Utility Commission of Texas.

h) Waste Water Treatment Facilities - United States Environmental Protection Agency (US EPA).

2.1 Project Set-up

Project set-up begins with users selecting data resolution from three different resolution alternatives being HUC 8, HUC 10 and HUC 12 watershed units as shown in **Figure 2**. Users can then input HUC IDs based on the selected HUC resolution and choose between 208 HUC 8, 1198 HUC 10, and 7564 HUC 12 watersheds within the Texas region. Once the project is started, the delineated watershed map is displayed on the initialization window and user can save the project by getting a link to the project file. If the user selects HUC 8 or HUC 10 as watershed resolution, the watershed is further sub-divided into HUC 12 sub-watersheds to reduce uncertainty in the spatial distribution of *E. coli* loads in large scale watersheds.

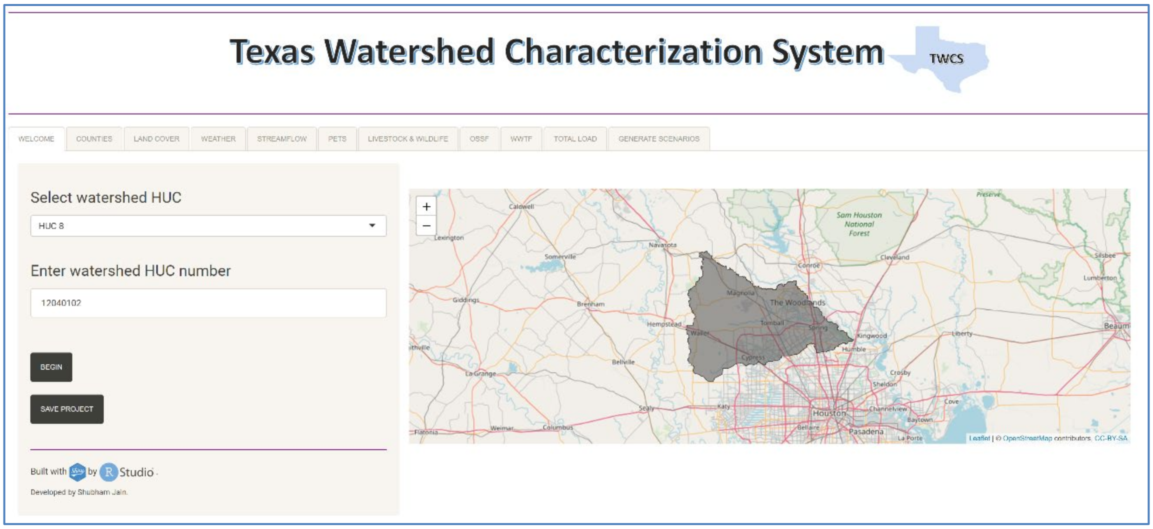

Figure 2. TWCS Project Initialization Tab

2.2 Input Customization

Published data sources for fecal coliform production rates suggest different concentrations due to difference in research methodology and thus it is necessary to provide user to enter fecal coliform production rate based on inputs from scientists and stakeholders for each indicator. Suggested fecal coliform production rates are pre-loaded in the tool based on rates generally used in various TMDL reports in Texas but are available to edit by user. Fecal coliform production rates available in literature are listed in **Table 1**. The rule of thumb of the ratio of fecal coliform to *E. coli* loads as 50% is set as default but can be changed as per user inputs (Erickson and Doyle, 2006).

Table 1 Suggested fecal coliform production rates (U.S. Environmental Protection Agency, 2001; Modified from Wagner, 2009).

Indicator	Concentration	Reference
Dogs and Cats	5×10^{9} cfu/AU/day	Horsley and Witten, 1996
Beef Cattle	5.4×10^{9} cfu/AU/day	Metcalf & Eddy, 1991
	1.04×10^{11} cfu/AU/day	EPA, 2000
	1.3×10^{11} cfu/AU/day	ASAE, 2003
Goats	2.54×10^{10} cfu/AU/day	Wagner and Moench, 2009
Sheep	1.8×10^{10} cfu/AU/day	Metcalf & Eddy, 1991
	1.2* $\times 10^{10}$ cfu/AU/day	EPA, 2000
	2×10^{11} cfu/AU/day	ASAE, 2003
Horses	4.2×10^{8} cfu/AU/day	EPA, 2000
	4.2×10^{8} cfu/AU/day	ASAE, 2003
Deer	5×10^{8} cfu/AU/day	EPA, 2000
Feral Hogs	1.08×10^{10} cfu/AU/day	EPA, 2000
OSSFs	10^{4} - 10^{5} #/ml	Metcalf & Eddy, 1991
	6.3×10^{6} MPN/100 ml	Overcash and Davidson, 1980

Suitable land cover for each livestock depends on watershed location and stakeholder's inputs and thus the tool allows user to select suitable land covers for each livestock and wildlife and obtain a suggested animal density per 1000 acres of selected suitable land based on the county numbers as shown in **Figure 3**. Stocking density also vary with land cover type and thus user can input different stocking density for each land cover type.

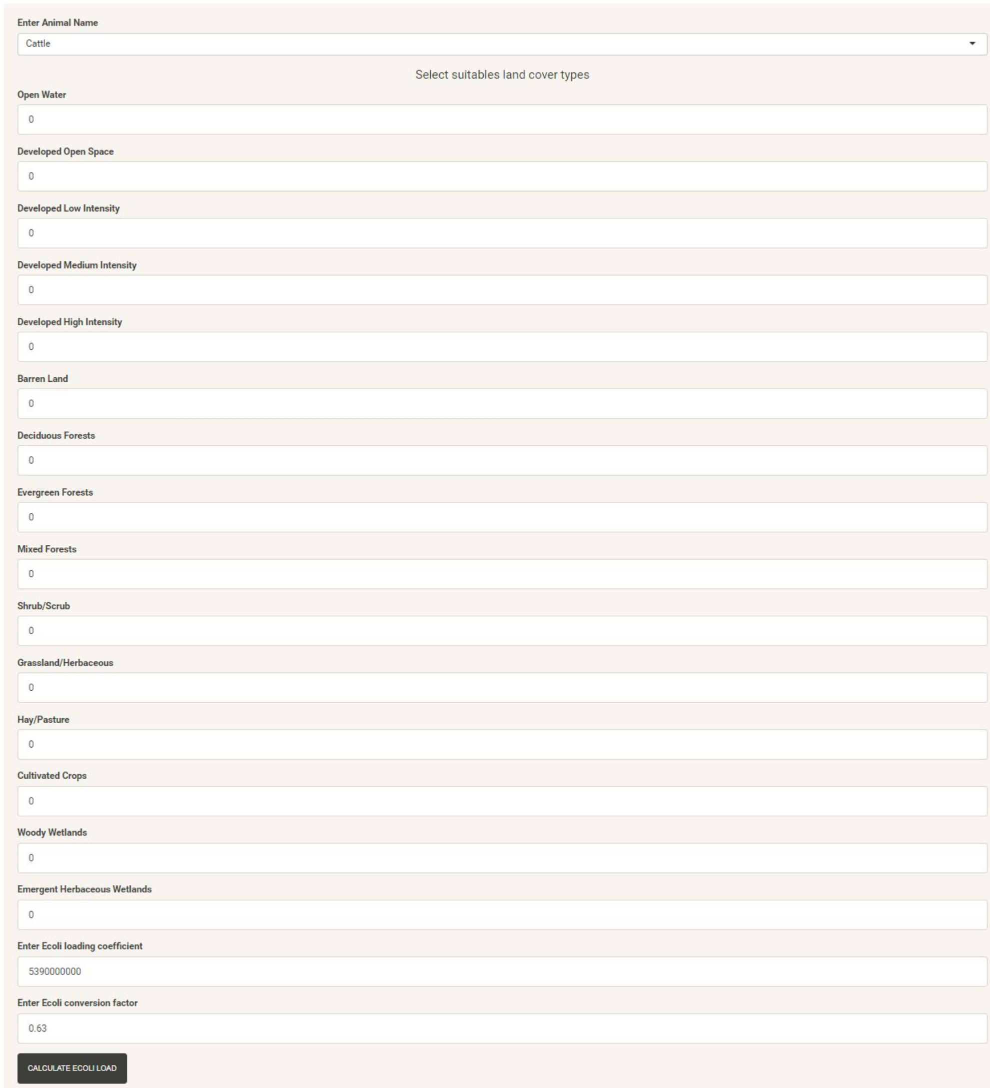

Figure 3. TWCS livestock inputs tab.

For On-site sewage facilities (OSSFs) the numbers generated by removing 911 address points that lie inside the city boundaries with a waste water treatment facility may not represent actual households with an OSSF as the address points may also include empty lots, electric poles or industrial locations and thus R handsontable package was used for user to be able to edit the OSSF numbers for each sub-watershed to get more realistic numbers and reduce uncertainty in data inputs. The user inputs can be entered in the tab-set panel as shown in **Figure 4**.

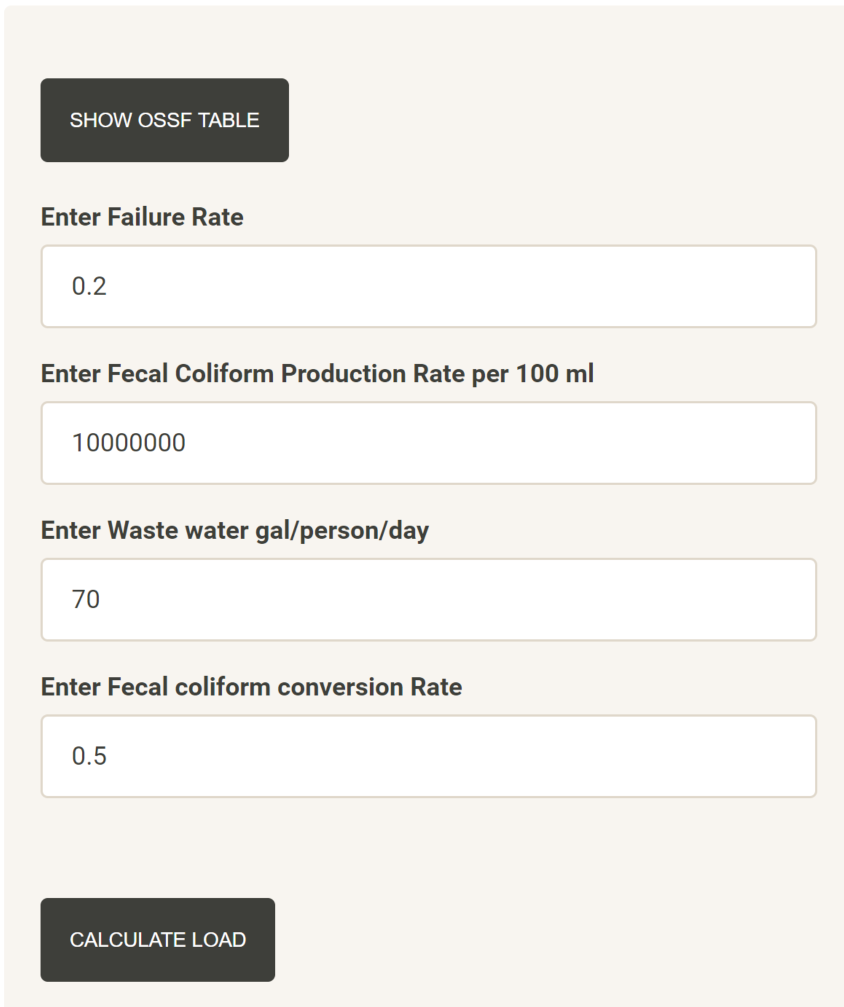

Figure 4. OSSF Inputs Tab.

Waste water facilities table was also developed using the R handsontable for user to add/remove WWTF depending on whether they discharge waste water into the stream and add missing discharge data.

2.3 Output Demonstration

After the inputs are customized, *E. coli* loads summaries for each sub-watershed are displayed for each indicator in their respective tabs through summary charts, tables and interactive leaflet maps as shown in **Figure 5**. This provides the user to look at highest priority areas for each indicator and append individual indicator load to calculate the total load on the watershed. Once the user appends all the indicator loads to the total load table, tables and charts for the total *E. coli* loads on each sub-watershed are available to view and download in the total loads tab. This also provides users with pie charts and box plots to look at contribution by each indicator and compare the highest contributing sources to develop best management practices.

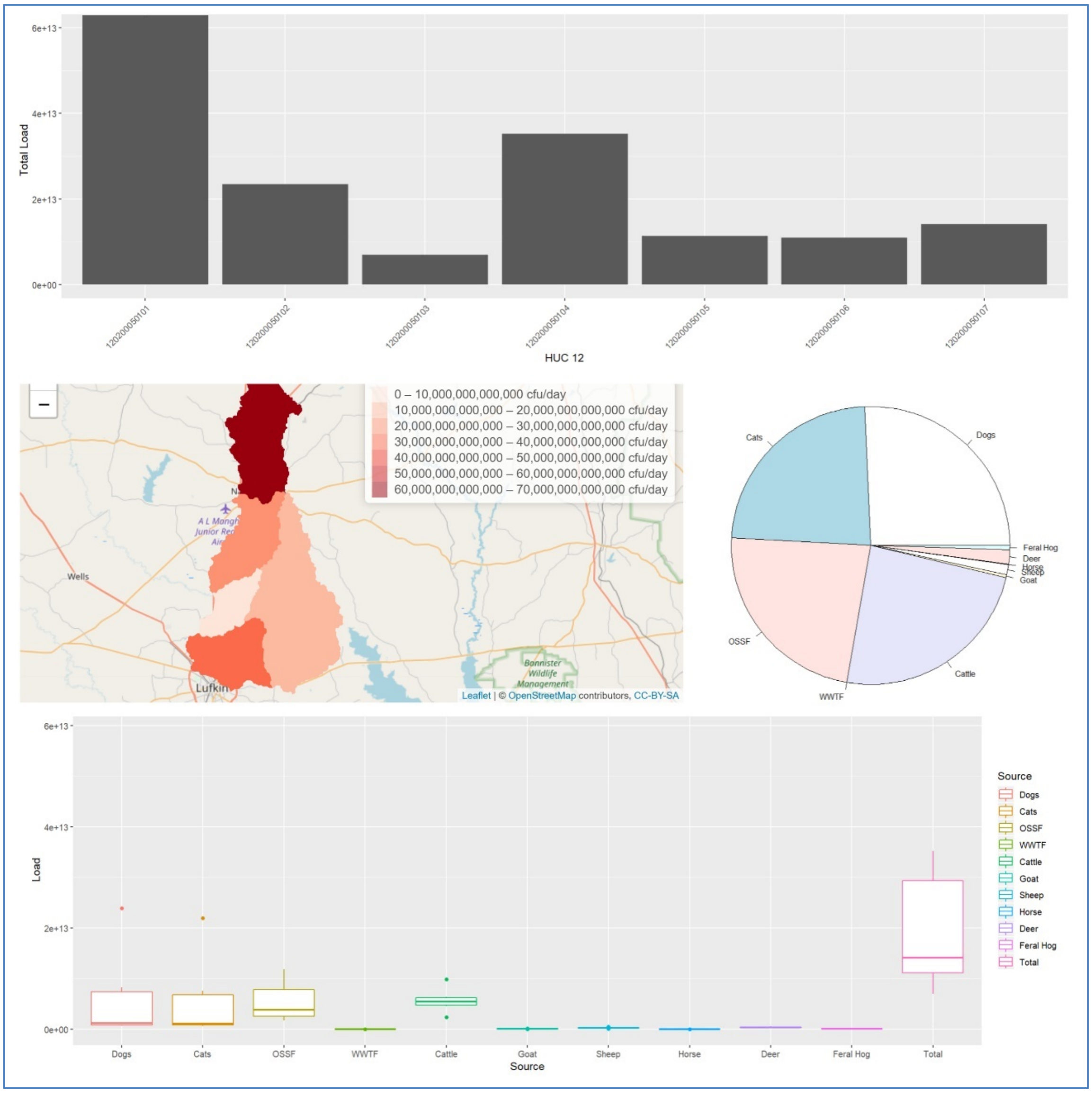

Figure 5. Total load outputs demonstration in TWCS

2.4 Scenario development

Best management practices are required to be developed in preparing watershed protection plans and developers need to identify the potential reduction in *E. coli* loads when these practices are applied. As the *E. coli* loads are calculated for each sub-watershed, the scenario development tab as shown in **Figure 6** allows users to develop best management practices by creating different scenarios and look at changes in *E. coli* loads on the watershed. After the highest priority sub-watersheds and indicators are identified, users can create load reduction scenarios by making the following changes:

a) Land cover change

b) Livestock Suitable land change

c) OSSF repairs

d) Pets Managed

e) Feral Hogs Reduction

f) Deer Reduction

Changes can be made to specific sub-watersheds depending on *E. coli* load results and stakeholder's inputs. 5 different scenarios can be prepared with individual or combined best management practices.

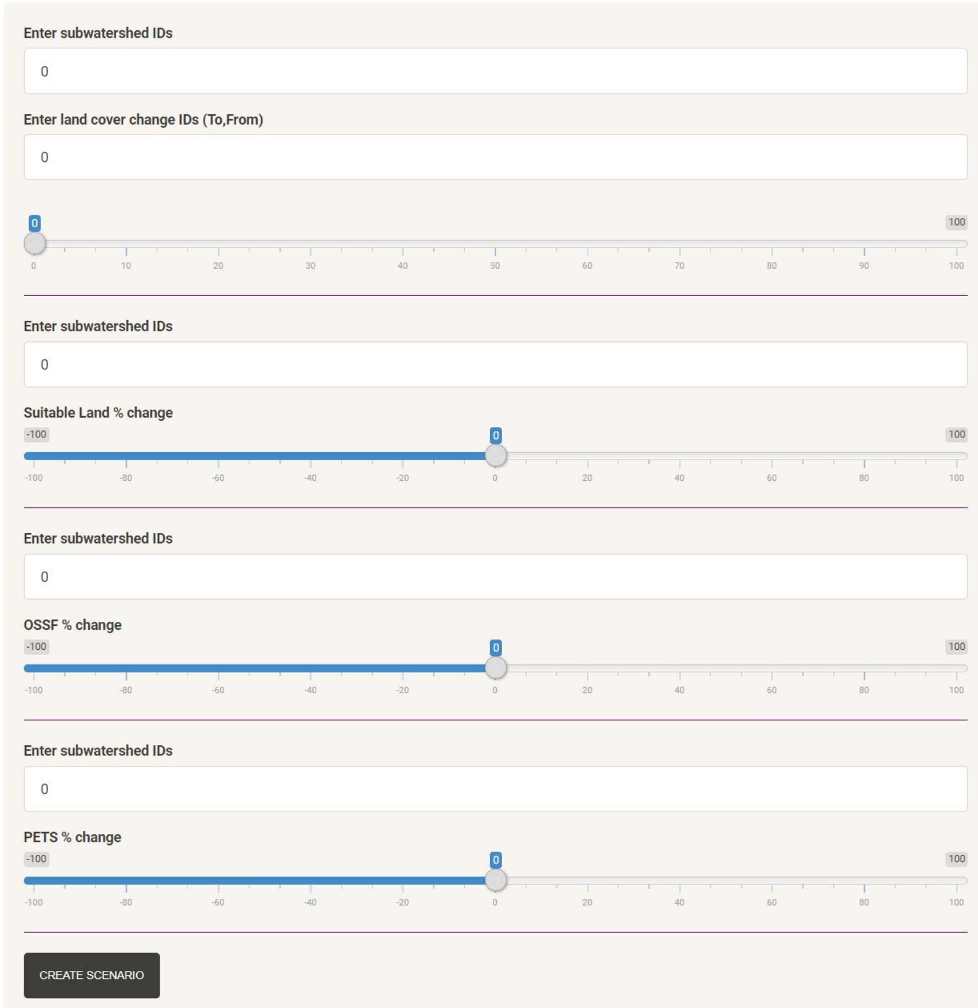

Figure 6. TWCS scenario development tab

3. TOOL IMPLEMENTATION

3.1 Study Area

The La Nana Bayou watershed as shown in **Figure 7** is located in the Neches river basin and has an area of 1838.21 square miles within Nacogdoches and Angelina counties. The watershed contains two bacteria impaired water bodies: La Nana Bayou and part of Angelina River above Sam Rayburn reservoir (*Draft 2016 Texas Integrated Report-Texas 303(d) List (Category 5)*, 2018). Approximately 39 percent of the watershed lies in the Angelina county and 61 percent in the Nacogdoches county and major urban areas include the city of Nacogdoches and parts of Lufkin. The major land cover classes in the watershed include Shrub/Scrub (17.37%), Evergreen Forest (15.44%), Woody Wetlands (13.97%) and Hay/Pasture (12.22%). Average 30 year annual precipitation and temperature vary between 1260-1360 mm and 18.66-18.80 degree Celsius respectively across the watershed ("PRISM Climate Group, Oregon State U," n.d.). Total watershed population obtained from Census 2010, is about 28,171 with major population lying in the cities of Nacogdoches and Lufkin.

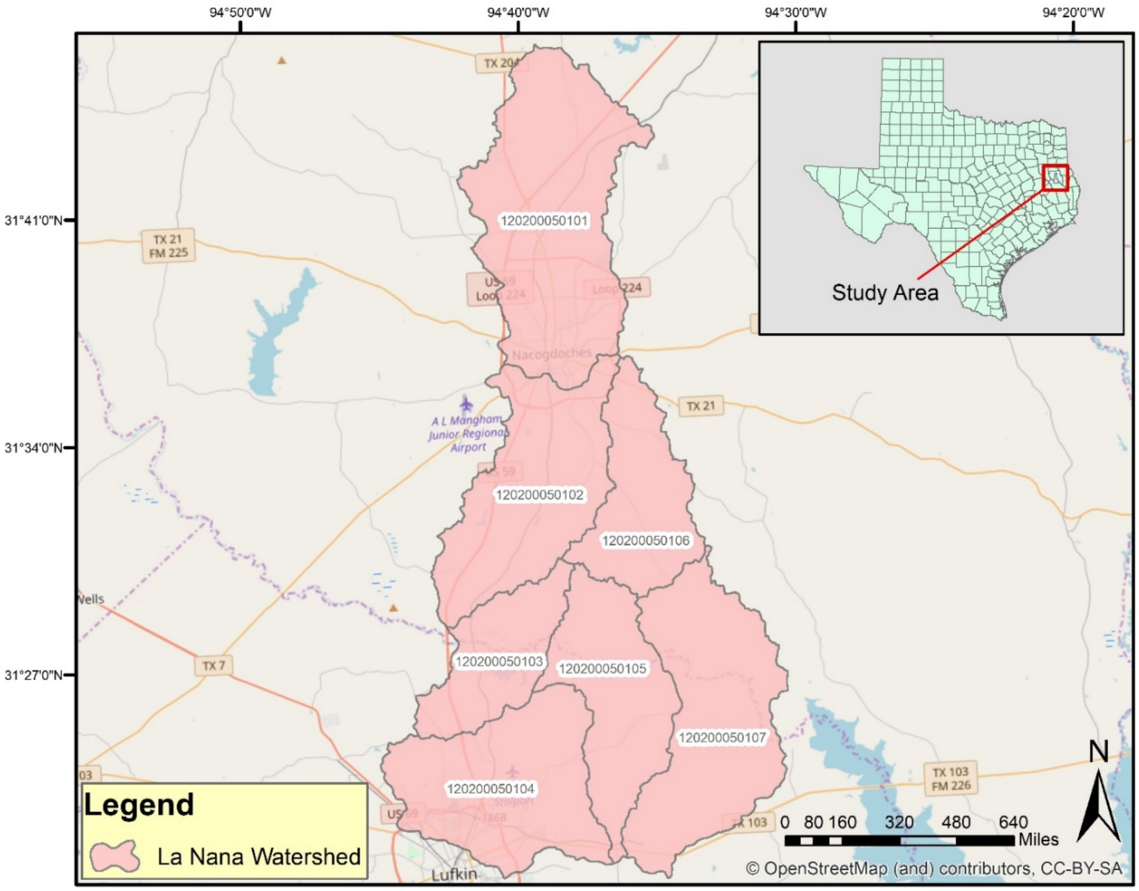

Figure 7. La Nana Bayou watershed (HUC - 1202000501).

3.2 Potential *E. coli* Load Estimation

Number of pets in each sub-watershed was calculated by using a dog density of 0.584 dogs per household and cat density of 0.638 cats per household as per stakeholder's recommendations. These densities are multiplied by total number of households in each sub-watershed to obtain total number of dogs and cats in the sub-watershed.

Livestock populations for the Angelina and Nacogdoches county as shown in **Table 2** obtained from National Agricultural Statistics Service (USDA-NASS) were used to determine the stocking density (AU/1000 Acres) of each livestock in the watershed. Livestock densities were uniformly applied to suitable land cover classes (Shrub/Scrub, Hay/Pasture, and Grasslands/Herbaceous).

Table 2. County Livestock and suitable area

County	County Area (Acres)	Cattle	Sheep	Goat	Horse	County Suitable Area (Acres)
Angelina	551029.26	16124	230	1412	1739	186774.02
Nacogdoches	625428.51	40852	190	548	2231	230188.32

Deer and Feral hog densities were taken as 22 Deer per 1000 acres and 30 Feral Hogs per 1000 acres and were uniformly applied to suitable land cover classes (Deciduous forests, Evergreen forests, Shrub/Scrub, Hay/Pasture, Grasslands/Herbaceous, Woody wetlands, Emergent herbaceous wetlands).

E. coli load from on-site sewage facilities was obtained from total number of 911 address points that lie outside the city boundaries and number of persons per household. OSSF failure rate was estimated to be 15 percent across the watershed. A constant sewer discharge of 70 gallons per person per day was used to model the E. col load from OSSF discharge. The OSSF numbers and population per household is as shown in **Table 3**.

Table 3. Sub-watershed on-site sewage facilities and average population per household

HUC 12	OSSF	Person/Household
120200050104	1785	2.67
120200050105	660	2.33
120200050103	460	2.32
120200050107	294	2.29
120200050106	377	2.55
120200050102	843	2.64
120200050101	1725	2.37

There are 5 waste water treatment facilities located within the watershed with discharge and average effluent *E. coli* concentration as shown in **Table 4**. Discharge and *E. coli* concentrations for each WWTF was used to determine daily estimated *E. coli* loads from these facilities.

Table 4. Waste water treatment facilities in La Nana Bayou watershed

Facility	ID	City	Discharge (MGD)	Concentration (per 100 ml)	HUC 12
ANGELINA & NECHES RIVER AUTHORITY	TX0056154	LUFKIN	0.37	126	120200050104
MOFFETT TWIN-OAKS MOBILE HOME PROPERTY TRUST	TX0054127	LUFKIN	0.049	126	120200050104
ANGELINA COUNTY WCID 1 WWTP	TX0133329	LUFKIN	0.06	126	120200050105
D & M WSC	TX0118613	DOUGLASS	0.1	126	120200050102
CITY OF NACOGDOCHES	TX0055123	NACOGDOCHES	7.15	126	120200050102

The *E. coli* loads were calculated using fecal coliform production rates as shown in **Table 5**. Daily fecal coliform production rates for each indicator was taken from various literature and TMDL reports. *E. coli* to fecal coliform ratio was taken to be 0.63 (Texas Water Resources Institute. et al., 2015).

Table 5. Applied fecal coliform production rates for La Nana Bayou watershed

Indicator	Fecal Coliform production rate
Cattle	8.55×10^{9} cfu/AU/day
Goat	4.32×10^{9} cfu/AU/day
Sheep	5.8×10^{10} cfu/AU/day
Horse	3.64×10^{8} cfu/AU/day
Deer	1.68×10^{9} cfu/AU/day
Feral Hogs	1.51×10^{8} cfu/AU/day
Dogs	5×10^{9} cfu/AU/day
Cats	5×10^{9} cfu/AU/day
OSSF	10×10^{6} / 100 ml
WWTFs	126 cfu/100ml

3.3 Scenario Development

The *E. coli* load results for La Nana Bayou indicated On-site sewage facilities as one of the major contributors of bacteria loading in the watershed. Thus, scenarios were developed to determine changes in load if OSSF repairs are conducted throughout the watershed.

4. RESULTS

The watershed analysis conducted using TWCS indicated potential *E. coli* loads as shown inTable 6**.** The results indicate Pets, Cattle and on-site sewage facilities as highest potential sources of *E. coli* in the La Nana Bayou watershed.

The total *E. coli* load map is as shown in **Figure 8**. Sub-watersheds 3,7 and 1 are the high priority areas for *E. coli* load reduction. Various scenarios generated for OSSF load reduction indicated a potential decrease in a load of about 3.09 x 1011 cfu/day by repairing and replacing 50 failing OSSFs in the watershed. These repairs need to be targeted at OSSFs located near the La Nana Bayou and Angelina River. **Figure 9A - Figure 16A** show potential *E. coli* loads for each bacteria source in the La Nana Bayou watershed.

Table 6. *E. coli* loads for *E. coli* sources in La Nana Bayou watershed

HUC12	Dog	Cat	Cattle	Goat	Sheep	Horse	Feral Hog	Deer	OSSF	WWTF	Total
120200050104	7.57E+12	8.27E+12	6.01E+12	8.55E+10	2.87E+11	1.80E+10	4.61E+10	3.76E+11	1.18E+13	1.98E+09	3.45E+13
120200050105	9.31E+11	1.02E+12	4.61E+12	6.56E+10	2.20E+11	1.38E+10	4.46E+10	3.64E+11	3.82E+12	2.84E+08	1.11E+13
120200050103	6.94E+11	7.58E+11	2.42E+12	3.44E+10	1.16E+11	7.26E+09	2.82E+10	2.30E+11	2.65E+12	0	6.94E+12
120200050107	5.96E+11	6.51E+11	6.38E+12	9.08E+10	3.05E+11	1.91E+10	6.82E+10	5.57E+11	1.67E+12	0	1.03E+13
120200050106	1.07E+12	1.17E+12	4.87E+12	6.94E+10	2.33E+11	1.46E+10	3.62E+10	2.96E+11	2.39E+12	0	1.02E+13
120200050102	5.96E+12	6.51E+12	5.45E+12	7.76E+10	2.61E+11	1.64E+10	4.92E+10	4.01E+11	5.53E+12	3.43E+10	2.43E+13
120200050101	2.19E+13	2.39E+13	9.86E+12	1.40E+11	4.71E+11	2.96E+10	6.37E+10	5.20E+11	1.02E+13	0	6.71E+13
1202000501	3.87E+13	4.23E+13	3.96E+13	5.63E+11	1.89E+12	1.19E+11	3.36E+11	2.74E+12	3.81E+13	3.66E+10	1.64E+14

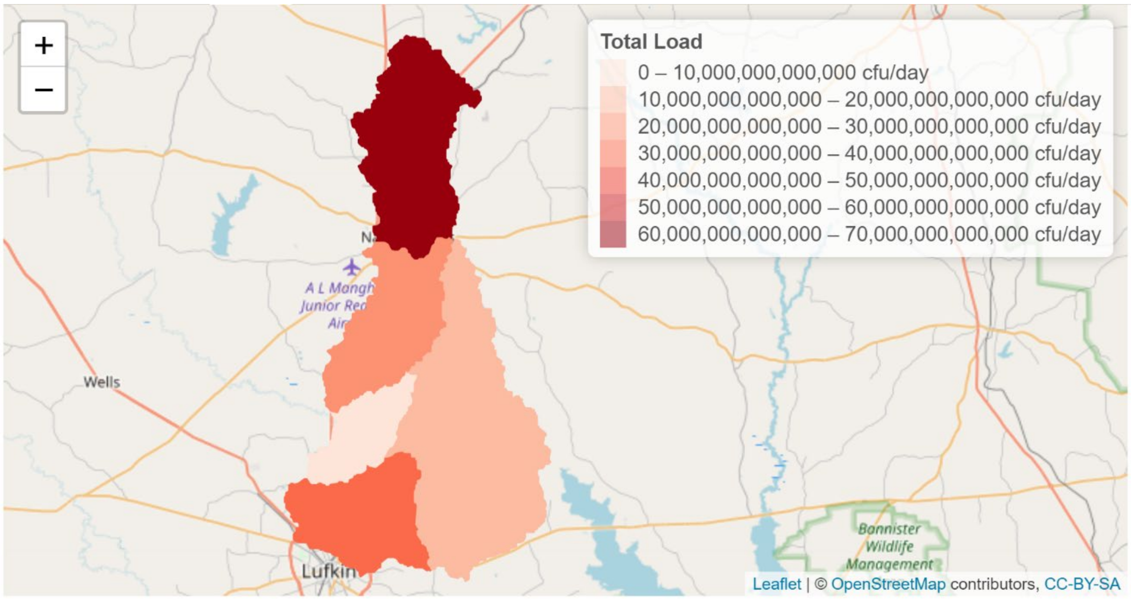

Figure 8. Total *E. coli* load in La Nana Bayou watershed

5. FUTURE WORKS

The future goals for the Texas Watershed Characterization System is to automate many watershed characterization processes including analyzing nutrient loadings on Texas streams, preparing flow duration curves and load duration curves, and reducing the uncertainty in *E. coli* load estimation in the Texas Watersheds. The TWCS data repository would be regularly updated as much as necessary.

Immediate goals for TWCS include:

a) Watershed initialization with multiple adjacent HUC watersheds.
b) Automated flow duration curves.
c) Automated load duration curves.
d) Provide water quality data for Assessment Units from Clean Rivers Program through API.
e) Provide permit data files for facilities within watershed.

Long term goals for TWCS include:

a) Develop linked Arc GIS online application to edit OSSF points.
b) Enhance the user interface to make it more user friendly.
c) Develop methodology to determine *E. coli* load transport and die off.

6. CONCLUSIONS

As the number of impaired water bodies are increasing due to vast population growth, there is a need for reduction in the time and effort required for decision-makers and scientists to develop watershed protection plans and TMDL reports such that more watersheds can be analyzed and policies can be adopted. Collection and analysis of watershed data is one of the most time taking processes in watershed planning and is a tedious process. With the development of TWCS, potential sources and loads of *E. coli* were determined for the La Nana Bayou with a web interface within minutes as it eliminated the process of data collection, and processing of large GIS datasets. With future work, users would be able to perform more tasks required in the development of TMDL reports such as Load and Flow duration curves, such that institutions can develop more characterization reports than they would be able to using the Texas Watershed Characterization System.

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APPENDIX A

E. COLI LOAD OUTPUTS

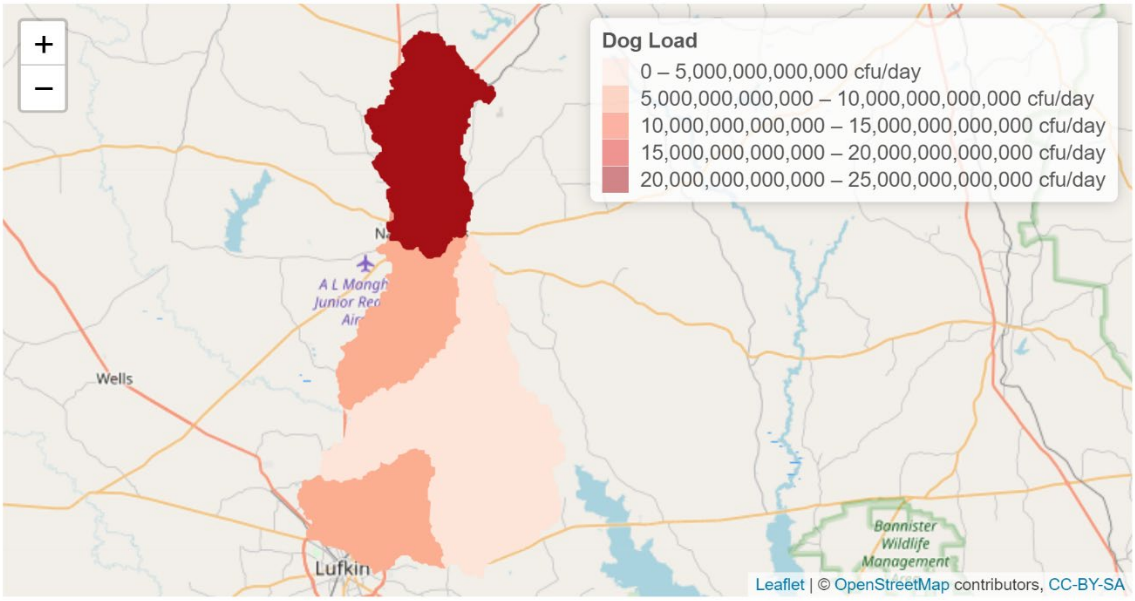

Figure 9A. Dog *E. coli* Load in La Nana Bayou watershed.

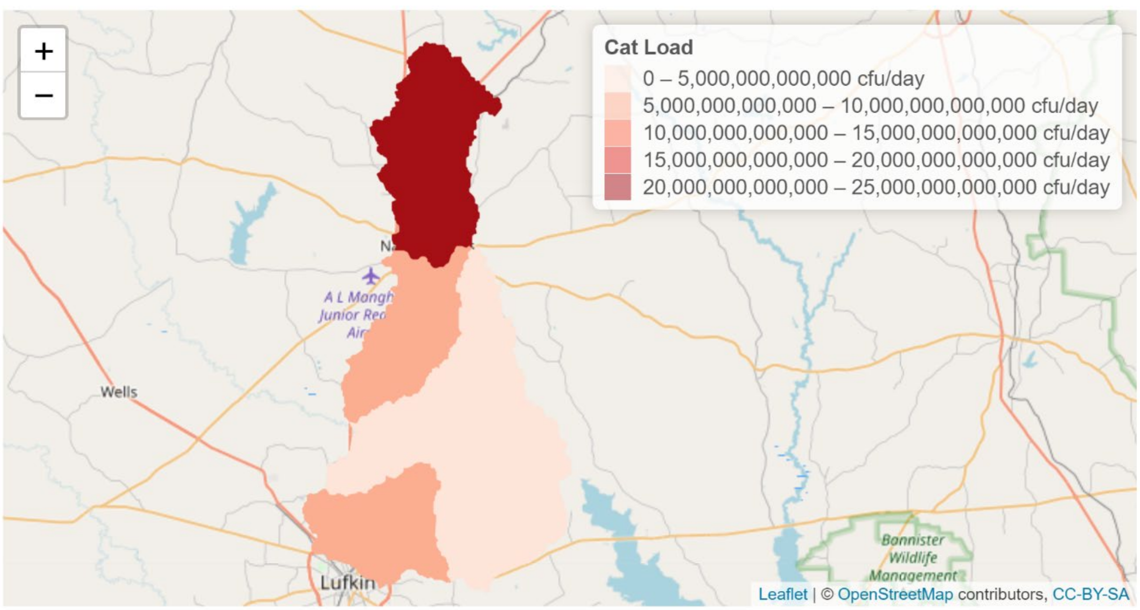

Figure 10A. Cat *E. coli* Load in La Nana Bayou watershed

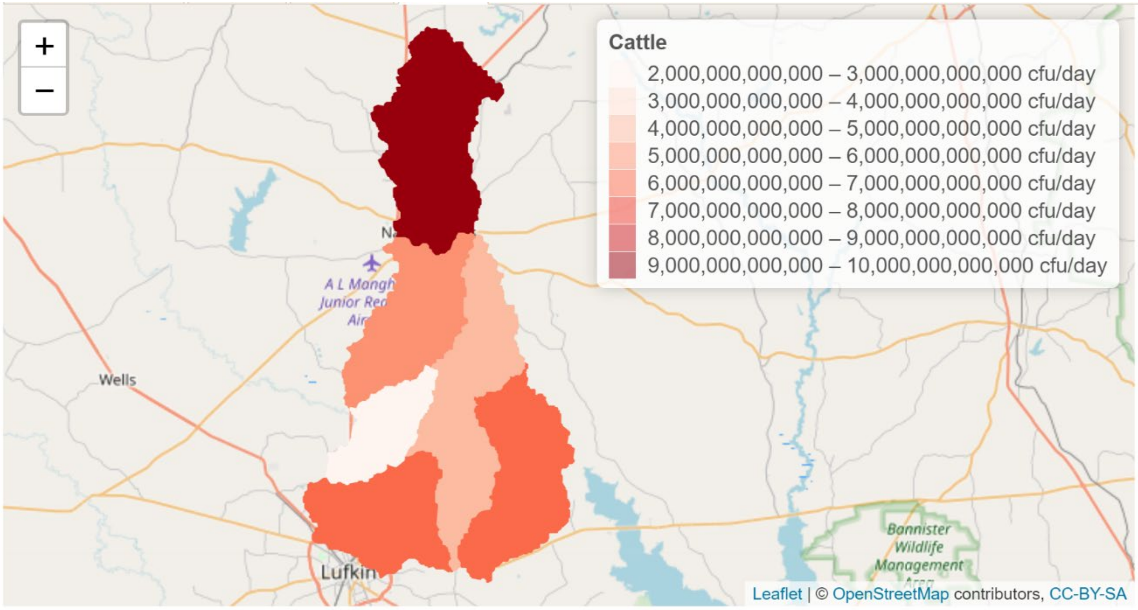

Figure 11A. Cattle *E. coli* load in La Nana Bayou watershed.

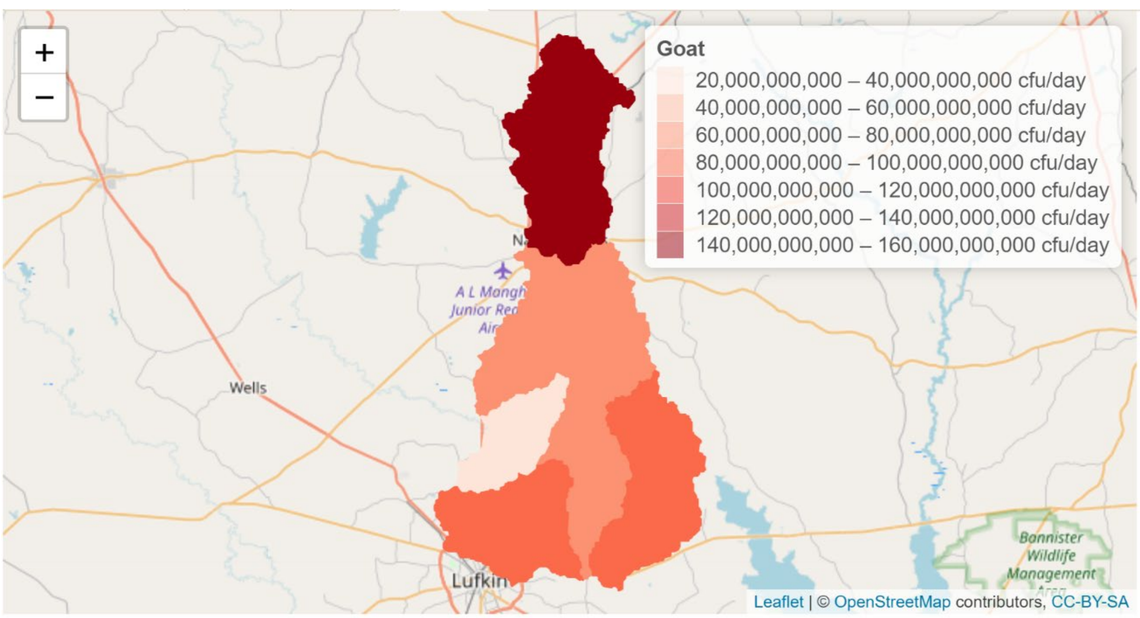

Figure 12A. Goat *E. coli* load in La Nana Bayou watershed.

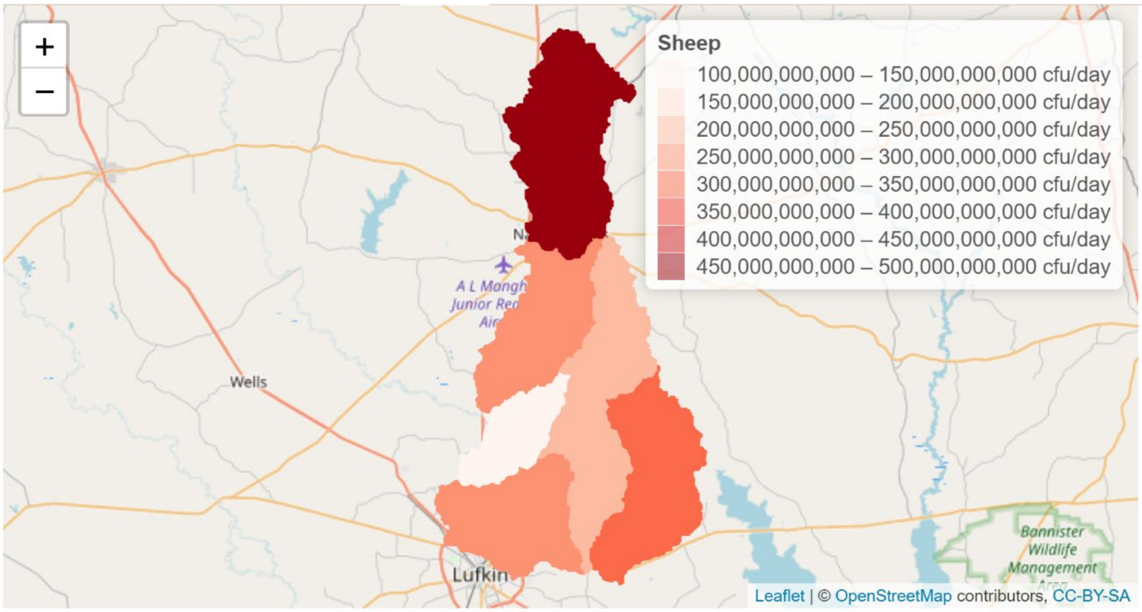

Figure 13A. Sheep *E. coli* load in La Nana Bayou watershed.

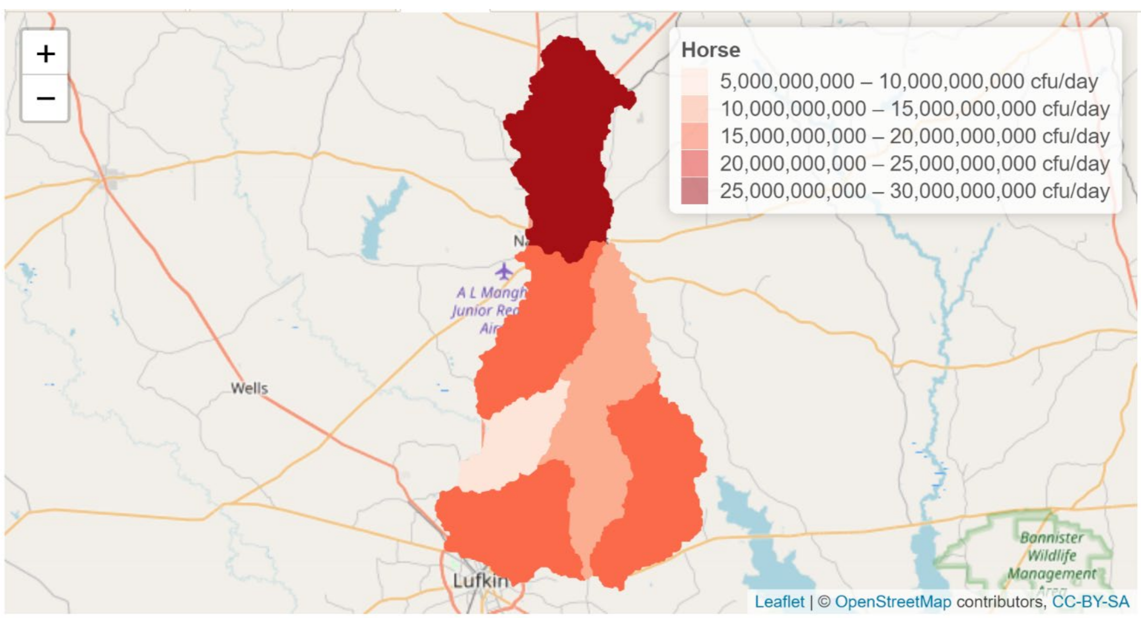

Figure 14A. Horse *E. coli* load in La Nana Bayou watershed.

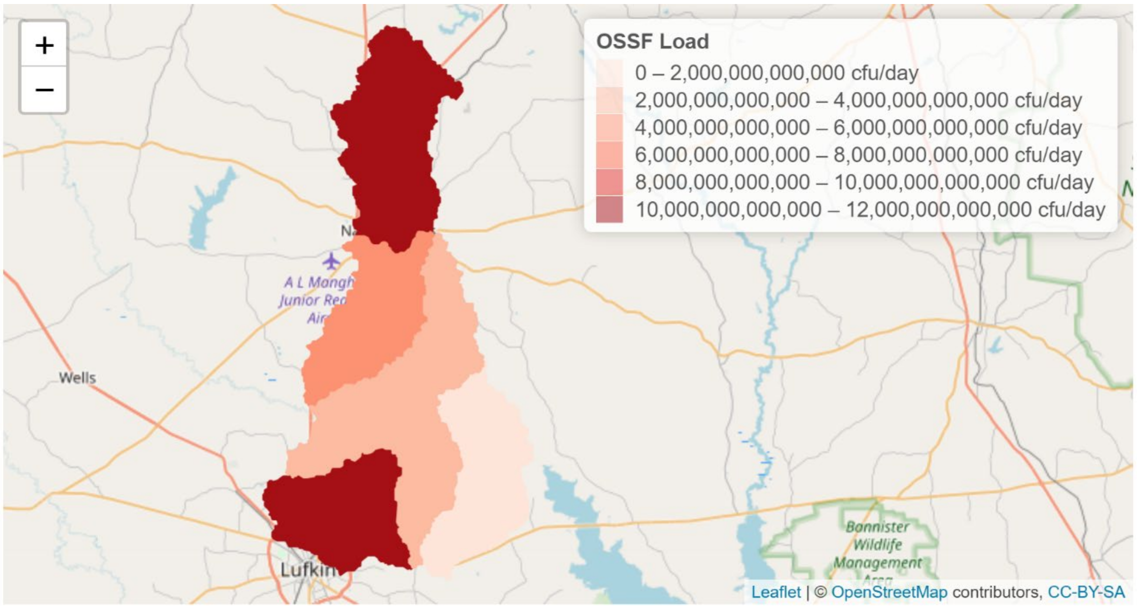

Figure 15A. OSSF *E. coli* load in La Nana Bayou watershed.

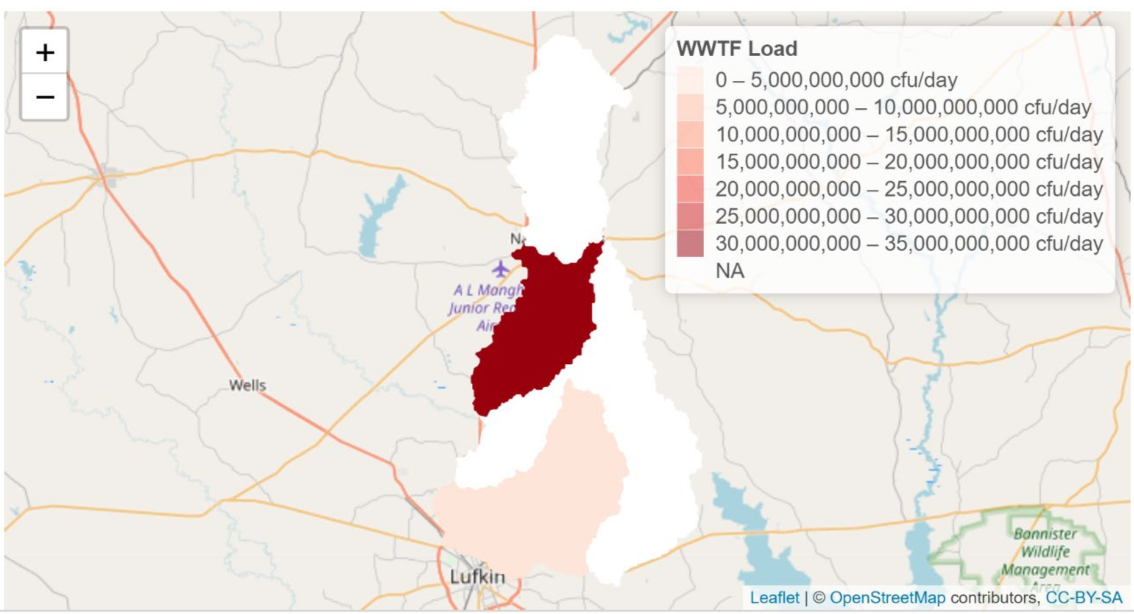

Figure 16A. WWTF *E. coli* load in La Nana Bayou watershed.

APPENDIX B

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