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Cover photo: Located in far east Texas and stretching into Louisiana, Caddo Lake is known for its extensive forests of baldcypress trees draped with Spanish moss. This famous lake is home to a rich ecosystem and a wide variety of wildlife. The cover photo was taken during normal water levels, but in 2011 the lake's levels dropped significantly during the drought. Photo credit: Texas Water Resources Institute

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Estimating daily potential *E. coli* loads in rural Texas watersheds using Spatially Explicit Load Enrichment Calculation Tool (SELECT)

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Abstract: When developing a watershed protection plan (WPP) or a total maximum daily load (TMDL), it is often difficult to accurately assess pollutant loads and sources for a watershed because insufficient water quality monitoring data are available. According to the Texas Commission on Environmental Quality, there are 274 bacterial impairments in Texas water bodies out of a total of 438 impaired water bodies. Bacterial data are often sparse, which hinders the development of WPPs or TMDLs. To address this lack of data, the Spatially Explicit Load Enrichment Calculation Tool (SELECT) was used to develop WPPs for 3 rural watersheds in Texas that are impaired due to *E. coli* bacteria: Buck Creek, 5 subwatersheds of Little Brazos River, and Lampasas River. SELECT is an automated geographical information system tool that can assess potential bacteria sources and relative loads in watersheds using spatial factors such as land use, population density, and soil type. The results show how the SELECT methodology was applied and adapted to each watershed based on stakeholder concerns and data availability.

Keywords: GIS, watersheds, TMDL, *E. coli* bacteria

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Terms used in paper

Short name or acronym	Descriptive name
BMPs	best management practices
CAFOs	concentrated animal feeding operations
CCN	Certificate Of Convenience And Necessity
CFU	colony forming units
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
GIS	geographic information system
HSPF	Hydrological Simulation Program- FORTRAN
NAIP	National Agriculture Imagery Program
NLCD	National Land Cover Dataset
NRCS	Natural Resources Conservation Service
OWTSs	on-site wastewater treatment systems
PNPI	Potential Nonpoint Pollution Index
SEDMOD	Spatially Explicit Delivery Model
SELECT	Spatially Explicit Load Enrichment Calculation Tool
SSURGO	Soil Surface Geographic Database
SWAT	Soil And Water Assessment Tool
TCEQ	Texas Commission on Environmental Quality
TMDL	total maximum daily load
TPWD	Texas Parks And Wildlife Department
WMAs	wildlife management associations
WPP	watershed protection plan
WWTFs	wastewater treatment facilities

INTRODUCTION

Accurately assessing watershed pollutant loads for the development of a total maximum daily load (TMDL) and watershed protection plan (WPP) is difficult because insufficient water quality monitoring data are available. A WPP is a stakeholder-driven process to restore or protect the water quality of a specific water body. The most common water body impairments in Texas and across the United States are due to bacteria (TCEQ 2008; USEPA 2008). Out of 438 impaired water bodies in Texas, 274 are impaired due to bacteria (TCEQ 2008). The development of bacteria WPPs and TMDLs can be hindered because of the sparse availability of measured bacterial concentrations. Bacterial impairment is usually assessed by measuring the actual concentration of an indicator organism. When the geometric mean concentration of the indicator organism exceeds the regulatory standards, the water body is considered impaired because of fecal contamination. In the State of Texas, *E. coli* is considered the regulatory indicator organism of fecal contamination in freshwater systems.

Developing and implementing a TMDL project is costly. According to the U.S. Environmental Protection Agency (EPA), "the national average cost of developing TMDLs per water body is estimated to be about $52,000, but can typically range from under $26,000 to over $500,000 depending on the number of TMDLs, their level of difficulty, and the extent to which impaired waters are clustered together for TMDL development (USEPA 2001b)." Considerable amounts of time and money are spent while developing a TMDL to allocate pollutant loads and to identify potential sources. Usually TMDL development is done using water quality models that require a significant amount of resources and time.

Models such as the Soil and Water Assessment Tool (SWAT) and Hydrological Simulation Program-FORTRAN (HSPF) have been used for modeling bacterial transport. Other simplistic microbial models, such as the Potential Nonpoint Pollution Index (PNPI), the Spatially Explicit Delivery Model (SEDMOD), and the Spatially Explicit Load Enrichment Calculation Tool (SELECT), have been developed to rank the potential pollution impacts of areas from nonpoint sources primarily using land use and potential sources in the watershed (Fraser et al. 1998; Munafo et al. 2005; Teague et al. 2009).

SELECT is an automated geographic information system (GIS) tool that can be applied to assess potential *E. coli* loads in a watershed based on spatial factors such as land use, population density, and soil type (Teague et al. 2009). SELECT is able to calculate potential *E. coli* loads and highlight areas of concern for best management practices (BMPs) to be implemented. Visual outputs of the program allow a decision maker or stakeholder to easily identify areas of a watershed with the greatest potential for contamination contribution and enable them to formulate management strategies to include in the WPP or TMDL implementation plan. SELECT calculates the potential *E. coli* loads by distributing the contributing sources spatially over the entire watershed. When applying SELECT, the population densities of potential contributors are determined using stakeholder input to accurately represent the watershed. However, potential *E. coli* loads generated using SELECT are the worst-case scenario because the tool calculates the largest amount of contribution possible from individual sources. SELECT is an analytical approach for developing an inventory of potential bacterial sources, particularly nonpoint source contributors, and distributing their potential bacterial loads based on land use and geographical location. The objective of this study was to use SELECT to calculate the potential *E. coli* loads for possible contributing sources in 3 watersheds—Buck Creek, Little Brazos River, and Lampasas River—and to determine the areas of and contributing sources of high concern.

STUDY AREAS

The SELECT methodology was applied to comparatively evaluate *E. coli* loads from various sources in 3 impaired water bodies in Texas: Buck Creek, Little Brazos River, and Lampasas River.

Buck Creek Watershed

Buck Creek (Figure 1) is a small, unclassified stream that originates southwest of Hedley, Texas in Donley County and flows 109 kilometers (68 miles) across the Oklahoma border to its confluence with the Prairie Dog Town Fork of the Red River (Gregory 2012). Buck Creek was first classified as an impaired water body due to bacterial contamination in the 2000 303 (d) List (TCEQ 2000). The study area includes only the portion of the watershed located in Texas, which encompasses an area of 74,851 hectares (184,960 acres) (Gregory 2012). Buck Creek encompasses portions of Donley, Childress, and Collingsworth counties in the Texas Panhandle. The watershed is mostly agriculturally populated with a few rural towns such as Wellington and Hedley with populations of 2,189 and 329 respectively (Texas Association of Counties 2011).

Little Brazos River Watershed

The Little Brazos River watershed (Figure 1) is located in the central Brazos River Basin and consists of 1 classified water body. This watershed contains 5 tributaries impaired for bacteria. These tributaries are located within close proximity of each other in Robertson County, and their subwatersheds have similar land use and water quality characteristics. The 5 impaired tributaries of the Little Brazos River watershed are Campbells Creek, Mud Creek, Pin Oak Creek, Spring Creek, and Walnut Creek. The watershed area containing the subwatersheds of the tributaries encompasses 84,693 hectares (209,280 acres) that lie almost entirely within Robertson County. The land use in the area is primarily agricultural, consisting of rangeland and pasture with mixed areas of forested lands and several small towns and communities such as Hearne (population 4,459), Franklin (population 1,564), and Calvert (population 1,192) (Texas Association of Counties 2011).

Lampasas River Watershed

The Lampasas River watershed (Figure 1) is located in south central Texas, begins in Hamilton County, and flows 121 kilometers (75 miles) through Lampasas, Burnet, and Bell counties. The study area only includes the length of the Lampasas River until it is dammed and forms Stillhouse Hollow Lake. The Lampasas River watershed above Stillhouse Reservoir encompasses 322,320 hectares (796,469 acres). The land use for the Lampasas River watershed is primarily agricultural containing rural towns such as the city of Lampasas with a population of 6,681 (Texas Association of Counties 2011). The lower portion of the watershed contains a portion of the Fort Hood-Killeen area.

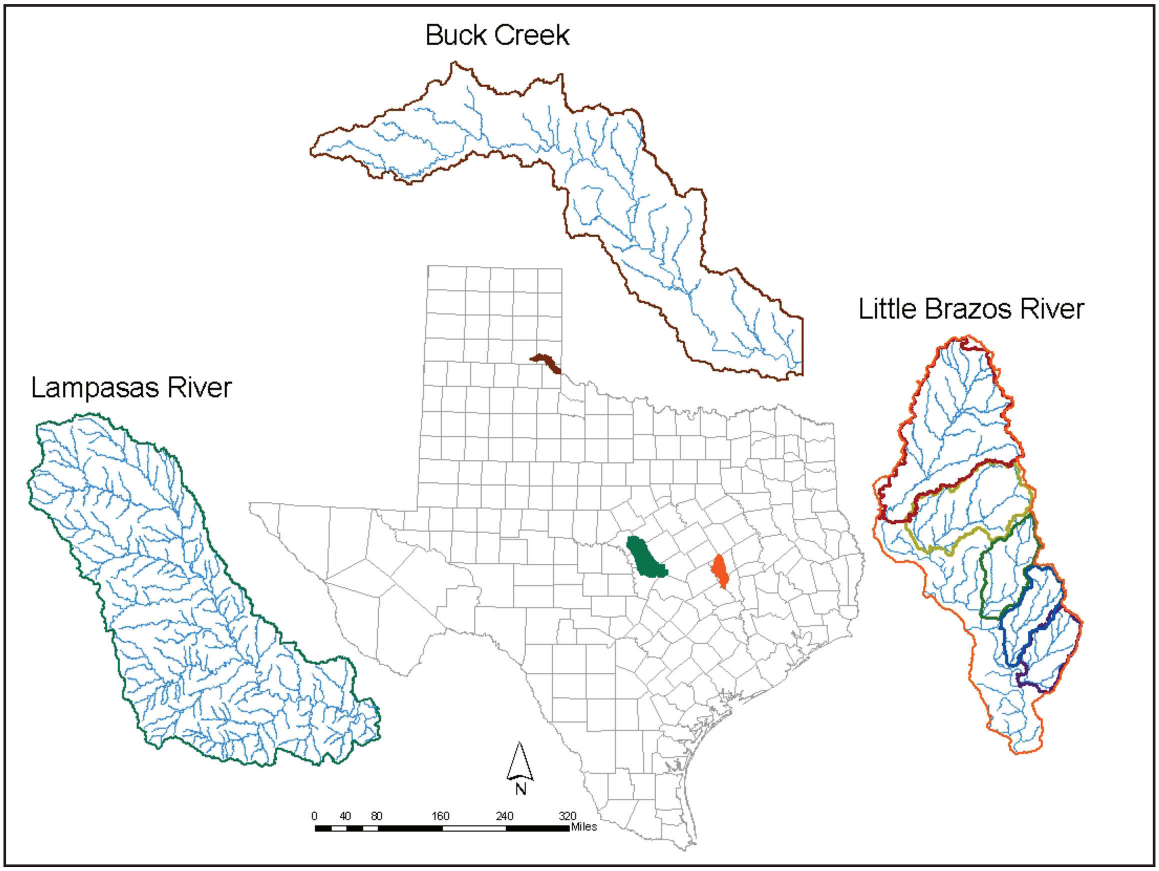

Figure 1. Spatial locations of Buck Creek, Little Brazos River, and Lampasas River watersheds in Texas.

METHODOLOGY

The SELECT methodology, developed by the Department of Biological and Agricultural Engineering and Spatial Sciences Laboratory at Texas A&M University, was used to independently characterize potential *E. coli* sources and estimate daily potential *E. coli* loads for the Buck Creek watershed, 5 Little Brazos River tributary watersheds, and the Lampasas River watershed.

A thorough understanding of the watersheds and potential contributors that exist is necessary to estimate and assess potential bacterial load inputs. Land-use classification data and data from state agencies, municipal sources such as wastewater treatment facilities (WWTFs), and local stakeholders on the number and distribution of pollution sources were entered in a GIS software format. Each watershed was divided into multiple smaller subwatersheds based on elevation changes along tributaries using flow direction and flow accumulation data as criteria in addition to the main segment of the water body. Rather than looking at contributions on a whole watershed basis, pollutant sources in the landscape were identified and targeted where they are most likely to have significant effects on water quality.

The role of a stakeholder group when applying SELECT to a watershed is to review inputs into SELECT. Individual stakeholders apply personal knowledge of the watershed to make those inputs as accurate as possible. Typically, a stakeholder group consists of farmers, ranchers, the public, project administrators such as personnel from state regulatory agencies, and Texas A&M AgriLife Extension Service personnel living in the watersheds.

Land-use data were provided by the Spatial Sciences Laboratory and was developed using National Agriculture Imagery Program (NAIP) images collected in 2005 paired with 2003 Landsat Satellite images. The land-use classification was verified using the 2001 National Land Cover Dataset (NLCD) classifications and ground-truthed data. Land-use classifications for the Buck Creek and the Little Brazos watersheds were open water, developed (further subclassified into roads and low, medium, and high intensity), barren land, mixed forest, riparian forest, rangeland, and cultivated land. For the Buck Creek watershed, managed pastures were further delineated from rangeland and cultivated land using USDA Farm Service Agency data. Land use was visually verified by stakeholders, and it was suggested that the land use categorized as cultivated land should be categorized as managed pasture for the Little

Brazos River watershed. The Lampasas River watershed land use was developed using the same procedure and data as the Buck Creek and Little Brazos River watersheds; however, it was determined that broader land-use categories could be used for the urban and forested areas. The land-use categories for the Lampasas River watershed were forest, rangeland, barren land, cultivated land, managed pasture, water, and urban.

Potential *E. coli* Load Estimation

Stakeholders determined the sources potentially contributing to the watershed bacterial loading. The analysis was conducted at a 30-meter-by-30-meter spatial resolution. First, each source was distributed to suitable areas in the watershed and then the *E. coli* load was calculated using the equations in Table 1. The fecal production rates for the sources were calculated using the highest in the range of values in EPA guidance (USEPA 2001a) for all of the *E. coli* sources. Doyle and Erikson (2006) estimate that 50% of fecal coliform are *E. coli*. Therefore, a conversion factor of 0.5 was applied to convert the fecal production rates from fecal coliform to *E. coli*. After the potential *E. coli* loads were calculated, the results were aggregated at the subwatershed level to distinguish areas of concern.

Potential *E. coli* Sources in the Buck Creek Watershed

Cattle, feral hogs, and deer were identified as manageable fecal contributors in the Buck Creek watershed. These animals

Table 1. Calculation of potentional E.coli loads from various sources.

Source	***E. coli* load calculation**
Cattle	$EC = \#\ Cattle * 10 * 10^{10}\ cfu/day * 0.5$[a]
Horses	$EC = \#\ Horses * 4.2 * 10^{8}\ cfu/day * 0.5$[a]
Sheep and goats	$EC = \#\ Sheep * 1.2 * 10^{10}\ cfu/day * 0.5$[a]
CAFOs	$EC = \#\ Permitted\ Head * 10 * 10^{10}\ cfu/day * 0.2$[b] $* 0.5$[a]
Poultry operations	$EC = Maximum\ Amount\ of\ Litter\ Utilized\ On\text{-}Site * 44{,}000\ cfu/gram$
Deer	$EC = \#\ Deer * 3.5 * 10^{8}\ cfu/day * 0.5$[a]
Feral hogs	$EC = \#\ Hogs * 1.1 * 10^{9}\ cfu/day * 0.5$[a]
Dogs	$EC = \#\ Households * \frac{1\ dog}{Household} * 5 * 10^{9}\ cfu/day * 0.5$[a]
OWTSs	$EC = \#OWTSs * Failure\ Rate * \frac{10*10^{6}\ cfu}{100\ mL} * \frac{70\ gal}{\frac{person}{day}} * \frac{Avg\ \#}{Household} * \frac{3758.2\ mL}{gal} * 0.5$[a]
WWTFs	$EC = Permitted\ MGD * \frac{126\ cfu}{100\ mL} * \frac{10^{6}\ gal}{MGD} * \frac{3758.2\ mL}{gal}$

[a] Fecal coliform to *E. coli* conversion factor using Doyle and Erikson (2006) rule of thumb estimating 50% of fecal coliform is *E. coli*.

[b] An 80% treatment efficiency was assumed for CAFOs, so 20% of the *E. coli* in the raw waste was assumed in the calculation of the potential *E. coli* load.

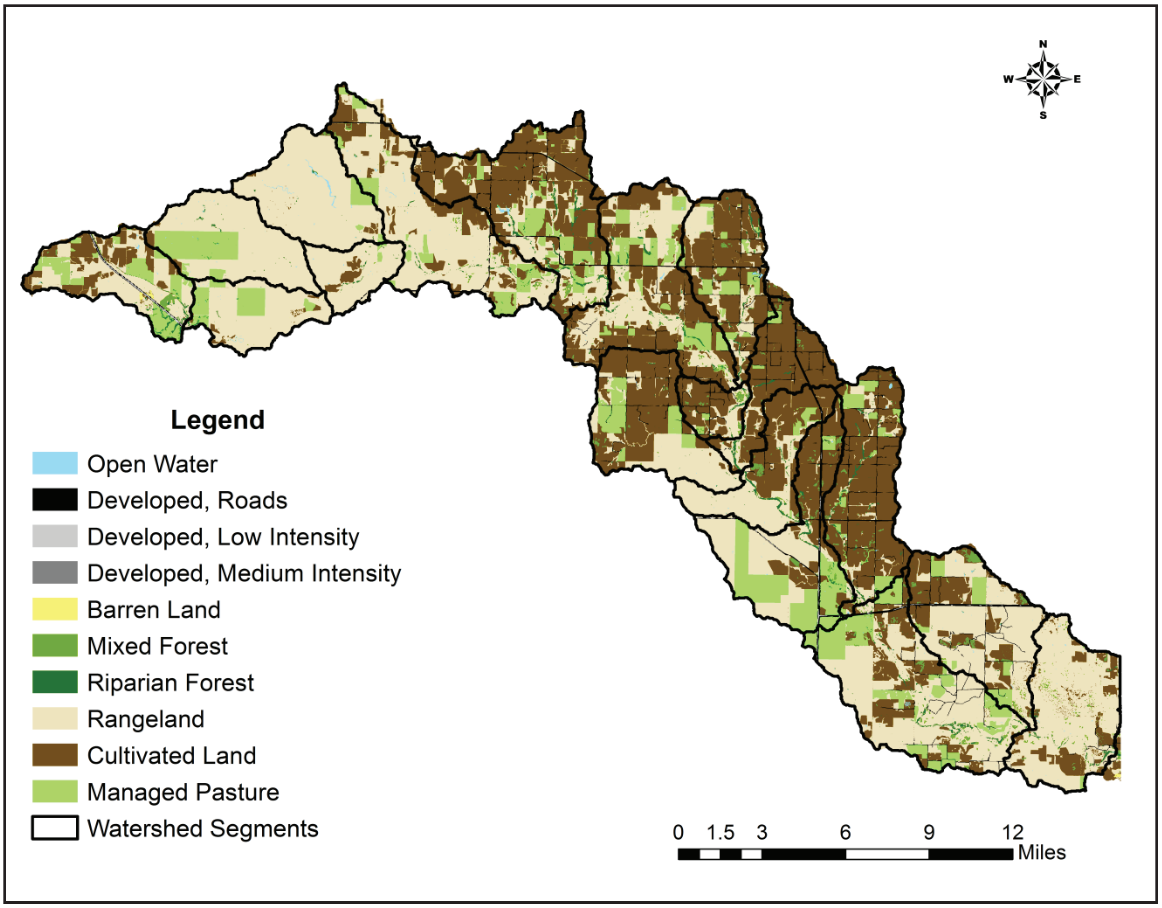

Figure 2. Buck Creek watershed land use.

were determined to be potential fecal contributors by state agencies and stakeholders, and sufficient data were available to label these as potential contributors.

Cattle

Populations of cattle in the Buck Creek watershed consist of those grazed on rangeland and those grazed on managed pasture (Figure 2). Using an average Natural Resources Conservation Service (NRCS) stocking rate of 10 hectares per animal unit (25 acres per animal unit) for rangeland and 3 hectares per animal unit (8 acres per animal unit) for managed pasture, the total watershed population of cattle in Childress, Collingsworth, and Donley counties was estimated at 6,640 animal units (454 kilograms live weight). Rangeland cattle accounted for 3,664 head and were evenly distributed in the rangeland, mixed forest, and riparian forest land uses, (Figure 2) while the remaining (2,976) managed pasture cattle were evenly distributed in the managed pasture use. Cattle numbers and distributions were verified with watershed stakeholders and determined to be representative of the Buck Creek watershed. The potential *E. coli* loads were calculated (Table 1) separately for range and pasture cattle and added together to create the total potential *E. coli* load from cattle.

Feral Hogs

No accurate estimate of feral hog numbers in the Buck Creek watershed exists. Stakeholders were asked to provide input regarding feral hog numbers in Buck Creek. Using this feedback, a population estimation of 7,310 animals was determined. Stakeholders also indicated that the feral hog population should be distributed across the rangeland, barren land, managed pasture, cultivated land, mixed forest, and riparian forest land uses (Figure 2) within a 100-meter buffer around streams. Applying this population estimate to these land uses resulted in a population density of 10 hectares (25 acres) per animal for the entire watershed area. Then, the daily potential *E. coli* load from feral hogs was estimated (Table 1).

Deer

Deer populations estimated in Buck Creek consist of white-tailed and mule deer. The SELECT methodology is not able to distinguish between separate deer species, therefore, combining the 2 populations into 1 was the most feasible scenario. The Texas Parks and Wildlife Department (TPWD) study conducted by Lockwood (2005) provided initial population estimates and associated animal densities for areas near Buck Creek. Using this information as a starting point, stakeholders were asked to provide input on the size and distribution of the deer herds in the watershed. In total, approximately 5,143 deer (990 mule deer and 4,153 white-tailed deer) were estimated to reside in the watershed, and their numbers were applied over areas of the rangeland, managed pasture, mixed forest, riparian forest, and cultivated land uses (Figure 2) at an average rate of 15 hectares (36 acres) per animal.

Potential *E. coli* Sources in the Little Brazos River Watershed

The potential *E. coli* sources in the Little Brazos River watershed were considered in estimating total potential *E. coli* loads from each subwatershed. To simplify for modeling purposes, the stocking rates for livestock, wildlife, and feral hogs were consistently applied for all 5 subwatersheds.

Cattle

The cattle population was calculated as 2 separate management practices as per stakeholders suggestions, pasture cattle and range cattle, to account for the different stocking rates associated with the different types of cattle management. For pasture cattle, the stocking rate of 0.8 hectares (2 acres) per animal unit was applied uniformly over the managed pasture (Figure 3) in each subwatershed. The estimated population for pasture cattle was 33,879 head. For range cattle, the stocking rate of 2 hectares (5 acres) per animal unit was applied uniformly over rangeland, mixed forest, and riparian forest (Figure 3) in each subwatershed and resulted in an estimated range cattle population of 25,710 head. The total estimated cattle population, including pasture and range cattle, for the Little Brazos watershed was 59,589 head. This count compares favorably to 43,601 head of cattle within the watershed calculated using the percentage of the watershed within each county and the 2007 Census of Agriculture county data (USDA-NASS 2007). The pasture cattle and range cattle results were then added together spatially to create the potential loads from cattle for each subwatershed.

Feral Hogs

For feral hogs, a density of 8 hectares (20 acres) per animal was chosen because it was previously applied to the Plum Creek watershed (Berg et al. 2008) and was found acceptable when presented to stakeholders. Feral hog population was calculated using the density multiplied by the area of land-use categories with the exception of open water and developed. Stakeholders agreed that the total population of feral hogs, 7,060 animals, was a reasonable number of feral hogs. Feral hogs were applied uniformly across rangelands, managed pasture, mixed forest, and riparian forest (Figure 3) within a 100-meter buffer around the stream network of each subwatershed.

Deer

For deer, a density of 15 hectares (37 acres) per animal (Lockwood 2005) was applied to areas with at least 8 hectares (20 acres) of contiguous habitat within the chosen land use. Deer were applied to the land uses of rangeland, managed pasture, mixed forest, and riparian forest (Figure 3) in each subwatershed. The number of deer estimated using this density and the equation from Table 1 were used to calculate the daily potential *E. coli* loads from deer.

Poultry Operations

For poultry operations, the maximum litter used on-site in tons per day was applied uniformly over the subwatershed where the poultry operation is located. The amount of poultry litter used on-site is regulated in tons per year. Since it is unknown when and in what quantities poultry litter is applied, a worst-case scenario where the maximum litter would be applied only once annually, was assumed. The *E. coli* load calculated was for the day that the litter was applied. The calculation could be refined by obtaining local information on clean-out schedules taking into account partial clean-out of the poultry houses. The *E. coli* concentration used was 45,000 colony forming units per gram of poultry litter (Schumacher 2003), which was the higher end *E. coli* concentration presented in the report. Using the maximum litter to be applied on-site and *E. coli* concentration in broiler litter, the potential *E. coli* load from poultry litter application on one particular day was estimated.

On-site Wastewater Treatment Systems

For on-site wastewater treatment systems (OWTSs), the *E. coli* load was calculated using the formula from Table 1. The number of systems was the number of homes from the 2000 Census Blocks (USCB 2000) with the homes removed from

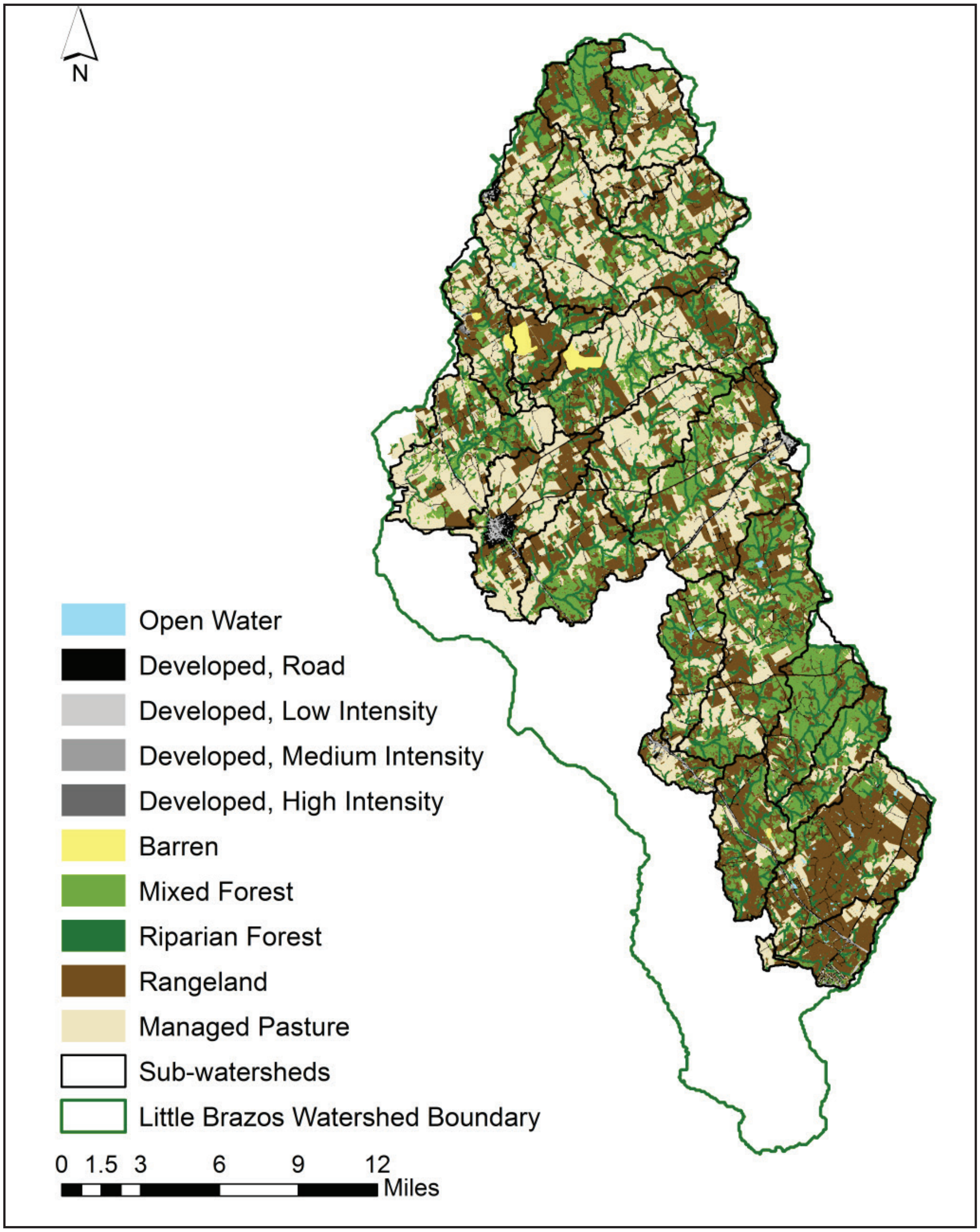

Figure 3. Land use of Little Brazos River 5 tributary watersheds.

areas falling within urban areas. There are 3 WWTFs within urban areas in the watershed: in the cities of Bremond, Calvert, and Franklin (Table 2). The estimated failure rate for the OWTSs within the watershed was calculated from the Septic Drainfield Limitation Class using the Soil Surface Geographic SSURGO database (USDA-NRCS 2004). The failure rate for each limitation class is as follows: very limited 15%, somewhat limited 10%, slightly limited 5%, and not rated 15%. The number of people per home was the average household size from the 2000 census blocks (USCB 2000). This resulted in a daily potential *E. coli* load from septic systems.

Table 2. Little Brazos River watershed WWTFs.

Subwatershed	WWTF	Permitted Discharge (MGD)
Mud Creek	City of Calvert	0.25
	City of Franklin	0.30
Walnut Creek	City of Bremond	0.22

Wastewater Treatment Facilities

The maximum permitted discharge rate for the WWTFs and an *E. coli* concentration of 126 colony forming units per 100 milliliters (Table 1) was applied to the subwatersheds in which the WWTFs are located. There are 3 WWTFs located in the Little Brazos watershed: 2 located in the Mud Creek watershed and 1 located in the Walnut Creek watershed (Table 2).

Potential *E. coli* Sources in the Lampasas River Watershed

To estimate potential *E. coli* loads in the Lampasas River watershed, domestic, livestock, and wildlife sources were considered and distributed on the appropriate land use (Figure 4). Potential domestic contributors included OWTSs, dogs, and WWTFs. Livestock included horses, goats, sheep, cattle, and concentrated animal feeding operations (CAFOs). Deer and feral hogs were identified as contamination-contributing wildlife that could be feasibly modeled.

On-site Wastewater Treatment Systems

For OWTSs, spatially distributed point data of each household were collected from residential 911 address data gathered from county agents within the watershed. Households within Certificate of Convenience and Necessity (CCN) areas (TCEQ 2012) were removed to exclude households being ser-

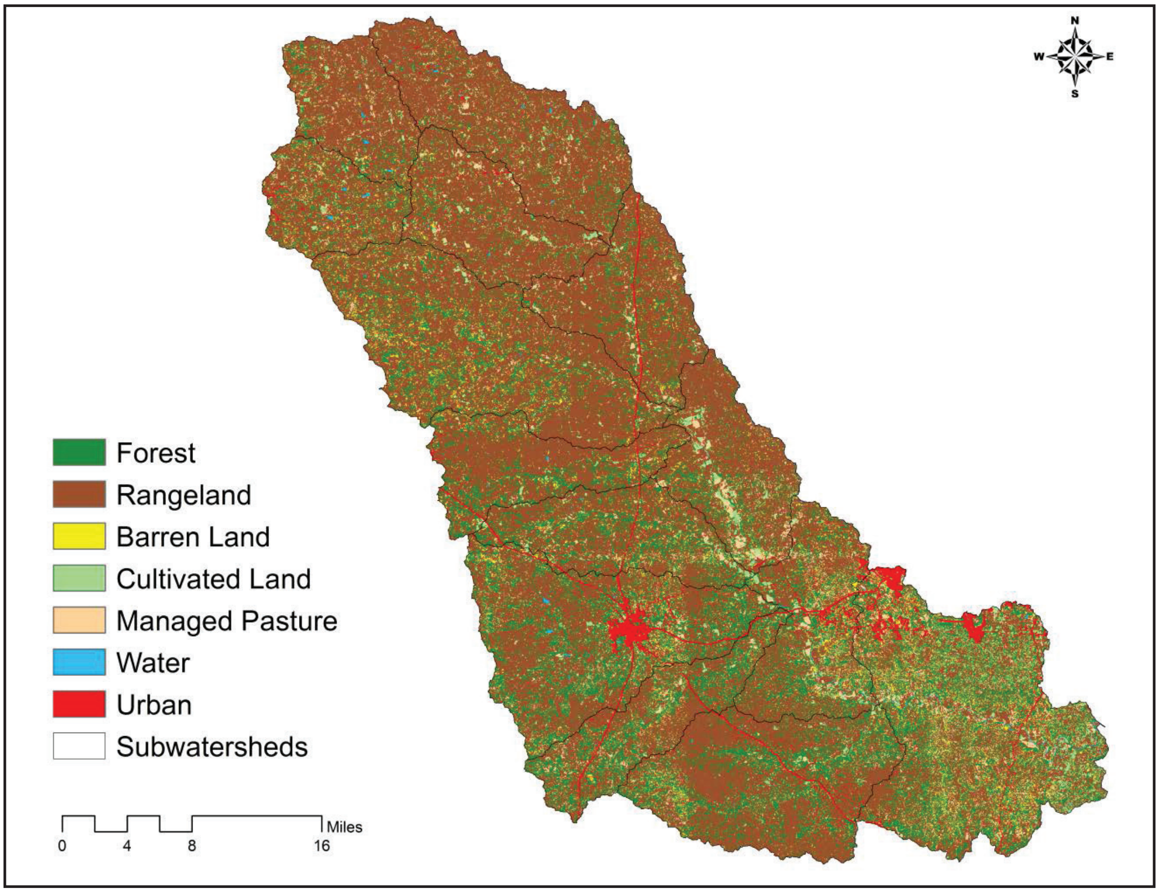

Figure 4. Lampasas River watershed land use.

viced by a WWTF. The number of people per home was the average household size from the 2000 census blocks (USCB 2000). A constant sewage discharge of 265 liters (70 gallons) per person per day was used in the calculations. A failure rate was determined for the OWTSs using SSURGO soil limitation classes (USDA-NRCS 2004) to calculate the percentage of *E. coli* contributing to the watershed due to septic failure.

Dogs

The potential *E. coli* load from dogs was calculated using the equation from Table 1. A dog density was determined by presenting the density of 0.8 dogs per household (AVMA 2002) to stakeholders. Stakeholders determined that a dog density of 1 dog per household would be more accurate for this area. The density was applied to the residential 911 addresses, resulting in an estimated dog population of 10,775.

Wastewater Treatment Facilities

The Lampasas River watershed contains 2 WWTFs located in separate subwatersheds. For WWTFs, the maximum permitted discharge and the *E. coli* concentration of 126 colony forming units per milliliters was applied to the subwatershed in which the WWTFs are located.

Livestock

The population for livestock in the watershed was estimated using the 2007 Census of Agriculture (USDA-NASS 2007) by considering only the number of animals in the watershed for each county. The percentage of the watershed in each county was calculated and that percentage was used to determine the number of animals in the watershed for each county from the total county population. Goats, sheep, and cattle were evenly distributed amongst the rangeland, forest, and managed pasture land uses (Figure 4). The estimated populations were 11,162 goats, 7,311 sheep, and 34,338 cattle for the entire watershed area (USDA-NASS 2007). Horses were evenly distributed on rangelands based on stakeholder input (Figure 4) and had an estimated population of 1,288 animals (USDA-NASS 2007).

Concentrated Animal Feeding Operations

Three CAFOs—2 dairies and 1 feedlot—are located in the Lampasas River watershed. For CAFOs, the permitted number of head of cattle was used to determine the potential *E. coli* load for the subwatershed where the CAFOs are located. An *E. coli* production rate of 1e+11 colony forming units per animal per day (USEPA 2001a) was applied with an assumed treatment efficiency of 80% resulting in an *E. coli* load of 2×10^{10} colony forming units per animal being applied to the subwatershed as discharge from a point source.

Feral Hogs

For feral hogs, the densities used for the Plum Creek (22 hectares per hog) and Geronimo Creek (10 hectares per hog) watesheds were presented to the stakeholders (Berg et al. 2008; Ling and McFarland 2011). Stakeholders decided a density of 13 hectares (32 acres) per animal should be applied uniformly across forest, rangeland, barren land, cultivated land, and managed pasture (Figure 4) within a 100-meter buffer around the stream network of the watershed. An estimated total population of 24,263 feral hogs was used with the equation from Table 1 to estimate the daily potential *E. coli* load from feral hogs. The density chosen for this watershed was more conservative than the densities chosen for the Little Brazos and Buck Creek watersheds. Feral hogs were a larger concern for stakeholders in the Little Brazos and Buck Creek watersheds than for stakeholders in the Lampasas River watershed, who chose to focus more on deer and human sources.

Deer

Wildlife management associations (WMAs) are located in areas around the Lampasas River watershed, shown in Figure 5, and have population-density estimations for deer located in these specific areas. The deer densities within the WMAs were applied uniformly over the entire area of the WMA without considering land-use types. For the areas not within a WMA, a density of 4 hectares (10 acres) per deer was applied over the entire area of the watershed without considering land-use types. An estimated population of 84,739 deer was used with the equation from Table 1 to estimate the potential *E. coli* load from deer for the watershed.

RESULTS AND DISCUSSION

The spatial watershed analyses performed with SELECT highlights subwatersheds that had the highest potential to contribute *E. coli* loads into a water body based on land-use characteristics and pollutant contributor populations. By using SELECT results for the Buck Creek and the Lampasas River watersheds, conclusions can be made about which sources have the highest potential to contribute *E. coli* and where those contributions are. The SELECT results for the Little Brazos watershed show which sources have the highest potential to contribute within the whole watershed. SELECT

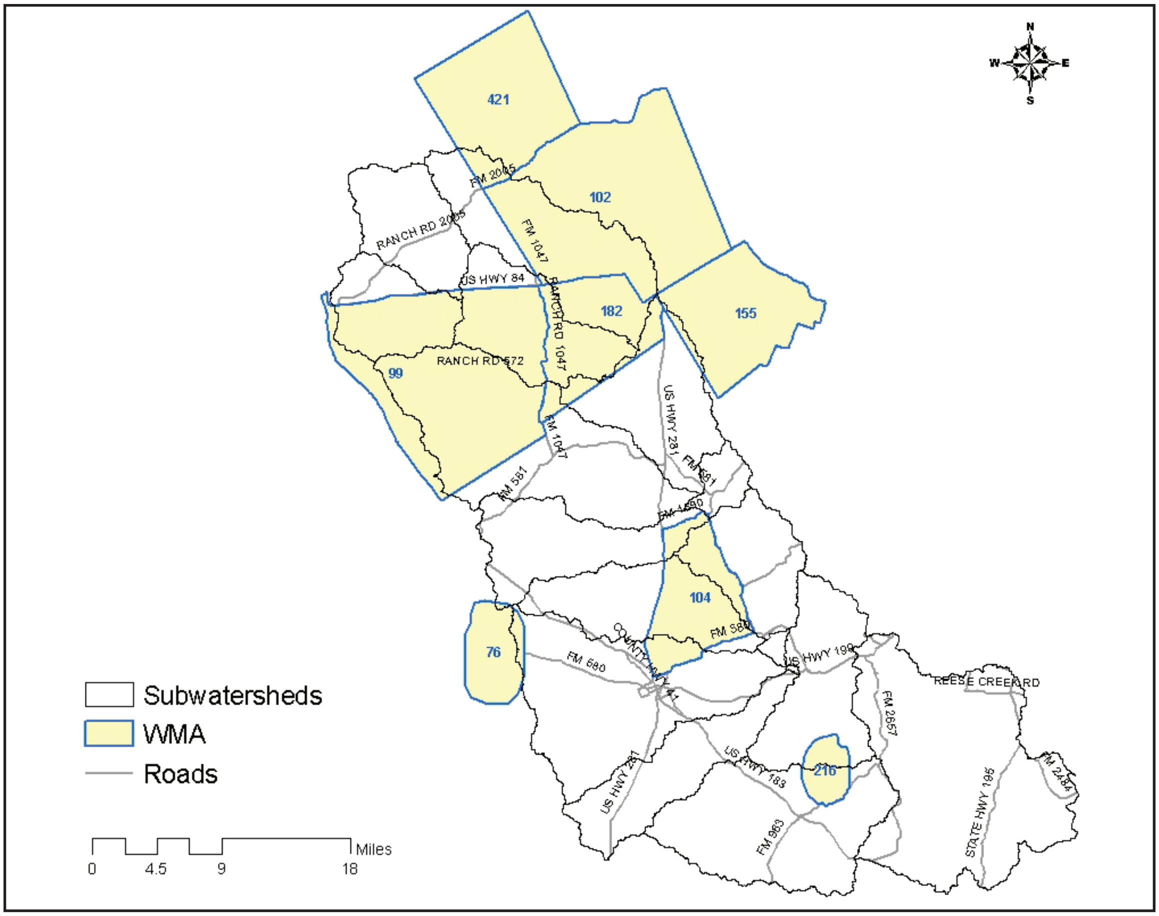

Figure 5. WMAs area locations in the Lampasas River watershed with deer population density estimations.

also compares the 5 tributary subwatersheds to each other to find which of them has the highest potential for *E. coli* contribution to the entire watershed.

The Lampasas River watershed had the highest number of potential contributors (10) modeled by SELECT compared to 3 sources for Buck Creek and 6 sources for Little Brazos River. More data were available for the Lampasas River watershed compared to the Buck Creek and Little Brazos River watersheds because the Lampasas River watershed is in a more urban area compared to Buck Creek and Little Brazos River.

Spatially Explicit *E. coli* Load Estimation for the Buck Creek Watershed

Cattle are potentially the largest contributors of *E. coli* bacteria in the Buck Creek watershed, while deer contribute the lowest *E. coli* load (Table 3). Cattle contribute the highest daily potential *E. coli* load for both the minimum and maximum, exceeding feral hogs by 1 order of magnitude and deer by 2 orders of magnitude.

Figure 6 illustrates the total potential load (or the combined

Table 3. Source-specific potential *E. coli* load ranges per subwatershed for the Buck Creek watershed.

Potential *E. coli* sources	Potential *E. coli* load (CFU/day)	
	Minimum	Maximum
Cattle (pasture and range cattle)	2.23e+12	4.20e+13
Deer	1.69e+10	1.06e+11
Feral hogs	5.31e+11	4.10e+12

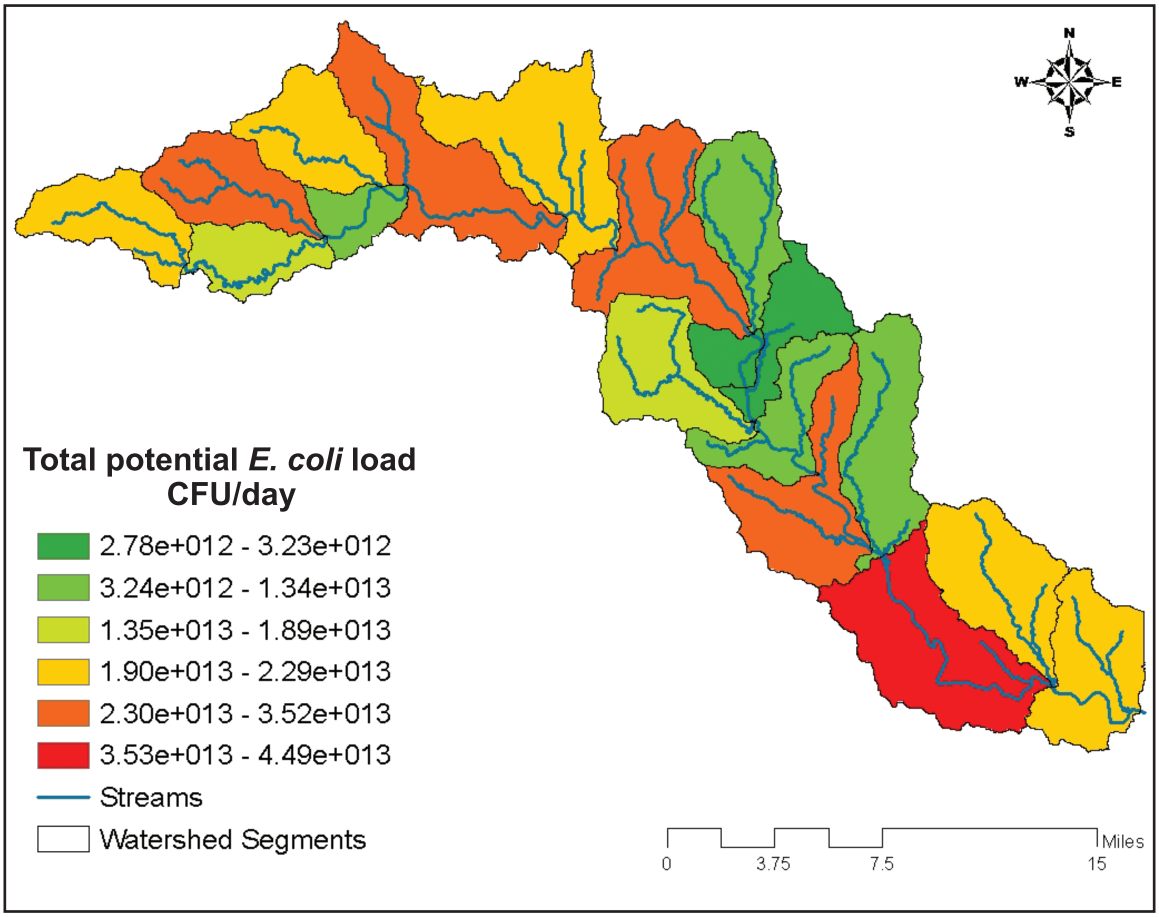

Figure 6. Total daily potential *E. coli* load from all considered sources in the Buck Creek watershed.

load), which includes loading potentials from cattle, deer, and feral hogs. Subwatersheds in red indicate areas with the highest potential for *E. coli* contributions to the creek while the darkest green represents areas with the lowest potential. The spatial analysis of *E. coli* sources shown in Figure 6 are largely determined by the dominant land use in each subwatershed. For example, those areas dominated by crop land have a lower potential for *E. coli* load than subwatersheds dominated by riparian forest or rangeland. The subwatersheds that had the highest total potential loads contained large areas of both rangeland and managed pasture. These subwatersheds had a higher contribution because there was more suitable land for cattle, the highest potential contributor.

Spatial Distribution of *E. coli* Sources in the Little Brazos River Watershed

Cattle are the highest potential contributors for all 5 of the Little Brazos tributary subwatersheds (Table 4) with feral hogs the second highest contributing potential source. Poultry operations are a higher potential contributor than feral hogs in the watersheds in which they are located. OWTSs are a significant potential contributor in the subwatersheds where there are hot spots for OWTSs. Deer and WWTFs are the lowest contributing potential sources.

To compare potential total loads of the tributary subwatersheds to each other and determine which subwatersheds were potentially contributing the most *E. coli* loads, ranges were selected as low, medium, and high. Subwatersheds that ranged from 2.31e+09 to 4.94e+12 colony forming units per day were considered low. Those subwatersheds with ranges from 4.95e+12 to 1.83e+14 colony forming units per day were classified as medium, and those subwatersheds ranging from 1.84e+14 to 4.05e+14 colony forming units per day were considered high.

The Walnut Creek and Mud Creek subwatersheds had total potential *E. coli* loads between the medium and high ranges (Figure 7). These ranges were primarily due to a larger amount of suitable areas for cattle, especially managed pasture where cattle have a higher stocking rate, compared to the other subwatersheds. The Pin Oak Creek subwatershed had a total potential *E. coli* load between low and medium range (Figure 7).

Table 4. Source specific potential *E. coli* load ranges per subwatershed for the 5 tributaries of the Little Brazos River watershed.

Watershed	**Potential *E. coli* sources**	**Daily potential *E. coli* load (CFU/day)**	
		Minimum	**Maximum**
Walnut Creek	Cattle	2.30e+9	3.36e+14
	Deer	1.05e+6	8.97e+10
	Feral hogs	0	5.78e+12
	Poultry operations	0	6.37e+13
	OWTSs	9.69e+6	5.41e+11
	WWTFs	0	1.05e+9
Mud Creek	Cattle	1.30e+14	2.55e+14
	Deer	3.68e+10	7.37e+10
	Feral hogs	2.22e+12	3.98e+12
	Poultry operations	0	9.37e+12
	OWTSs	6.15e+6	2.53e+12
	WWTFs	0	1.43e+9
Pin Oak Creek	Cattle	1.73e+13	1.09e+14
	Deer	6.29e+9	3.33e+10
	Feral hogs	7.73e+11	2.08e+12
	OWTSs	2.25e+10	4.63e+11
Spring Creek	Cattle	3.58e+13	7.40e+13
	Deer	1.37e+10	2.99e+10
	Feral hogs	9.70e+11	1.79e+12
	OWTSs	6.07e+10	2.67e+11
Campbells Creek	Cattle	4.80e+12	6.64e+13
	Deer	1.81e+9	2.70e+10
	Feral hogs	1.31e+11	2.05e+12
	OWTSs	4.25e+9	1.72e+12

These results indicate Pin Oak Creek as a low potential contributor of bacterial contamination to the Little Brazos River in comparison with the other 4 subwatersheds. This low potential is likely attributable to the Pin Oak Creek subwatershed having less managed pasture and more forest than the Walnut Creek and Mud Creek subwatersheds. The Spring Creek subwatershed had a total potential *E. coli* load in the medium range (Figure 7). Rangeland and forest dominate the Spring Creek subwatershed, which are suitable areas for feral hogs, the second highest contributing source. The Campbells Creek subwatershed had a total potential *E. coli* load between the very low and medium range (Figure 7). These results indicate the potential bacterial contribution of Campbells Creek into the Little Brazos River is very low. However, the smaller size of the Campbells Creek subwatershed in comparison to the other subwatersheds may skew the results somewhat.

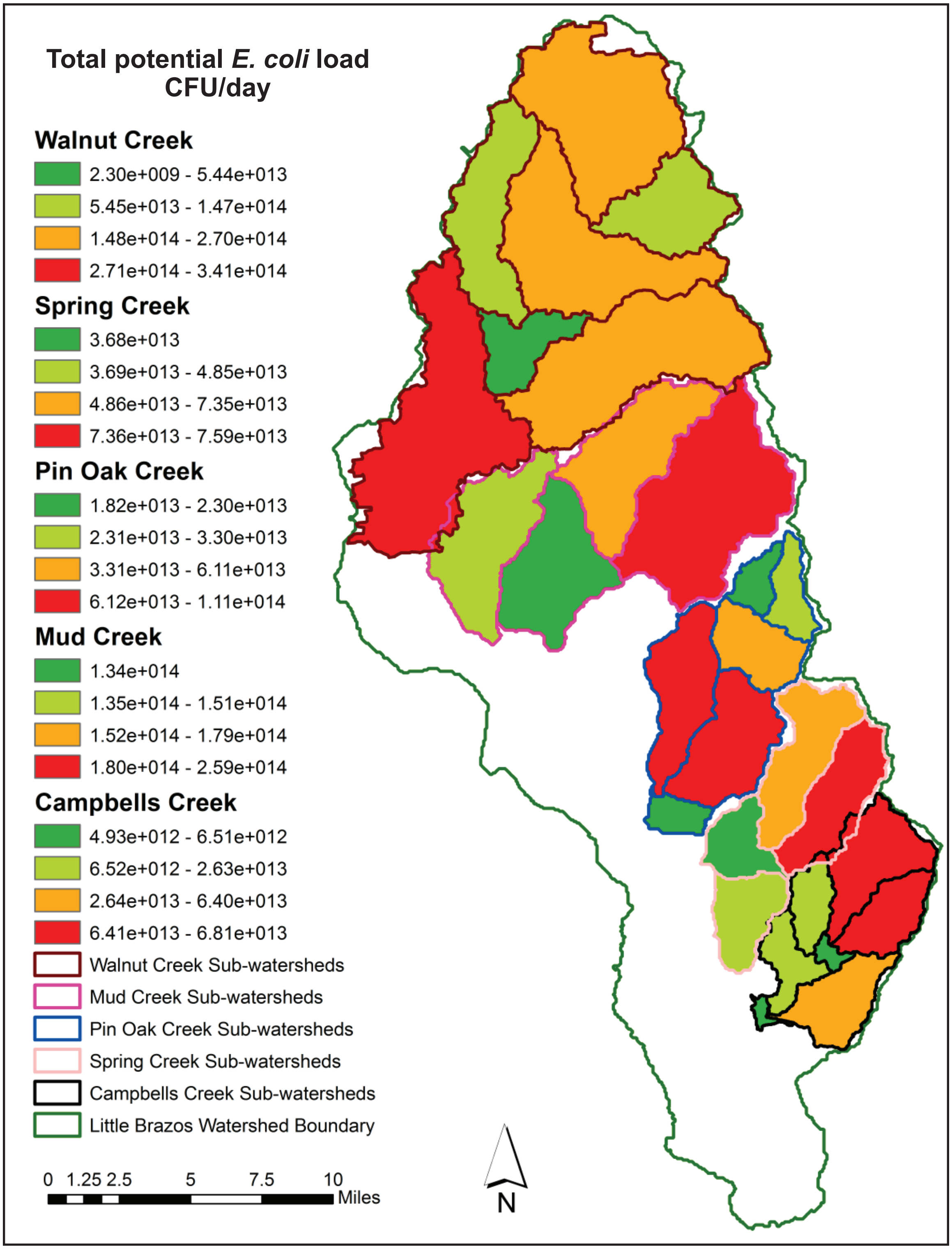

Figure 7. Total daily potential *E. coli* loads from all considered sources in the 5 tributary watersheds of the Little Brazos River watershed.

Table 5. Source-specific potential *E. coli* load ranges per subwatershed for the Lampasas River watershed.

Potential *E. coli* sources	**Daily potential *E. coli* load (CFU/day)**	
	Minimum	**Maximum**
Cattle	6.09e+13	3.91e+14
Horses	8.36e+9	8.47e+10
Goats	1.83e+12	9.56e+12
Sheep	1.31e+12	8.18e+12
Deer	1.04e+12	4.04e+12
Feral hogs	4.65e+12	1.86e+13
OWTSs	3.24e+11	1.24e+13
WWTFs	0	1.19e+10
Dogs	2.25e+11	1.06e+13
CAFOs	0	3.20e+13

Total Daily Potential *E. coli* Loads Resulting from Various Sources in the Lampasas River Watershed as Predicted by SELECT

Table 5 illustrates the source-specific *E. coli* ranges used to determine the contribution of each source to the Lampasas River watershed. The largest contributor for the Lampasas River watershed is cattle with feral hogs the second largest. OWTSs and dogs are also high contributors. CAFOs contribute more than feral hogs in the subwatersheds where they are present. Goats, sheep, and deer are not significant contributors, and they contribute *E. coli* loads with minimums and maximums all to the order of 10^{12}. The sources that contribute the least *E. coli* are horses and WWTFs.

Figure 8 illustrates the total potential load, or the combined load, which includes loading potentials, from all of the contributing sources applied in the Lampasas River watershed. Subwatersheds in red indicate areas with the highest potential for *E. coli* contributions to the river while the darkest green represents areas with the lowest potential. The subwatershed considered the highest contributor in the Lampasas River watershed, as predicted by SELECT, is most likely because of 1) the large size of the subwatershed in comparison to the other subwatersheds and 2) the subwatershed's land uses of forest, rangeland, and managed pasture, which are suitable areas for almost all of the animal contributors. The second highest potentially contributing subwatersheds have land use that is primarily rangeland, which is suitable for cattle, the highest contributing source for the Lampasas River watershed.

Potential Issues

The SELECT model results are a daily snapshot of what is potentially occurring in a watershed and do not account for fecal buildup or *E. coli* die-off. Because of this, *E. coli* production rates used in the model can vary widely from the actual *E. coli* present in the fecal material on land.

SELECT does not take into account direct fecal deposition into the creek, timing of the fecal deposition, or distance of the fecal deposition from the water body. Direct fecal deposition into the creek would have a greater impact on water quality than land deposition. If fecal matter is deposited right before it rains, then the bacteria will more likely end up in the water body because of surface runoff. The effect of deposition timing would not apply to most sources, including livestock and wildlife, because application does not differ greatly from day to day. However, the timing of fecal deposition for CAFOs and poultry litter applications in relation to a rainfall event can impact water quality because the manure or litter is not applied daily. Fecal deposition close to the water body is also more likely to impact water quality than at farther distances.

In addition, the animal densities provided by stakeholders can vary. In particular, livestock densities can change drastically from season to season and from year to year. These issues can impact the watershed planning process because the SELECT results might reflect that cattle is the highest potential contributor of bacteria to the watershed, whereas, the fecal material might not be reaching and contaminating the water body, but other sources could be contaminating the water more direct-

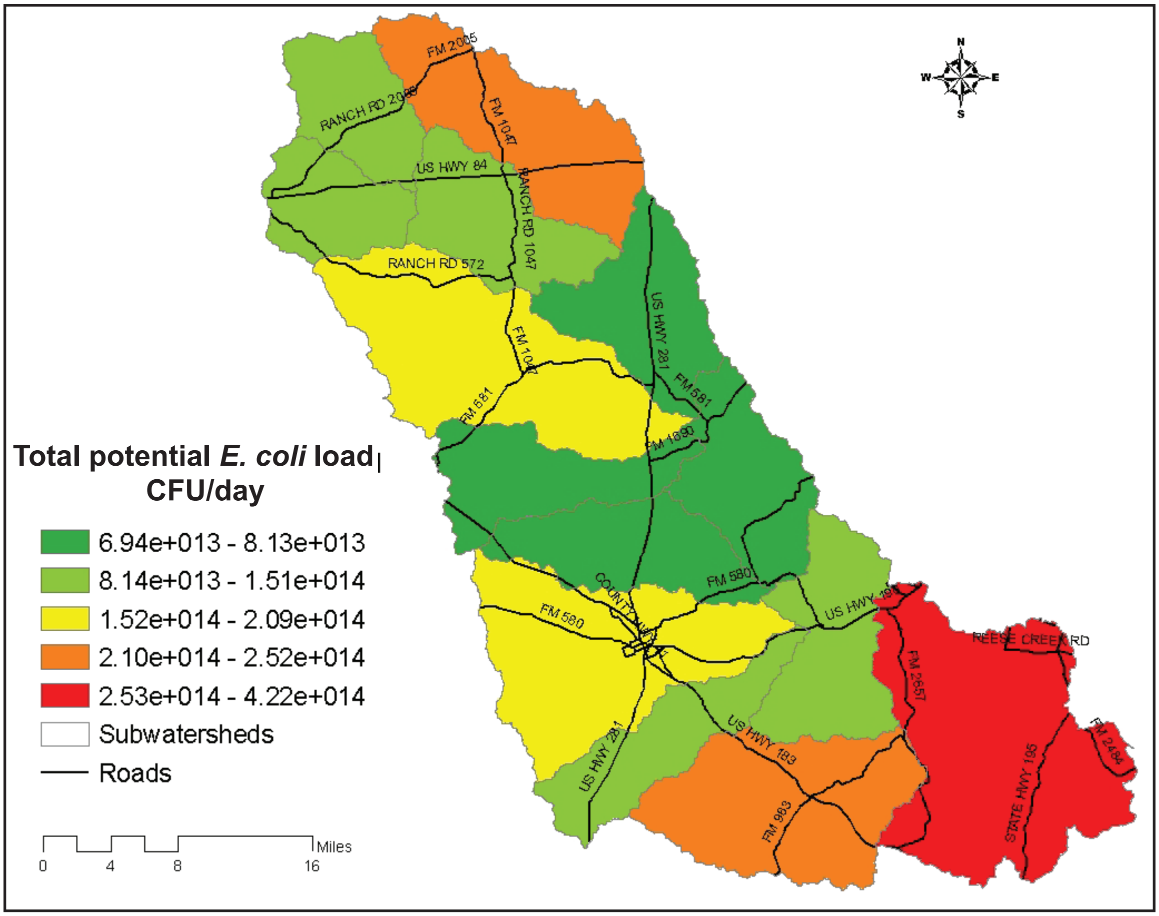

Figure 8. Total daily potential *E. coli* load from all considered sources in Lampasas River watershed.

ly. These issues would thus influence the BMPs chosen to be implemented in the watershed and impact their effectiveness.

CONCLUSIONS

The SELECT methodology was applied to 3 rural watersheds located in different regions of Texas: Buck Creek, Little Brazos River, and Lampasas River. The SELECT methodology was adapted for each watershed individually, based on perceived potential contributing sources and data availability. SELECT is unable to reflect the true total potential loading of the watershed because the lack of data regarding wildlife contributions makes it impossible to include all sources. Once additional source data become available, they could easily be adapted into the SELECT methodology and applied to a watershed. The model considered cattle the highest potential contributor for all 3 watersheds. This suggests that BMPs implemented to reduce pollutant contributions from cattle will yield the largest load reductions as compared to management targeted at other contributors. The SELECT methodology was able to highlight both contributing sources of most concern and areas of highest concern, allowing more effective application of these BMPs. The SELECT methodology can be easily adapted and applied to watersheds to reflect stakeholder knowledge and concerns.

The next steps for the SELECT methodology is to add other potential contributing sources to the model that cannot currently be modeled, such as birds, raccoons, and squirrels. Another improvement to SELECT would be to include fecal buildup and *E. coli* die-off into the model. The SELECT outputs could also be combined with another water quality model that routes the potential *E. coli* loads through the watershed using either surface runoff or through the soil to determine how much *E. coli* is reaching the stream. Surface runoff could be measured or modeled and, in combination with a digital elevation model (DEM), the path of the runoff from the land surface into the water body could be determined.

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