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Cover photo: As Texas continues to face water challenges and drought, many communities are seeking to conserve water in various sectors, including lawn and landscape water use. ©Jose Manuel Gelpi Diaz, Crestock

Effects of an off-stream watering facility on cattle behavior and instream *E. coli* levels

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Robert Knight⁵, C. Allan Jones⁶, Jamie L. Foster⁷

Abstract: Excessive levels of fecal bacteria are the leading cause of water quality impairment in Texas, and livestock with direct access to water bodies are potentially a significant source of these bacteria. To help address this, the effect of providing alternative off-stream watering facilities to reduce manure, and thus bacterial, deposition in or near surface waters was evaluated from July 2007 to July 2009 in Clear Fork of Plum Creek in central Texas. An upstream-downstream, pre-treatment, and post-treatment monitoring design was used with off-stream water provided only during the second year of the study. Flow, *Escherichia coli* (*E. coli*) concentration, and turbidity were measured twice monthly. Cattle movements were tracked quarterly using global positioning system collars to assess the effect of providing alternative water on cattle behavior. Results showed that when alternative off-stream water was provided, the amount of time cattle spent in the creek was reduced 43%. As a result, direct deposition of *E. coli* into Clear Fork of Plum Creek was estimated to be reduced from 1.11×10^7 to 6.34×10^6 colony forming units per animal unit per day. Observed pre-treatment and post-treatment instream *E. coli* loads suggested similar reductions; however, these reductions were not statistically significant.

Keywords: cattle, *E. coli*, GPS collars, off-stream water, best management practice

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Terms used in paper

Short name or acronym	Descriptive name
AU	animal unit
BMP(s)	best management practice(s)
cfu	colony forming units
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
GPS	global positioning system
TMDL	total maximum daily load
USGS	United States Geological Survey

INTRODUCTION

Livestock with direct access to water bodies have been identified as significant sources of bacteria in numerous bacterial total maximum daily loads (TMDLs) in Texas (TCEQ 2007a, 2007b). Because excessive levels of fecal indicator bacteria (*Escherichia coli* [*E. coli*], *Enterococcus*, and fecal coliforms) are the number one cause of water quality impairment in Texas, causing 295 of the 516 water quality impairments in the state (TCEQ 2008), and beef cattle production is the largest agricultural enterprise in Texas, it is critically important to identify effective and accepted management practices that address potential contributions. In the Plum Creek watershed, where this study takes place, there are an estimated 33,000 beef cattle, representing the primary class of livestock. Because livestock are often the easiest potential agricultural source to manipulate to reduce bacterial loads, the Plum Creek Watershed Protection Plan targeted agricultural nonpoint source management measures addressing the potential impact of animals grazed near streams or drainage areas or those permitted direct access to stream and riparian corridors (Berg et al. 2008).

Cattle are drawn to streams and adjacent riparian areas by water, shade, and the quality and variety of forage present (Kauffman and Krueger 1984). The length of time cattle spend in a stream, however, plays a significant role in potential fecal contamination (Mosley et al. 1999). When cattle have stream access, a portion of their fecal matter is deposited directly into the stream (Larsen et al. 1988) and can be a significant source of contamination. Gary et al. (1983) observed that cattle spent 5% of the day in or adjacent to the stream and that 6.7% to 10.5% of defecations were deposited directly in the stream. Feces deposited in streams have a greater impact on water quality than that deposited away from streams. Larsen et al. (1994) found that manure deposited 0.6 meters and 2.1 meters from a stream contributed 83% and 95% less bacteria, respectively, than that deposited directly in a stream.

Tiedemann et al. (1987) and Mosley et al. (1999) suggested that animal access to streams had a greater impact on stream bacterial levels than stocking density. Thus, riparian protection is needed to reduce manure deposition in or near surface waters (Ball et al. 2002). Exclusion of livestock from riparian areas by fencing of streams is frequently recommended to reduce manure inputs to surface water (Godwin and Miner 1996; McIver 2004). Numerous studies have shown that fencing of streams, alone or in combination with other best management practices (BMPs), can reduce *E. coli* levels by 37% to 46% (Meals 2001, 2004), *Enterococcus* by 57% (Line 2003), and fecal coliforms by 30% to 94% (Brenner et al. 1994; Brenner 1996; Cook 1998; Hagedorn et al. 1999; Lombardo et al. 2000; Meals 2001; Line 2002; Line 2003; Meals 2004).

However, exclusionary fencing is costly to install and maintain (Godwin and Miner 1996; Sheffield et al. 1997; Byers et al. 2005), results in loss of grazing area and ranching income, restricts access to reliable water sources, and may be inconvenient and impractical for many ranches. Thus, many ranchers oppose it (McIver 2004). Other concerns have recently been raised regarding the impact of increasing wildlife populations in fenced riparian zones, potentially negating *E. coli* loading reductions provided by restricting livestock access (Hagedorn 2012).

Another practice available to protect riparian areas and reduce manure deposition in or near surface waters is the development of alternative watering facilities (FCA 1999; Tate et al. 2003; Byers et al. 2005). A permanent or portable off-stream water supply provides livestock another drinking water source, which can be used alone or in conjunction with other practices to reduce the time livestock spend near surface waters and in riparian areas. To achieve optimum uniformity of grazing and the greatest use of alternative water sources, cattle should not have to travel more than 200 to 300 meters to water (McIver 2004). Alternative water sources benefit livestock producers by improving grazing distribution, reducing herd health risks caused by drinking or standing in contaminated water, decreasing herd injuries from cattle traversing steep or unstable streambanks, increasing water supply reliability during droughts, and increasing weight gains in beef cattle by 0.1 to 0.2 kilograms/day (Willms et al. 1994; Buchanan 1996; Porath et al. 2002; Willms et al. 2002; Veira 2003; Dickard 1998).

Alternative off-stream water supplies can also provide environmental benefits including reduced manure deposition and bacterial contamination of surface waters and reduced streambank destabilization and erosion due to trampling and overgrazing of banks. Previous research demonstrated that cattle spent 85% to 94% less time in streams (Miner et al. 1992; Clawson 1993; Sheffield et al. 1997) and 51% to 75% less time within 4.6 meters of streams when an off-stream watering facility was available (Godwin and Miner 1996; Sheffield et al. 1997). As a result, Godwin and Miner (1996) suggested that under baseflow conditions, off-stream watering was nearly as effective as fencing in reducing manure inputs to surface water, thus reducing water quality impacts of grazing cattle at a reduced cost. Sheffield et al. (1997) confirmed this, finding that as a result of the reduction in time cattle spent in and near streams, instream fecal coliform concentrations were reduced by an average of 51%. However, results varied among sites with statistically significant reductions in fecal coliform levels of 99%, 87%, and 57% being observed at 3 sites and a 53% increase, which was not statistically significant, being observed at 1 site. Further, Byers et al. (2005) found that providing water troughs decreased the amount of time cattle spent with-

in 12 meters of a stream, but that the result was dependent on time of year with a reduction of 40% observed in March 2002, 96% in December 2002, and approximately 60% in July 2003. Byers et al. (2005) also found that although alternative water did not impact stormwater *E. coli* concentrations, median baseflow *E. coli* loads decreased 95% in 1 pasture and 85% in another when water troughs were available. However, as a result of drought, streamflow was 51% smaller in the second year of the study when the troughs were available, thus impacting the load differences.

With the exception of the study conducted by Byers et al. (2005), which used global positioning system (GPS) collars, previous studies used light beam counters (Godwin and Miner 1996), visual observations (Miner et al. 1992; Sheffield et al. 1997), and time-lapse cameras (Clawson 1993) to evaluate cattle behavior during daylight hours. However, nighttime observations can be critical because cattle exhibit bimodal grazing patterns (early morning and evening) with certain breeds spending a greater portion of the night grazing as compared to daytime (Pandey et al. 2009). The use of GPS and geographic information system (GIS) technology allows livestock behavior to be evaluated with greater spatial and temporal resolution. Animals can be tracked 24 hours a day using GPS receivers incorporated into animal collars (Pandey et al. 2009). Agouridis et al. (2005) evaluated GPS collars to determine accuracy for applications pertaining to animal tracking in grazed watersheds and found the collars were accurate within 4 to 5 meters and thus acceptable for most cattle operational areas (Pandey et al. 2009).

Observation periods of these earlier studies were also generally of short duration, focusing on specific seasons. These studies also targeted the Pacific Northwest (Miner et al. 1992; Clawson 1993; Godwin and Miner 1996), Eastern (Sheffield et al. 1997), and Southeastern United States (Byers et al. 2005). These are regions with conditions different from much of Texas and the mid-section of the country where a majority of U.S. cattle production occurs. Finally, these studies, with the exception of Byers et al. (2005), did not evaluate the impacts of off-stream water on *E. coli* levels, which are the focus of most TMDLs in Texas. Therefore, the objectives of this study were to assess the effect of providing an off-stream watering facility on reducing the percent time cattle spend in streams and riparian zones and the level of bacterial contamination of streams. Stakeholders, natural resource agencies, and others working to improve water quality need this information not only to better understand the effectiveness of alternative water as a water quality BMP but to improve the predictive capabilities of water quality models used for TMDLs and watershed-based plans. The results are applicable to Texas, the mid-section of the United States, and other regions around the world with similar climates and grazing systems.

MATERIALS AND METHODS

Site description

This study was conducted on a commercial cow-calf operation located in Caldwell County, Texas, bisected by Clear Fork of Plum Creek. Although the drainage area above the ranch is only 26 square kilometers, Clear Fork of Plum Creek is typically a perennial stream as a result of a number of springs. The creek is 0.3 to 10.3 meters wide and less than 1 meter deep. Thus, the creek is generally not of sufficient depth for cattle to cool off in. The average slope of the stream is 0.3% while the average slope perpendicular to the stream is 5.4%. Clear Fork of Plum Creek is a tributary of Plum Creek, which is listed on the 303(d) List as impaired by excessive levels of *E. coli* and is the focus of watershed restoration efforts through a watershed-based plan.

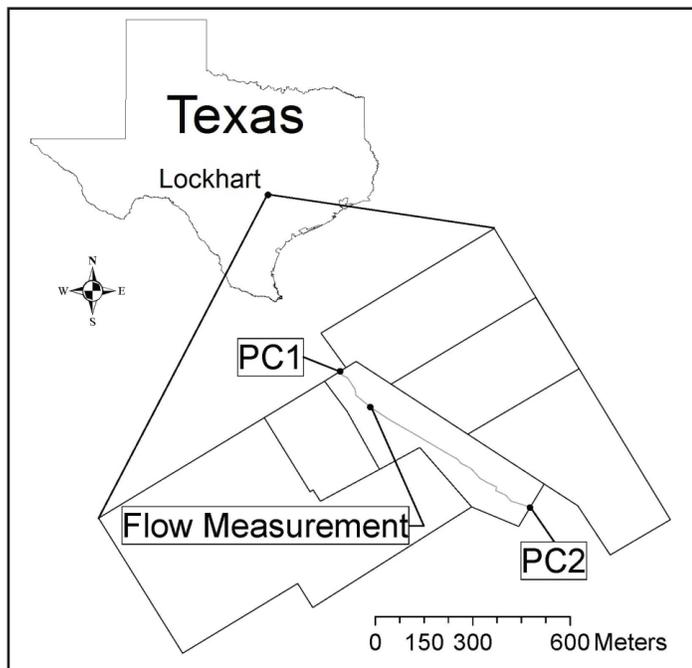
The ranch is in the Texas Blackland Prairies Ecoregion (Omernik 1987) where annual precipitation averages 89 centimeters. However, as the result of a severe drought, which began in the spring of 2008, only 56 centimeters of rainfall was received in Year 1 and 40 centimeters received in Year 2. Average annual temperatures were normal (20 °C) in Year 1 and higher than average (20.6 °C) during Year 2.

The flood plain soils along the creek are dominated by the Tinn series, a very deep, moderately well-drained, very slowly permeable soil formed in calcareous clayey alluvium. Upgradient of the Tinn soil is the Branyon clay, which, like the Tinn soil, is a very deep, moderately well-drained, very slowly permeable soil. Finally, soils in the upland areas of the ranch are comprised of Lewisville soils, very deep, well-drained, moderately permeable soils on slopes of 0% to 10% (Soil Survey Staff 2011).

The predominant forage in the creek pasture is common bermudagrass (*Cynodon dactylon* L.). Vegetation in the 3 off-creek pastures (Figure 1) is WW-B Dahl Bluestem (*Bothriochloa bladhii* L.), Old World Bluestem (*Bothriochloa ischaemum* L.), and native grasses. Vegetation along the creek consists primarily of common bermudagrass with few trees or other typical riparian vegetation present. Less than 5% of the stream and its riparian area is shaded; thus, shade is not a major attractant of cattle to the creek and riparian zone. With the exception of the creek pasture, most of the operation was in row crop production until 2003 when it was converted to pastureland in 2004.

The site of this study has many similarities to that of the Byers et al. (2005) study with a few notable exceptions. In general, stream slopes, forages present, and the climate of both sites are very similar. Daily highs and lows in this study area are on average only 2 °C and 3 °C warmer, respectively, than those of Byers et al. (2005). Rainfall is on average 28.9 centimeters lower in this study area compared to those of Byers

Figure 1. Pasture configuration, water sample collection sites, and flow measurement site at cooperating ranch near Lockhart, Texas.



et al. (2005) and as such, humidity is on average lower in this study area, as well. The most notable difference between study areas is the amount of riparian vegetation. In this study, riparian shade was present in less than 5% of the riparian area, whereas it comprised 78% to 85% of the riparian area of Byers et al. (2005). This is not surprising as the region of Byers et al. (2005) study was primarily forested (94% forested) whereas the region of this study was primarily comprised of crop and grass lands with only 14% forested.

Pasture management

Four pastures, ranging in size from 12 to 15 hectares were used during the study (Figure 1). Cattle had complete and continuous access to the creek and creek pasture throughout the study. Cattle were allowed access to the other pastures as needed. During the first year of the study (July 2007–July 2008), pastures were stocked with 54 crossbred cows with calves and 2 bulls (57 animal units [AUs]). During the second year of the study (July 2008–July 2009), the pastures were stocked with 72 cows with calves and 3 bulls (76 AUs). The stocking rate was increased in the second year as the cooperating landowner consolidated herds from 2 ranches in response to the severe drought, making feeding, watering, and caring for the livestock easier until conditions improved. Water troughs supplying well water were present in all pastures but were turned off during the first year of the study (with the exception of 2 weeks in January 2008), forcing the cattle to water in the creek

only. In January 2008, several calves became ill with bovine respiratory disease and water troughs were activated for a period of 2 weeks then turned off again and remained off until July 6, 2008. The troughs were turned on for the second year of the study and provided cattle an alternative water source. Distance between the water trough and stream in the creek pasture was approximately 137 meters.

GPS tracking of cattle

Each quarter throughout the 2-year study, 6 to 8 randomly selected cows were collared with Lotek® GPS 3300LR collars (Lotek Wireless Inc., Newmarket, Ontario, Canada). The collar manufacturer reports that, with differential correction applied, horizontal accuracies of position readings have errors less than 5 meters. Positional readings were collected at a 5-minute fixed interval, providing up to 6,624 locations by each collar each quarter. Cattle movement was tracked for 21 to 23 days, and then the collars were removed.

Collar data were downloaded using Lotek host software and differentially corrected using data from the nearest National Geodetic Survey Continuously Operating Reference Stations base-station. Differentially corrected collar data were then combined with sensor data and converted to database files for analysis.

To analyze positional readings collected from the GPS collars, ArcView (ArcGIS 9, ArcMap Version 9.2, ESRI, Redlands, CA) software was used. For each collar, the number of positional points in the stream—within 0.6 meters of the midpoint of the stream and within 4.6 meters of the stream—were determined using the “Select by Location” function. Percent time spent within each distance from the stream was determined by dividing the number of positional points within each buffer by the total number of positional readings taken. Percent time was then converted to minutes per day.

Instream sampling procedures

Sites located at the inflow and outflow of Clear Fork of Plum Creek to the ranch, PC1 (29°53'35.81"N/97°45'21.06"W) and PC2 (29°53'23.28"N/97°45'2.67"W), respectively, were monitored to assess effectiveness of alternative off-stream water (Figure 1). These sites are approximately 0.8 kilometers apart. Grab samples were collected and analyzed on a semi-monthly basis at both sampling sites when water was flowing. Water samples were collected directly from the stream, midway in the water column into sterile Whirl-Pak® bags. Bags were held upstream of the sampler and care exercised to avoid contact with sediment and the surface micro layer of water. After collection, samples were placed on ice for transport to the lab where they were stored at 4 °C until analysis.

Flow calculation

Flow depth was measured semi-monthly in conjunction with water sample collection. Measurements were made in a 0.9 meter corrugated metal culvert located at a stream crossing 0.16 kilometers below PC1 and 0.64 kilometers above PC2. Manning's equation (Grant 1991) was used to estimate flow rate for each sampling event. The Manning roughness coefficient (n) was determined from field measurements of flow depth and velocity and compared to published values by Grant (1991) for corrugated metal subdrains. Slope (S) from PC1 to PC2 was determined using field evaluation of slope. Area (A) and hydraulic radius (R) were obtained from published values (Grant 1991) based on the observed depth (d) in relation to the culvert depth (D).

Analytical methods

Water sample analysis was conducted within 6 hours of collection. *E. coli* in water samples were enumerated using U.S. Environmental Protection Agency (EPA) Method 1603 (EPA 2006). If counts were greater than 200 colonies at the highest dilution, the count was reported as too numerous to count. Results were reported as colony forming units (cfu) per 100 milliliters. Finally, an AquaFluor™ Handheld Fluorometer/Turbidimeter (model 8000-010, Turner Designs, Sunnyvale, CA) was obtained in February 2008 allowing measurement of turbidity throughout the remainder of the study. Turbidity measured in water samples was reported in nephelometric turbidity units.

Additionally, to approximate deposition of *E. coli* in the stream before and after alternative off-stream water was provided, percent time spent by cattle in the stream as determined by the GPS collars was multiplied by published fecal coliform production values (5.4×10^9 cfu/AU/day) (Metcalf and Eddy 1991) and then converted to *E. coli* concentrations by multiplying the result by 0.63 as EPA suggests (Hamilton et al. 2005).

Evaluation of *E. coli* loads

Flow rate at the time of each grab sample was assumed to represent the daily average (cubic meters per second). These flow rates, along with the *E. coli* concentrations, were used to estimate the daily loads for the upstream and downstream sites, PC1 and PC2 respectively. The daily load contributed by the study area was calculated by subtracting the upstream load from the downstream load (PC2 – PC1). This was converted to an AU basis by dividing the daily loads contributed by the study area by the number of AUs present in the study area during the respective period (57 AUs during Year 1 and 76 AUs during Year 2).

Statistical analysis

The statistical software, Minitab (Minitab Inc., State College, Pennsylvania), was used for all statistical calculations. Basic statistics and graphical summaries of each dataset were created to evaluate means, medians, quartiles, confidence intervals, and normality using the Anderson-Darling Normality Test. As a majority of datasets were not normally distributed, they were evaluated with nonparametric statistics. The Mann-Whitney statistical test was used to assess the differences in median (1) minutes cattle spent per day instream and within 4.6 meters of the creek; (2) flows; (3) *E. coli* concentrations; (4) *E. coli* loads from the study area; and (5) turbidities observed between sites and/or periods (with versus without alternative water). An alpha level of 0.05 was used as the level of significance, thus results were considered statistically significant when $p < 0.05$. Regression analysis was used to evaluate the relationship between *E. coli* concentrations at PC1 and PC2, as well as between *E. coli* concentrations and turbidity. Coefficient of determination values were used to evaluate the strength of regression equations for *E. coli* concentrations. Finally, analyses of covariance were developed using the Minitab General Linear Model, specifying the responses as PC2 turbidity, the model as the treatment period (with alternative water) or calibration period (without alternative water), and the covariate as PC1 turbidity.

RESULTS AND DISCUSSION

GPS tracking of cattle

Comparison of the amount of time cattle spent in and near the creek with and without alternative water indicated that providing alternative off-stream water reduced the time cattle spent in the stream and within 4.6 meters of the creek (Figure 2).

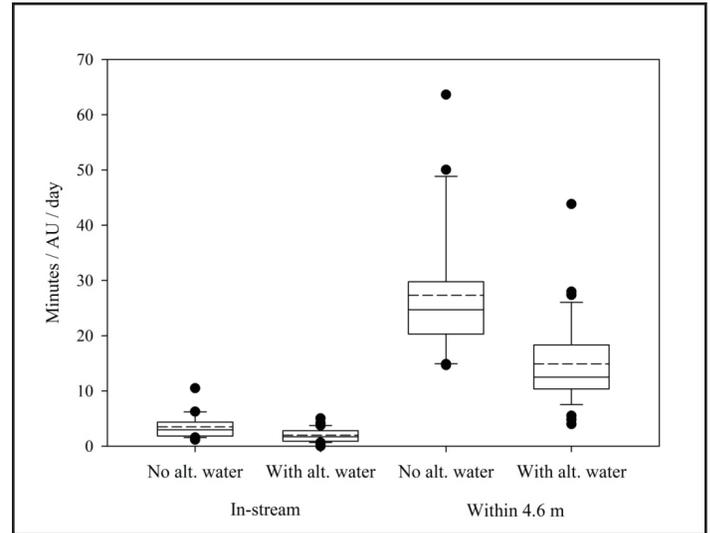
Because shade along the riparian zone was limited (< 5%) and stream depth was not suitable for cooling, it can be assumed that observed reductions resulted from cattle drinking from the alternative water supply and not the stream. Analysis of the GPS collar data (Table 1) indicated that providing alternative off-stream water significantly reduced the median amount of time cattle spent in and near the creek ($p < 0.01$).

The amount of time cattle spent within 4.6 meters of the creek was reduced 52% from 25 to 2 minutes/AU/day when provided with off-stream water, compared to the 75% reduction from 15 to 4.25 minutes/AU/day found by Godwin and Miner (1996) and 51% reduction from 12.7 to 6.2 minutes/AU/day found by Sheffield et al. (1997). Although the percent reductions from this study were similar to those of Sheffield et al. (1997), the amount of time cattle spent near the stream varied substantially between the studies.

Further, this study found that providing alternative off-stream water reduced stream use from 3.0 to 1.7 minutes/AU/day, compared to reductions from 25.6 to 1.6 minutes/AU/day (Miner et al. 1992), 4.7 to 0.7 minutes/AU/day (Clawson 1993), and 6.7 to 0.7 minutes/AU/day (Sheffield et al. 1997). Based on the percent time cattle spent in the stream (as determined by the GPS collars), along with published fecal coliform loading rates (Metcalf and Eddy 1991) and the *E. coli* conversion factor suggested by EPA (Hamilton et al. 2005), we estimated the median daily deposition of *E. coli* in the stream was reduced from 1.11×10^7 cfu/AU/day to 6.3×10^6 cfu/AU/day when alternative water was provided.

The reduction in the percent time cattle spent in the stream observed by this study (43%) was half the reductions of 85% to 94% observed by previous studies (Miner et al. 1992; Clawson 1993; Sheffield et al. 1997). Additionally, the amount of time cattle spent in the stream varied substantially among studies from 3 minutes per day in this study to almost 26 minutes per day (Miner et al. 1992) indicating the site-specific nature of this measurement. Stream width, depth, accessibility, and adjacent shade play a major role in the amount of time cattle spend in and near streams, and thus the percent reductions achievable by providing alternative water. As such, TMDLs and other watershed studies that use percent time cattle spend in streams for assessing direct deposition rates would benefit from GPS collars studies to validate models. For example, it was estimated by Orange County, Texas, TMDL stakeholders that, on average, cattle drinking water from bayous spend 10 minutes per day in the stream during June, July, August, or September, and 5 minutes per day in March, April, May, October, and November, but that cattle did not stand in the bayous to drink from December through February (TCEQ 2007a). Using these assumptions from the TMDL, cattle spend 5.4 minutes/day in the stream on average

Figure 2. Time (minutes/AU/day) that cattle spent in and near (within 4.6 meters) Clear Fork of Plum Creek with and without alternative off-stream water provided. The boundary of the box closest to zero indicates the 25th percentile, the solid line within the box represents the median, the dashed line represents the mean, the boundary of the box farthest from zero indicates the 75th percentile, the whiskers above and below the box indicate the 10th and 90th percentiles, and the circles indicate data points beyond the 10th and 90th percentiles.



overall throughout the year. Although this estimate is within the range observed by previous studies, it is 80% higher than the findings of this study, potentially overestimating the bacterial loading allocated to direct deposition from cattle into the creek. Because of this, evaluation of the time cattle spend in impaired water bodies using GPS collars or other suitable methods is suggested for development of TMDLs and other

Table 1. Descriptive statistics of time, in minutes/day and percent of day (in parenthesis) that cattle spent in and near Clear Fork of Plum Creek with and without alternative off-stream water provided.

Distance from creek	Statistic	No alternative water min/day (%)	With alternative water min/day (%)	Percent reduction
Instream	Mean	3.5 (0.2%)	2.0 (0.1%)	
	sd	2.2 (0.1%)	1.2 (0.1%)	
	Median*	3.0 (0.2%)a	1.7 (0.1%)b	43%
	Max	10.5 (0.7%)	5.0 (0.3%)	
4.6 m	Mean	27 (1.9%)	15 (1.0%)	
	sd	12 (0.8%)	8 (0.6%)	
	Median*	25 (1.7%)a	12 (0.8%)b	52%
	Max	64 (4.4%)	44 (3.1%)	

*For each site, medians followed by same letter are not significantly different ($p < 0.05$).

watershed planning projects in order to improve the accuracy of associated water quality models.

Flow

Two continuously monitored United States Geological Survey (USGS) flow gages are located on Plum Creek, 1 at Lockhart and 1 at Luling. Flows at the USGS station at Lockhart are heavily influenced by wastewater discharges and, as such, were not well-correlated with those observed in Clear Fork of Plum Creek ($r^2 = 0.17$). However, observed flows were well-correlated ($r^2 = 0.79$) with Plum Creek flows at Luling (Figure 3).

Median streamflow observed during Year 2 (0.003 cubic square meters/second) was significantly lower ($p < 0.001$) than that observed during Year 1 (0.014 cubic square meters/second). From the spring of 2008 through the end of the study, the region experienced a severe drought (Figure 4). As a result, during the second year of the study when alternative water was provided, flow was reduced 79% compared to that observed during the previous year. Flow ceased in the creek for 3 months during Year 2 (mid-September–October 2008 and June 2009–July 2009).

This drought not only impacted flow but also impacted ranch management decisions (resulting in the increased stocking rate during Year 2), pasture condition (resulting in decreased forage availability and groundcover during Year 2), and ultimately instream *E. coli* levels and loading.

E. coli concentrations

A total of 84 samples were collected from the 2 water-sampling sites (PC1 and PC2), of which 48 were collected during Year 1 (July 2007 to July 2008) and 36 during Year 2 (July

2008 to July 2009). Fewer samples were collected during Year 2 as a result of periods with no streamflow as previously noted.

E. coli concentrations at PC2 were correlated with those at PC1 throughout the study ($p < 0.01$), indicating that inflowing *E. coli* concentrations significantly impacted *E. coli* concentrations at the downstream site. Further, coefficient of determination values were moderate to high for both Year 1 ($r^2=0.58$) and Year 2 ($r^2=0.83$). However, *E. coli* concentrations increased between PC1 and PC2 during both years (Figure 5), indicating that loading from the study area contributed to *E. coli* concentrations at the downstream site (PC2). During Year 1, median *E. coli* concentrations increased 73 cfu/100 milliliters ($p = 0.09$) from 88 cfu/100 milliliters at PC1 to 161 cfu/100 milliliters at PC2. During Year 2, the increase of 323 cfu/100 milliliters from 147 cfu/100 milliliters at PC1 to 470 cfu/100 milliliters at PC2 was significant ($p = 0.01$).

This increase during Year 2, when alternative water was provided, was unexpected and inconsistent with the estimated 43% reduction in direct deposition of *E. coli* calculated based on the GPS collar data. The extreme drought that reduced flows by 79% and influenced ranch management decisions to increase stocking rate 34% provide an explanation for much of this increase. With more cattle having access to the creek and less flow to dilute any direct deposition, it would be expected that concentrations would increase, even with the decreased amount of time cattle spent in the stream during Year 2. Based on Year 1 cattle numbers (57 AU), median flow (0.014 centimeters), and estimated median daily deposition of *E. coli* in the stream (1.11×10^7 cfu/AU/day), it was calculated that direct deposition would contribute 52 cfu/100 milliliters to the median inflowing (PC1) concentration (88 cfu/100 milliliters); therefore, inflowing *E. coli* and direct deposition together (140 cfu/100 milliliters) represent an estimated 87% of the median *E. coli* concentration observed at PC2 during

Figure 3. Comparison of flows measured in Clear Fork of Plum Creek to those measured at USGS gage at Luling, Texas.

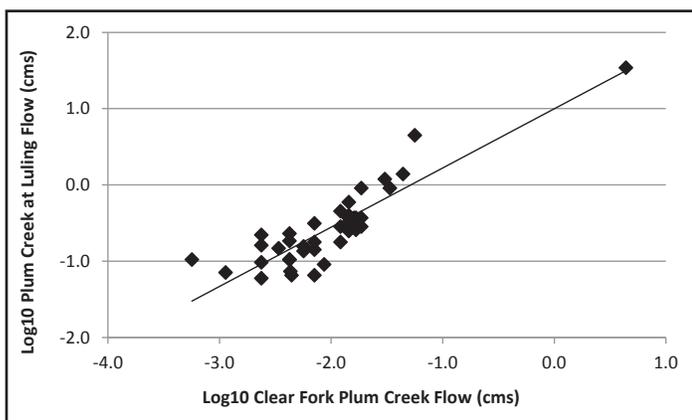
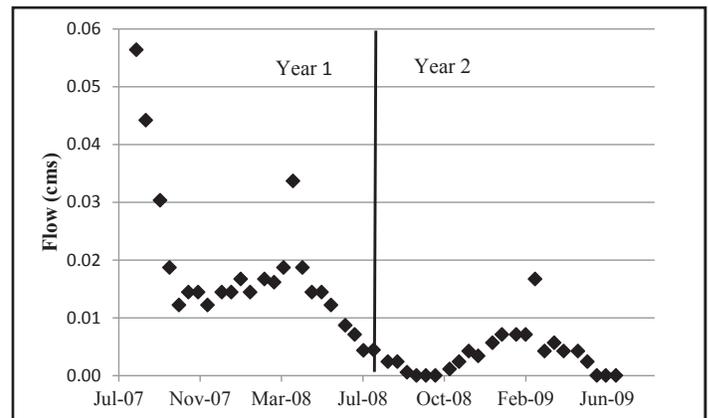


Figure 4. Discharge (centimeters) measured in Clear Fork of Plum Creek, July 2007–July 2009. Discharge measured on July 26, 2007, of 4.38 centimeters (154.83 cfu) is not shown.



Year 1 (161 cfu/100 milliliters). Using the same method for Year 2, it was calculated that direct deposition would contribute 186 cfu/100 milliliters to the median inflowing (PC1) concentration (147 cfu/100 milliliters); therefore, inflowing *E. coli* and direct deposition (333 cfu/100 milliliters) represent an estimated 71% of the median *E. coli* concentration observed at PC2 during Year 2 (470 cfu/100 milliliters).

This evaluation suggests inflowing *E. coli* concentrations, direct deposition by cattle, and reduced dilution resulting from reduced flow all contributed to the *E. coli* concentrations at PC2; however, they do not fully explain the concentrations observed. Approximately 13% of the *E. coli* during Year 1 and 29% during Year 2 are unaccounted for. A portion of the unaccounted *E. coli* likely results from the variability observed in the *E. coli* concentrations. *E. coli* concentrations were highly variable, with standard deviations often exceeding mean *E. coli* concentrations (Harmel et al. 2010; Wagner et al. 2012). Natural variability in *E. coli* concentrations resulting from the complex nature of bacterial deposition, survival, and transport is likely a significant factor in determining the observed *E. coli* concentrations (Harmel et al. 2010). Due to the drought and resulting increased stocking rate, degraded pasture conditions, and reduced flows during Year 2, significant changes in the fate and transport of *E. coli* likely occurred making comparisons of the 2 years difficult.

Measurement uncertainty may have also contributed to data variability. McCarthy et al. (2008) found that combined uncertainty in discrete *E. coli* samples ranged from 15% to 67% and averaged 33%. However, because the field technician, collection methods, lab analyst, and lab methods used were consistent throughout the study, this impact is considered to be consistent across sites and years.

Finally, although not quantified, increased use of the creek

by wildlife during the drought could have also impacted *E. coli* concentrations during Year 2. It is logical that wildlife would increasingly use the creek as other water sources in the area were depleted. Thus, even though use of the stream by cattle as documented by the GPS collars decreased significantly when alternative water was provided, increased wildlife use likely contributed to the overall increase in *E. coli* concentrations as well. Further, as noted by Hagedorn (2012), removal of livestock can open areas to more wildlife contributions. Thus, it is a possibility that with cattle spending more time further from the stream, possibly more wildlife inhabited the riparian area as well.

E. coli loading

Contrary to the *E. coli* concentration results, daily *E. coli* loading to the stream per animal unit in the study area (cfu/AU/day) was substantially lower during Year 2 when alternative water was provided (Figure 6). These contradictory results are likely a result of the lower flows observed in Year 2. The median *E. coli* load in Year 2 (6.2×10^6 cfu/AU/day) was 57% lower than in Year 1 (1.44×10^7 cfu/AU/day); however, the observed difference was not significant ($p = 0.47$). As a result of the variability in the daily loading observed during Year 1, a 99% change in loading or greater would have been required to observe a significant difference in the loadings between years. Despite this, these results are remarkably similar to the estimated Year 1 and 2 *E. coli* depositions in the stream of 1.11×10^7 and 6.34×10^6 cfu/AU/day, respectively, calculated using the GPS collar data and published fecal coliform data.

Even though observed *E. coli* loading and those estimated using GPS collar data are remarkably similar and both indicated reductions of more than 40%, this study cannot con-

Figure 5. *E. coli* concentrations at PC1 and PC2 in Year 1 (no alternative water provided) and Year 2 (alternative water provided).

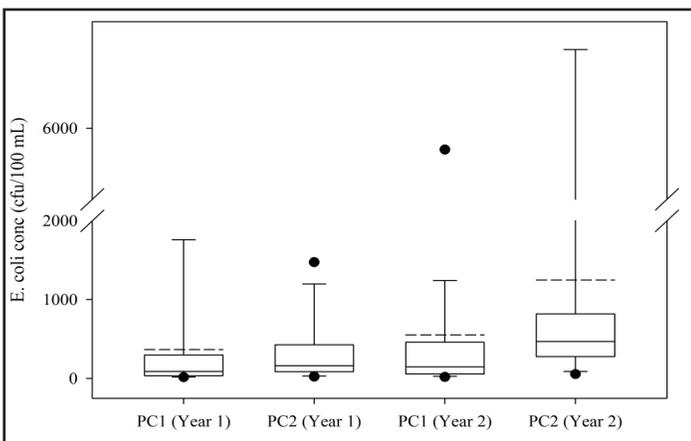
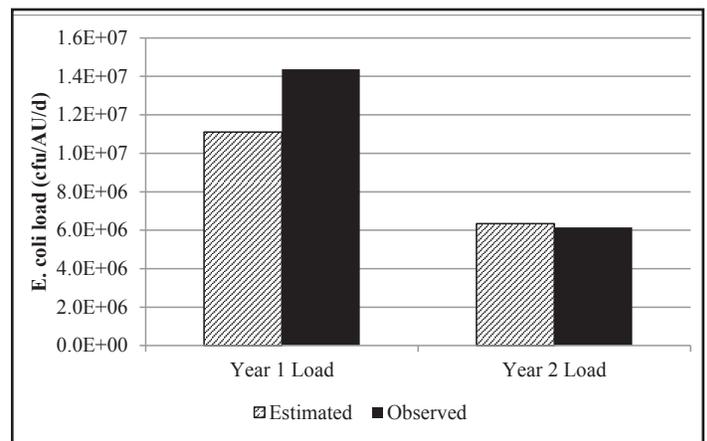


Figure 6. Estimated and observed instream *E. coli* loading (cfu/AU/day) during Year 1 (no alternative water) and Year 2 (alternative water provided).



clusively attribute *E. coli* loading reductions to the alternative water source because of the confounding influence of increased stocking rate, decreased streamflow, and likely increase in wildlife presence, which all contributed to increased *E. coli* concentrations in Year 2.

Turbidity

Median turbidity levels (Table 2) were typically 40% higher at PC1 than at PC2 indicating turbidity generally improved as the creek flowed through the ranch; however, differences were only significant for Year 1 ($p < 0.01$). Much of the observed turbidity at PC1 likely arose from a low water crossing located approximately 0.5 kilometers upstream of the site. Turbidity levels flowing into the study area played a greater role in determining the levels at PC2 during Year 2. During Year 2, turbidity at PC1 and PC2 were correlated ($p = 0.01$; $r^2=0.36$), unlike Year 1 when no correlation between sites was observed ($p = 0.98$, $r^2=0.00$). Analysis of covariance between observed turbidities in Years 1 and 2 indicated no significant treatment effect resulted from providing alternative water ($p = 0.93$).

Turbidity was primarily measured to evaluate its use as a predictor of *E. coli* concentration, as streambed sediment disturbance is suspected to influence *E. coli* levels (Jackson et al. 2011). However, regression analysis results indicated turbidity was not a good predictor of *E. coli* concentrations in Clear Fork of Plum Creek ($p = 0.51$; $r^2=0.01$). Similarly, McDonald et al. (2006) did not observe a significant correlation between fecal *enterococci* and turbidity. This differs from the findings of Huey and Meyer (2010) that turbidity is an effective predictor of *E. coli* in the upper Pecos River Basin in New Mexico. Collins (2003) developed a statistical model to determine median *E. coli* concentrations based on turbidity that explained 70%

Table 2. Turbidity levels, in nephelometric turbidity units, measured at PC1 and PC2 during Years 1 and 2.

Period	Statistic	PC1	PC2
Year 1	Mean	35	17
	sd	20	8
	Median*	29a	16b
	Max	62	31
Year 2	Mean	14	12
	sd	11	13
	Median*	10a	6a
	Max	43	47

*For each site, medians followed by same letter are not significantly different ($\alpha = 0.05$).

of the observed *E. coli* variance. Similarly, Brady et al. (2009) found that a model based on turbidity and rainfall performed well at predicting *E. coli* levels (81% correct responses) in the Cuyahoga River, Ohio. Thus, turbidity does have utility as a predictor in some watersheds; however, this should be determined on a case-by-case basis and used with caution.

SUMMARY AND CONCLUSIONS

Use of GPS collars was found to be a very useful tool, one that would benefit not only future BMP evaluations but also TMDL studies that use percent time cattle spend in streams for assessing direct deposition rates. Performing GPS collar studies can enhance water quality models, allowing them to more accurately predict *E. coli* loading. In this study, GPS collars indicated the amount of time cattle spent in the stream could be reduced 43%, from 3.0 to 1.7 minutes/AU/day, by providing alternative off-stream water. As a result, direct deposition of *E. coli* into Clear Fork of Plum Creek was estimated to be reduced 4.8×10^6 cfu/AU/day from 1.11×10^7 cfu/AU/day when no alternative water was provided to 6.3×10^6 cfu/AU/day once alternative water was provided, and observed pre-treatment and post-treatment *E. coli* loads suggested similar reductions. However, drought-induced reductions in streamflow and increases in stocking rate and wildlife presence resulted in increased *E. coli* concentrations.

Although this study did not provide conclusive evidence of reduced *E. coli* concentrations resulting from providing alternative off-stream water supplies, this practice is still highly recommended due to the significant reductions observed in the time cattle spent in and near the stream, which has been shown in other studies to provide comparable bacteria reductions as exclusionary fencing of streams. Further, this study supports McIver (2004) who noted alternative water supplies alone would not achieve water quality improvements unless implemented in conjunction with good grazing management (appropriate stocking rate, evenly distributed grazing, avoiding grazing during vulnerable periods, and providing ample rest after grazing events). As a result of the severe drought during this study, these principles could not be strictly adhered to, thus likely confounding the even larger improvements in water quality that could have otherwise been achieved with the use of alternative water supplies.

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