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Article

Turbidity as an Indicator of Water Quality in Diverse Watersheds of the Upper Pecos River Basin

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Abstract: Microbial concentrations, total suspended solids (TSS) and turbidity vary with stream hydrology and land use. Turbidity, TSS, and microbial concentrations, loads and yields from four watersheds were assessed: an unburned montane forest, a catastrophically burned montane forest, urban land use and rangeland prairie. Concentrations and loads for most water quality variables were greatest during storm events. Turbidity was an effective indicator of TSS, *E. coli* and *Enterococci* spp. The greatest threat to public health from microbial contamination occurs during storm runoff events. Efforts to manage surface runoff and erosion would likely improve water quality of the upper Pecos River basin in New Mexico, USA.

Keywords: land use; wildfire; turbidity; *E. coli*; microbial concentrations; total suspended solids; storm runoff; *cryptosporidium* spp.

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1. Introduction

The Pecos River originates in high alpine mountains and travels through arid and semi-arid regions where ephemeral tributary contributions generated by highly variable precipitation events provide additional in-stream flow. The river drains approximately 115,000 km^2 as it flows 1,490 km through New Mexico and west Texas before joining the Rio Grande near Del Rio, Texas.

Competing interests for the river's water include domestic drinking water and municipal uses, agricultural irrigation, livestock watering, a growing dairy industry, the water demands of native and non-native vegetation in riparian and upland watershed areas, and the need to protect endangered species. In order to meet these obligations, intensive studies of both water quality and quantity in the upper Pecos River basin have been conducted [1].

In surface water systems such as the upper Pecos River region, enteric microorganisms are transported at higher concentrations during storm runoff events than during baseflow conditions [2]. Representative sampling for these organisms is difficult in streams and rivers of the southwestern United States where runoff events are extremely flashy with short-term peak flows that may last only a matter of hours, depending on patterns and amount of precipitation. Therefore, periodic discrete grab sampling has a low probability of identifying microbial concentrations that indicate risk to human health.

Land use, topography, vegetation, climate and hydrology impact the water quality of a watershed [3]. Runoff from snowmelt and storm events in areas burned by forest fires exhibit higher levels of suspended solids and turbidity relative to unimpacted watersheds [4]. Increased surface runoff contributes to turbidity, which is an easily measured variable that is often associated with total suspended solids (TSS) [5] and microbial concentrations [6].

To assess these relationships, four sites were selected in the upper Pecos River basin on the basis of watershed characteristics (Figure 1). Potentially pathogenic microorganisms, *Escherichia coli*, *Enterococci* spp., *Cryptosporidium* spp. and *Giardia duodenalis*, were assessed for each watershed. Correlations were calculated between turbidity, total suspended solids, stream flow, and microorganisms to determine the validity of turbidity as an indicator of water quality.

Montezuma/Lower Gallinas: The Gallinas River supplies 90–95 percent of the municipal water supply to the city of Las Vegas, NM (population 15,000). The river headwaters are in mountainous topography on the eastern slopes of the Sangre de Cristo Mountains with a peak elevation of 3,563 m at Elk Mountain. The river flows approximately 35 km southeast to the City of Las Vegas at 1,981 m and meanders 70 km through semi-arid plains before reaching its confluence with the Pecos River [4].

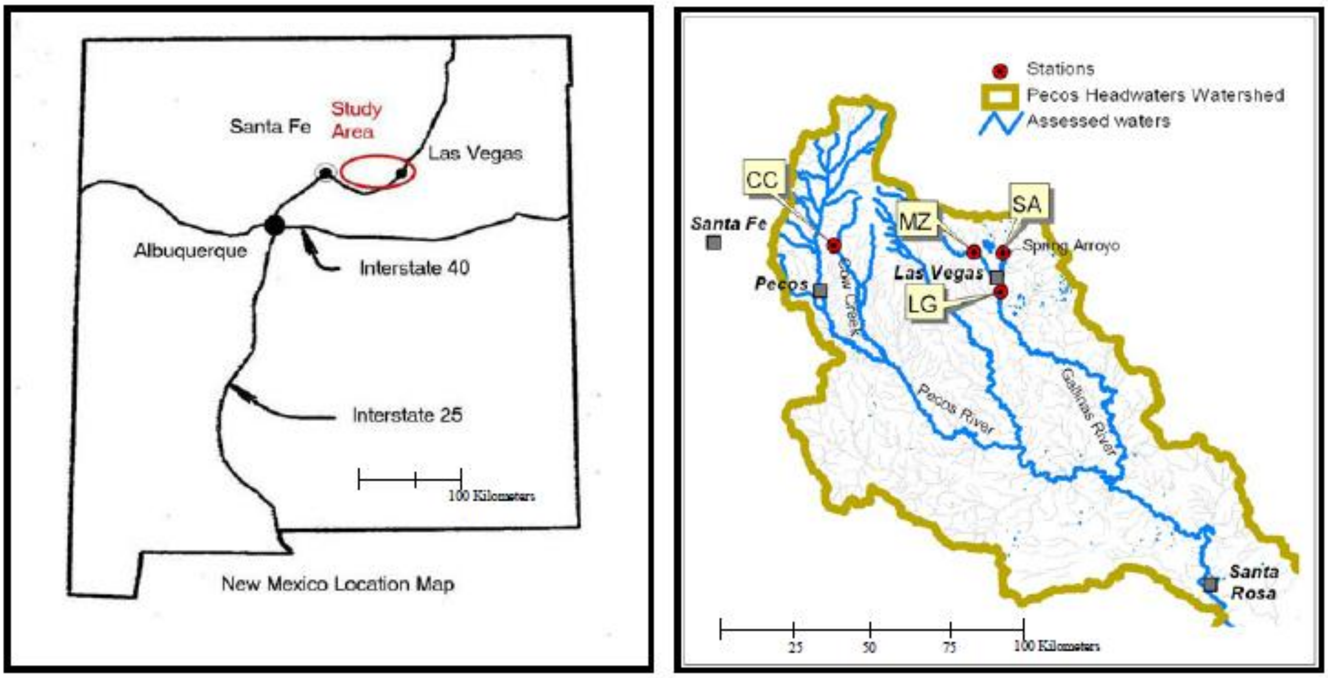
Las Vegas is in the pinyon-juniper woodland zone between the Sangre de Cristo Mountains and the eastern plains of New Mexico. The average annual precipitation ranges from 760 mm at elevations greater than 2,744 m to 380 mm in Las Vegas. Most of the precipitation occurs in the months of June through September.

The mean annual discharge in the Gallinas River from 1926 to 2006 was 18 million m^3 at U.S. Geological Survey (USGS) gauging station 8380500 upstream from the municipal diversion [7]. Not all of this water is suitable for diversion to storage facilities. During periods of increased runoff and high turbidity, diversion gates are closed and river water passes downstream. The Las Vegas Drinking Water Treatment Department avoids diverting Gallinas water into the reservoirs when turbidity exceeds 20 NTU.

Two locations on the Gallinas River were selected for monitoring (Figure 1). The Montezuma site (MZ) was located 1.6 km above the municipal drinking water diversion at USGS gauging station. The Lower Gallinas (LG) site was 0.8 km downstream from the city of Las Vegas. The MZ site represents 218 km^2 of the upper reaches of the Gallinas watershed, extending from the city drinking water diversion to the headwaters. There are approximately 100 dwellings above this monitoring site.

All of the dwellings utilize private septic systems or pit latrines, introducing the possibility of human fecal contamination. Domestic animal populations and livestock grazing in the flood plain and riparian zones are another potential source of fecal contamination. An abundance of wildlife resides throughout the area, including large ungulates (elk and deer) and a variety of mammals, birds and reptiles.

Figure 1. Upper Pecos River Basin with monitoring sites Upper Gallinas River near Montezuma (MZ), Cow Creek (CC), Lower Gallinas River (LG) and Spring Arroyo (SA).



The downstream LG monitoring site represents 38 km^2 of urban watershed, calculated using an effective runoff area for the city of Las Vegas, rather than its entire watershed area (455 km^2). The City's storm water flows directly into the Gallinas River upstream of the station, and fecal contamination may be present from overflowing sanitary sewers, livestock and pets in the city and on the eastern range, and a variety of wildlife including elk, deer and pronghorn.

Cow Creek: The Viveash fire of May/June, 2000 burned 117 km^2 in the Cow Creek watershed, primarily Santa Fe National Forest property on the west slope of Elk Mountain and the ridge separating the Cow Creek and Gallinas watersheds. The fire advanced across the entire watershed and extended northeast onto Elk Mountain and the upper Gallinas watershed, where it burned approximately 5% (10 km^2) of the headwaters of the Gallinas watershed.

Post fire U.S. Forest Service analysis indicated that a significant portion of the burned area was rated as "burn severity high", which occurred due to the high level of forest fuels in the watershed. The intense heat induced soil hydrophobicity in the severely burned zones, and post-fire observations indicated that the soil was prone to excessive runoff due to lower infiltration rates [4]. Areas traditionally covered with vegetation and forest soils showed evidence of poor water infiltration capacity and severe erosion.

The Cow Creek monitoring site (CC) is located upstream from the confluence of Cow Creek and Bull Creek on the west slope of Elk Mountain in the upper Pecos River watershed (Figure 1). There are less than ten dwellings above the monitoring site, utilizing septic systems or pit latrines. Free-range cattle graze the area in summer and elk and deer are present year round in the 105 km^2 watershed.

Spring Arroyo: Shortgrass prairie rangeland dominates the Spring Arroyo watershed to the north of Las Vegas. The Spring Arroyo monitoring site (SA) is located on the ephemeral waterway upstream of its confluence with the Pecos Arroyo, which joins the Gallinas River upstream from the LG station (Figure 1). Land use in the 91 km^2 watershed is principally grazing of beef cattle. The topography, vegetation, climate and hydrology are in contrast to the forested montane watersheds to the west. Other sources of fecal contamination consist of septic systems and wildlife, including elk, deer and pronghorn.

2. Results and Discussion

2.1. Stream Hydrology

Storm events in the region were not evenly distributed. With the exception of one major spring snowstorm in 2004, no single event affected two monitoring stations simultaneously. Mean daily stream flow varied greatly between the four watersheds. The largest watershed, MZ, maintained a higher mean flow, 0.67 meter cubed per second (m^3/s), and higher median, 0.18 m^3/s, than the other three sites (Table 1). The other montane site, CC, had the second greatest mean flow, 0.25 m^3/s, and a median value of 0.14 m^3/s (Table 1). The LG site had a mean flow of 0.18 m^3/s and a median value of 0.04 m^3/s. For the three perennial streams, watershed size was significantly correlated with total discharge, with an R^2 value of 0.9928. The ephemeral SA site produced the lowest mean flow at 0.05 m^3/s with a median of 0.00 m^3/s and experienced flow on 17% of the 269 days of monitoring (Table 1).

The comparison of means for flow indicates that each of these monitoring sites was significantly different. The montane monitoring sites, CC (114%) and MZ (209%), demonstrated lower coefficient of variation (CV) values than the urban LG site (719%) and rangeland SA site (1,039%). The CC site ranged from 0.11 to 2.28 m^3/s. The MZ site compared most closely to the CC site, with a range from 0.06 to 20.97 m^3/s. The LG and SA sites exhibited high variability with minimum flows of 0.0028 and 0.0000 m^3/s, respectively, and maximum flows of 22.99 and 16.98 m^3/s, respectively.

Total volume discharged from the various watersheds varied between monitoring sites. Total discharge from the MZ site was the highest at 7.5×10^6 m^3, followed by the CC site at 4.3×10^6 m^3. However, the MZ watershed is roughly twice the size of the CC watershed. The yield per ha from CC, 428.7 m^3/ha, was approximately 20% larger than that from MZ, at 342.2 m^3/ha. The total discharge from the urban LG watershed, 3.1×10^6 m^3, was less than that from the montane sites, but due to the smaller effective runoff area of the impervious urban watershed, it experienced the largest yield, 815.8 m^3/ha. The total discharge of the Gallinas River at the LG site was less than MZ due to diversions by the city of Las Vegas and local agriculture. The SA site had the lowest discharge (0.9×10^6 m^3) and yield (88.6 m^3/ha) due to its location in a low precipitation area, high evapotranspiration rates, and resultant ephemeral nature.

Mean daily stream flow was stratified into base flow and event flow for each watershed using U.S. Army Corps of Engineers FLUX software. The CC site had most of its total discharge as base flow (56.8%) with 43.2% of the total discharge as event flow from snow melt and rainfall events. The

MZ and LG sites have similarly stratified flow regimes, with 37.2% and 34.7%, respectively, of total discharge resulting from base flow and 62.8% and 64.3%, respectively, of total discharge resulting from event flow. The SA site received 95.2% of its discharge from event flow and 4.7% from base flow following precipitation events.

Table 1. Flow stratification results for Montezuma (MZ), Cow Creek (CC), Lower Gallinas (LG), and Spring Arroyo (SA) for 2003 and 2004. (Stream Stratification based on Daily Mean Discharge).

	Stream Monitoring Sites			
	MZ	**CC**	**LG**	**SA**
	Stream Stratification by Flow (m^3/s)			
Base Flow	<0.29	<0.17	<0.12	<0.03
Event Flow Range	0.29–17.55	0.17–207	0.12–21.73	0.03–3.79
Mean (overall)	0.67	0.25	0.18	0.05
Median (overall)	0.18	0.14	0.04	0.00
CV	209%	114%	713%	1,039%
Watershed Size (km^2)	218	101	38	91
	Total Stream Discharge ($\times 10^6$ m^3 and percentage)			
Base Flow	2.8 (37%)	2.5 (57%)	1.1 (35%)	0.04 (4.7%)
Event Flow	4.7 (63%)	1.9 (43%)	2.0 (65%)	0.86 (95.2%)
Total Discharge	7.5	4.3	3.1	0.9

2.2. Turbidity and Total Suspended Solids

The FLUX flow weighted mean for turbidity was greater at MZ than CC, 91.3 NTU and 25.8 NTU, respectively (Table 2). However, at baseflow the MZ site showed lower turbidity than the burned CC site, 4.7 NTU and 18.5 NTU, respectively. For event flow, MZ values were significantly higher than those from CC, with results of 142.6 NTU and 35.4 NTU, respectively ($p < 0.05$). The LG site showed the highest flow weighted mean turbidity values overall, 2,147 NTU. There was a large difference between base flow and event flow values, possibly resulting from rapid runoff during storm events from the effective runoff area of the urban/commercial watershed. The SA site experienced high turbidities for base flow and event flow with values of 1,681 NTU and 1,508 NTU, respectively. The higher value for base flow is possibly from a first-flush effect after a long period of zero flow. The SA site exhibited a flow weighted mean of 1,516 NTU.

TSS concentrations were lowest at the MZ (13.4 mg/L) and CC sites (80.3 mg/L) (Table 2). At both locations, TSS, turbidity and stream discharge were highly correlated. TSS concentrations at the SA and LG sites were more than one order of magnitude greater than at the montane sites, with values of 1,477 and 3,988 mg/L, respectively. The mean TSS for LG and SA were highest, followed by the CC site and the MZ site. TSS loads were lowest at MZ (100,182 kg), followed by the other montane site, CC (347,360 kg). The ephemeral SA site discharged 1,376,396 kg and LG was highest at 12,346,480 kg. Turbidity and TSS were significantly correlated at all monitoring stations, suggesting that turbidity is a reliable indicator of total suspended solids in the upper Pecos River basin.

Table 2. Flow Weighted Turbidity (NTU), Total Suspended Solids (TSS) Concentration (mg/L), Load (kg), TSS Yield (kg/ha), *E. coli & Enterococci* Concentrations and Yield Results for Montezuma (MZ), Cow Creek (CC), Lower Gallinas (LG), and Spring Arroyo (SA) for 2003 & 2004, based on Daily Mean Flow.

	Stream Monitoring Sites			
	MZ	**CC**	**LG**	**SA**
	Turbidity (NTU)			
Base Flow	4.7	18.5	102	1,681
Event Flow	142.6	35.4	3,284	1,508
Mean	91.3	25.8	2,147	1,516
	TSS Concentration & Load			
Mean TSS (mg/L)	13.4	80.3	3,988	1,477
TSS Load (kg)	1.0×10^5	3.5×10^5	1.2×10^7	1.4×10^6
	TSS Yield (kg/ha)			
Base Flow	0.8	19.6	58.9	0.7
Event Flow	3.8	14.8	3,190	130
Total	4.6	34.4	3,249	131
	***E. coli* Concentration (mpn/100 mL)**			
Base Flow	1,096	256	4,159	5,416
Event Flow	2,574	17	48,551	6,557
Mean	2,024	153	32,701	6,503
	***E. coli* Yield (mpn/ha)**			
Base Flow	1.39×10^8	6.25×10^8	1.21×10^{10}	2.27×10^8
Event Flow	5.55×10^8	3.14×10^7	2.54×10^{11}	5.54×10^9
Total	6.93×10^8	6.55×10^8	2.66×10^{11}	5.57×10^9
	***Enterococci* Concentration (mpn/100 mL)**			
Base Flow	1,881	90	5,939	29,369
Event Flow	6,031	34	31,037	5,746
Mean	4,488	66	22,076	6,862
	***Enterococci* Yield (mpn/ha)**			
Base Flow	2.39×10^8	2.19×10^8	1.73×10^{10}	1.23×10^9
Event Flow	1.30×10^9	6.20×10^7	1.63×10^{11}	4.86×10^9
Total	1.54×10^9	6.80×10^8	1.80×10^{11}	6.10×10^9

TSS yields varied greatly between sites as a function of TSS load and watershed area. CC experienced a higher yield for base flow than event flow, with values of 19.6 kg/ha and 14.8 kg/ha, respectively. The MZ watershed experienced higher yield with increasing flow, rising from 0.8 kg/ha at base flow to 3.8 kg/ha for event flow. Total TSS yields were significantly higher ($p < 0.05$) for CC than MZ, 34.4 kg/ha to 4.6 kg/ha, respectively. Despite the smaller watershed area and lower discharge rates, mass transport of suspended solids from the CC site was over three times greater than that from the MZ site. The SA site experienced lower yields (131 kg/ha) than might be expected from the TSS concentrations due to the low flow conditions and the relatively large area of the watershed. The LG site discharged the greatest yield (3,249 kg/ha) due to its smaller surface area and high loads.

TSS yield and turbidity values varied between base flow and event flow and between different monitoring sites (Table 2). Comparison of the montane sites indicates that the MZ site had the lowest turbidity values for base flow but a higher turbidity than CC for event flow. TSS yield per stratum at CC was evenly distributed, with a slightly higher value for base flow over event flow. For every site except SA, the turbidity values for base flow were lower than those for event flow. This suggests loading from surface runoff during storm events.

For the three perennial sites, MZ, CC, and LG, TSS and turbidity were significantly correlated with stream discharge (Table 3). This suggested loading from surface runoff during storm events. Turbidity and TSS were significantly correlated at all four sites, suggesting that turbidity may be used as an indicator of elevated suspended solids in each of these watersheds (Table 3). The ephemeral SA site, with its high number of days without flow and high variability in flow rates, did not show significant correlations between TSS/turbidity and discharge. This does not mean that stream discharge is not the source of TSS and turbidity. It indicates that whenever there was flow, either high or low, TSS and turbidity concentrations were extremely high. It is also suggestive of the ephemeral nature of the arroyo.

Table 3. Spearman Rank Correlation Value and p-value for Turbidity, Total Suspended Solids and Daily Mean Flow at Montezuma (MZ), Cow Creek (CC), Lower Gallinas (LG), and Spring Arroyo (SA) for 2003 & 2004.

	MZ	**CC**	**LG**	**SA**	**All Sites**
TSS *vs.* Flow	0.469	0.510	0.514	0.280	0.149
p-value	0.0007*	0.0002*	<0.0001*	0.2289	0.0426*
NTU *vs.* Flow	0.816	0.629	0.469	0.368	0.190
p-value	<0.0001*	<0.0001*	0.0001*	0.1106	0.0096*
TSS *vs.* NTU	0.599	0.910	0.964	0.862	0.900
p-value	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*

*Significant Correlations ($p < 0.05$)

2.3. E. Coli *and* Enterococci *spp.*

During the 2003 and 2004 sampling seasons the following number of bacteria samples were collected at each site, respectively: MZ, 22 and 10; CC, 23 and 10; LG, 24 and 19; and SA 5 and 2 (Table 5). Results were reported as most probable number per 100 milliliters (mpn/100 mL).

The LG discharge data exhibited the most variable flow of the four sites during both monitoring seasons and experienced much higher concentrations of bacteria than other monitoring locations throughout the study (Table 2). The SA site experienced flow on 17% of the 269 days incorporated in this study. This resulted in seven samples being analyzed for bacteria concentrations. Of these, five occurred during the 2003 sampling season and two occurred within the 2004 sampling season. SA bacteria samples exhibited much higher concentrations of *E. coli* and *Enterococci* spp. than those from the CC and MZ monitoring sites and similar concentrations to those from the LG station (Table 2).

E. coli concentrations at the CC site were higher for base flow (256 mpn/100 mL) than for event flow (17 mpn/100 mL), with a flow weighted mean of 153 mpn/100 mL, the lowest of the four sites. The LG site exhibited the highest *E. coli* concentrations, with a flow weighted mean of 32,701 mpn/100 mL. Base flow and event flow resulted in 4,159 and 48,551 mpn/100 mL, respectively. The MZ and SA sites fell between the other two sites with means of 2,024 and 6,503 mpn/100 mL, respectively (Table 2). The LG site, using an effective runoff area of 3,800 ha, exhibited yields up to 3 orders of magnitude greater than the montane sites, and two orders greater than the SA site (Table 2). The CC site exhibited a greater yield for base flow (6.25×10^8 mpn/ha) than event flow (3.14×10^7 mpn/ha), while the other monitoring sites exhibited in greater yields for event flow.

Flow weighted mean concentrations of *Enterococci* spp. at the CC site were significantly lower than the other three sites. Concentrations were greater at this site for base flow (90 mpn/100 mL) than event flow (34 mpn/100 mL), similar to *E. coli* concentrations. This also occurred at the SA site, which exhibited a much greater value for base flow (29,369 mpn/100 mL) than event flow (5,746 mpn/100 mL). Due to the low flow conditions of base flow at the SA site, the flow weighted mean concentration was 6,862 mpn/100 mL. The MZ and LG sites exhibited greater concentrations for event flow.

The LG site exhibited bacteria yields of up to 3 orders of magnitude greater than the other sites, probably as a result of the impervious nature of the urban runoff area. The CC site had a greater yield for base flow than event flow. Due to low flow conditions at the SA site, there were greater yields for event flows than base flow.

Spearman Rank Correlations were calculated for *E. coli* and *Enterococci* spp. against TSS and turbidity. Turbidity and *E. coli* were significantly correlated at all sites, and turbidity and *Enterococci* spp. were significantly correlated at the three perennial sites (Table 4). TSS was significantly correlated with *E. coli* and *Enterococci* spp. at the three perennial sites (Table 4).

Table 4. Spearman Rank Correlation Value and p-value for Turbidity, Total Suspended Solids, *E. coli* and *Enterococci* spp. at Montezuma (MZ), Cow Creek (CC), Lower Gallinas (LG), and Spring Arroyo (SA) for 2003 & 2004.

	MZ	**CC**	**LG**	**SA**	**All Sites**
NTU *vs. E. coli*	0.367	0.335	0.794	0.486	0.747
p-value	0.0187*	0.0284*	<0.0001*	0.0490*	<0.0001*
NTU *vs. Enterococci* spp.	0.401	0.409	0.807	0.417	0.709
p-value	0.0098*	0.0068*	<0.0001*	0.0954	<0.0001*
TSS *vs. E. coli*	0.340	0.489	0.810	0.347	0.711
p-value	0.0304*	0.0010*	<0.0001*	0.1712	<0.0001*
TSS *vs. Enterococci* spp.	0.215	0.426	0.836	0.237	0.652
p-value	0.1765	0.0047*	<0.0001*	0.3517	<0.0001*

*Significant Correlations ($p < 0.05$)

2.4. Cryptosporidium *spp. and* Giardia Duodenalis

Comparison of means test for *Cryptosporidium* spp. concentrations was not significantly different for each of the four monitoring sites. Concentrations of *Cryptosporidium* spp. at the CC site showed higher values for base flow than for event flow, with a flow-weighted mean of 1.7 counts (cts)/L. Event flow at this site exhibited a flow-weighted mean of 1.1 cts/L, and the total flow-weighted mean for this watershed was 1.4 cts/L. For the CC watershed, 13 samples were analyzed for *Cryptosporidium* spp. and *Giardia duodenalis* during the 2003 monitoring season and seven samples were analyzed during the 2004 season. Of the 20 samples examined, 11 were negative for *Cryptosporidium* spp.

It was not possible to analyze *Cryptosporidium* spp. for flow weighted mean by stratum at the SA site because there were less than three cells found for each event flow. Composite samples were analyzed for three events during the 2003 monitoring season and for two events during the 2004 season. Of the five samples examined, all were found to be positive for *Cryptosporidium* spp. The total flow weighted mean for the watershed resulted in a concentration of 4.4 cts/L.

Concentrations of *Cryptosporidium* spp. at the MZ site indicated higher values for event flow than for base flow, with a flow-weighted mean of 0.2 cts/L. Base flow at this site exhibited a flow-weighted mean of 0.1 cts/L, and the total flow weighted mean for this watershed was 0.2 cts/L. For the MZ watershed, 10 samples were analyzed during the 2003 monitoring season and three samples were analyzed during the 2004 season. Of the 13 samples examined, five were negative for *Cryptosporidium* spp. cells.

Concentrations of *Cryptosporidium* spp. at the LG site indicated higher values for base flow than for event flow, with a flow-weighted mean of 19.6 cts/L. Event flow at this site experienced a flow-weighted mean of 2.5 cts/L, and the total flow weighted mean for this watershed was 8.7 cts/L. For the LG watershed, three samples were analyzed during the 2003 monitoring season and eight samples were analyzed during the 2004 season. Of the 11 samples examined, three were found to be negative for *Cryptosporidium* spp. cells.

Cryptosporidium spp. yield per hectare reflects these concentrations and stream discharge values. The CC watershed produced a slightly greater water yield than that from the MZ watershed, 428.7 m^3/ha *versus* 342.2 m^3/ha. However, due to the higher concentrations of *Cryptosporidium* spp. found there, the total yield was a full order of magnitude greater, 6.09×10^5 cts/ha compared to 5.55×10^4 cts/ha, respectively. Yield was greater for base flow over event flow at the CC site, but greater for event flow over base flow at the MZ site. The LG site exhibited yields of one order of magnitude greater than the CC and SA sites and two orders greater than the MZ site. While concentrations were high at SA, the low levels of surface runoff from this site resulted in a yield comparable to that from the CC site.

Comparison of means test for *Giardia duodenalis* indicated that concentrations from each of the four sites were not significantly different. It was not possible to perform *Giardia* flow weighted means on the CC and SA monitoring sites due to the low number of positive samples from these sites. The CC monitoring site had two positive samples from the 20 that were processed. Likewise, the SA site was positive for two out of five samples. For the same reasons, it was impossible to obtain stratification results for the LG site, where three of the 11 samples processed were positive for *Giardia*. However, the total concentration for the LG site, when compared to the forested MZ watershed, exhibited much higher values, 25.9 cts/L *versus* 0.4 cts/L. This was reflected in the *Giardia* yields for the two watersheds as well, where the LG results were two orders of magnitude greater than the MZ data.

An anomaly in the results from the *Giardia* testing may help to explain the low number of positive samples found at all four sites. Upon final enumeration under fluorescent microscopy, particles of

Giardia cysts were discovered when no complete cysts were present. This phenomenon could have resulted from a breakdown during the testing procedure in highly turbid samples or possible scouring on the streambed during transport with large amounts of suspended solids. Further testing must be conducted to fully explain this occurrence.

Correlations for *Cryptosporidium* and *Giardia* data with total suspended solids (mg/L), turbidity (NTU) and flow from the four monitoring sites indicated that only *Giardia* correlated significantly with flow at the SA site and with total suspended solids at the MZ site.

3. Experimental Section

The study incorporated 269 days: 27 May–14 November 2003 and 29 April–9 August 2004. At the four monitoring sites (Figure 1), base flow grab samples were routinely collected every two weeks and event samples were collected at discharge-initiated intervals using flow based automated sampling systems. The total number of samples analyzed is listed in Table 5. Each site was equipped with a Campbell Scientific, Inc. CR10x datalogger in tandem with a Teledyne-ISCO, Inc. 3,700 portable sampler and a non-submersible N_2 pressure transducer and bubbling system. Rating curves were developed for each station and verified regularly with manual flow measurements [8].

Multiple flow-weighted samples collected through an event hydrograph were composited into two samples representing the rising and the falling limb of the event hydrograph based on flow volumes as described in Standard Methods protocol 1060B [9]. For small events, individual samples representing the rising and falling limbs of the hydrograph were composited into one sample.

Samples were collected in sterilized, one-liter, high-density polyethylene Nalgene brand bottles according to Standard Methods protocol 9060A as described for surface waters and transported as described in Standard Methods protocol 9060B and processed upon arrival at the laboratory [9].

Water samples were assessed for TSS, turbidity, *E. coli*, *Enterococci* spp., *Cryptosporidium* spp. and *Giardia duodenalis*. TSS and turbidity were assessed according to Standard Methods, protocol 2540D and 2130B, respectively [9].

Table 5. Total Number of Samples Collected per Analyte for Montezuma (MZ), Cow Creek (CC), Lower Gallinas (LG), and Spring Arroyo (SA) for 2003 & 2004.

	MZ	**CC**	**LG**	**SA**	**Total**
Turbidity	50	50	65	20	185
TSS	51	50	65	20	186
E. coli	43	43	51	7	144
Enterococci spp.	44	43	51	7	145
Cryptosporidium spp.	19	29	13	12	73
Giardia duodenalis	19	29	10	12	70

Bacterial enumeration was conducted using IDEXX Laboratories techniques, as described for *E. coli* in Standard Methods 8310B [9] and *Enterococci* spp. by the American Society for Testing and Materials protocol D6503-99 [10]. Results were reported in mpn/100 mL. Quality control blanks and duplicate samples were processed for quality assurance and quality control. Protozoan enumeration was conducted as described by U.S. EPA analytical method 1623 [11] and reported in counts per liter (cts/L).

Turbidity and TSS were evaluated as potential indicators of enteric microorganisms in four watersheds under varying hydrological conditions. Spearman Rank correlations, coefficient of variation (CV), and Kruskal-Wallis nonparametric one-way analysis of variance tests for comparison of means were performed for stream discharge and water quality analytes between monitoring sites using Statistix 7 from Analytical Software, Inc. Daily mean flow data and composite sample values were used for statistical analysis. U.S. Army Corps of Engineers FLUX software was used to statistically determine event and base flow levels, watershed flow weighted mean concentrations, and loading calculations. This program estimates tributary mass discharges (loadings) from sample data and daily mean flow records. Significant difference was evaluated at $p < 0.05$. Watershed yield was calculated by dividing loading at each site by watershed area. Yields from the Lower Gallinas (LG) monitoring site were calculated using an effective runoff area of 38 km^2 for the city of Las Vegas, rather than its entire watershed area (455 km^2).

4. Conclusions

Turbidity and TSS were significantly correlated at all monitoring stations, suggesting that turbidity is a reliable indicator of total suspended solids in the upper Pecos River basin. Most monitoring sites and study variables showed increased concentrations of water quality variables for event flow over base flow. This illustrates the necessity for automated event sampling to accurately depict hydrological effects on watershed loading.

Significant correlations were exhibited between turbidity and *E. coli* in all four of the watersheds and between TSS and *E. coli* in the three perennial watersheds. Additionally, turbidity and TSS were significantly correlated with *Enterococci* spp. at the three perennial watersheds. These correlations suggest that the City of Las Vegas may consider using turbidity as an indicator of fecal coliform bacteria and develop its use as a tool for managing surface water diversions into the city's drinking water reservoirs.

Cryptosporidium spp. and *Giardia duodenalis* were detected in each of the four watersheds. The presence of these potential pathogens in all watersheds is cause for caution for the City of Las Vegas drinking water facility and for the general population in contact with these surface waters.

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