Bacterial loading during flooding: a case study from 2010 on the Bi-national Rio Grande

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Abstract

Escherichia coli (*E. coli*) bacteria loadings were tracked during the summer 2010 major flood event of the Rio Grande using the Soil and Water Assessment Tool (SWAT) hydrologic model. This bi-national watershed spanning Texas and Mexico has loading from urban point source sewage outfalls and non-point source loadings from rangeland and agricultural areas located upstream of a urban centre (Laredo/Nuevo Laredo). Flood events represent a high risk for human health since bacterial loadings increased during the flood. Sampling during flood conditions is dangerous and therefore there are comparatively few studies that have examined bacterial values in rivers during flood events. Therefore, the safest way to obtain bacterial concentrations during a flood event is through hydrologic modelling. Significantly, the initial assumption of constant bacterial loading within the basin is not valid. As demonstrated by previous research there is a strong linear correlation between streamflow and *E. coli* values. The outcomes of this study will provide guidelines for users of the SWAT model to predict bacteria fate and transport during future flood events and will therefore assist communities in improving management of their water supplies. Finally, use of satellite precipitation data as primary input for the SWAT model potentially extends the findings of this study to areas of the developing world that lack ground monitoring of precipitation.

Keywords: bacteria, SWAT, flood, sewage, Texas, Mexico, Rio Grande.

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1 Introduction

This study utilized the SWAT model to simulate bacterial transport in the Rio Grande watershed during a July 2010 flood event. Study focuses on *Escherichia coli* (*E. coli*), a part of the group of faecal coliforms, present in the polluted Rio Grande. Analysis is based on comparison of major flood event data with more normal flow conditions that occurred before and after the flood. This study connects watershed hydrology with faecal bacteria statistical time series analysis to determine how the SWAT program can be utilized to facilitate future predictions of bacteria fate and transport within the Rio Grande.

2 Study area

This study examined segments of the Rio Grande both upstream and downstream of Laredo, Texas (United States) and Nuevo Laredo, Tamaulipas (Mexico, fig. 1). The upper segment begins at Columbia Bridge, which is located approximately 33 km north of Laredo. The basin outlet is located in the town of Rio Bravo, Texas, which is 26 km south of Laredo. The examined watershed is defined between the basin inlet and outlet and has an area of 2,589.375 km^2.

The basin examined is divided into 26 subbasins by the SWAT model's Watershed Delineation Tool (fig. 1). The outlet of six subbasins along the Rio Grande corresponds with this study's field sampling sites, which are located in and downstream of Laredo and include Texas Commission of Environmental Quality (TCEQ) segments 20650 and 15816, table 1. This study's sites correspond with the water quality sampling locations of the Texas Clean River program operated by the TCEQ with local support from the City of Laredo Health Department. As with the TCEQ program water samples were collected on the US side of the river.

Table 1: TCEQ stations and SWAT model subbasins with sampling sites.

Sampling Site	TCEQ Station	SWAT Subbasins
1	15816	26
2	13196	25
3	15815	22
4	15814	19
5	13202	18
6	20650	14

The primary sample site of this study was site 4, fig. 1, which corresponded with the location of the International Boundary and Water Commission (IBWC) streamflow gage (15814) and also was the outlet for subbasin 19. This site is adjacent to International Bridge II that connects the downtown areas of Laredo and Nuevo Laredo. Immediately upstream, within 1 km, of site 4 there are significant (10123 m^3/sec) point source dischargers of raw sewage on the Mexican side of the river (Negrete [2]).

Three sample sites (sites 1-3; fig. 1) were examined downstream of Laredo. Site 1 is located near the water intake pipe for the town of Rio Bravo, Texas and where there is only ranch land present on the opposing Mexican side. Sites 1 and 2 are located 18 and 13 km downstream of site 4, respectively. Site 2 is within 2 km downstream of the Wastewater Treatment Plant for Nuevo Laredo.

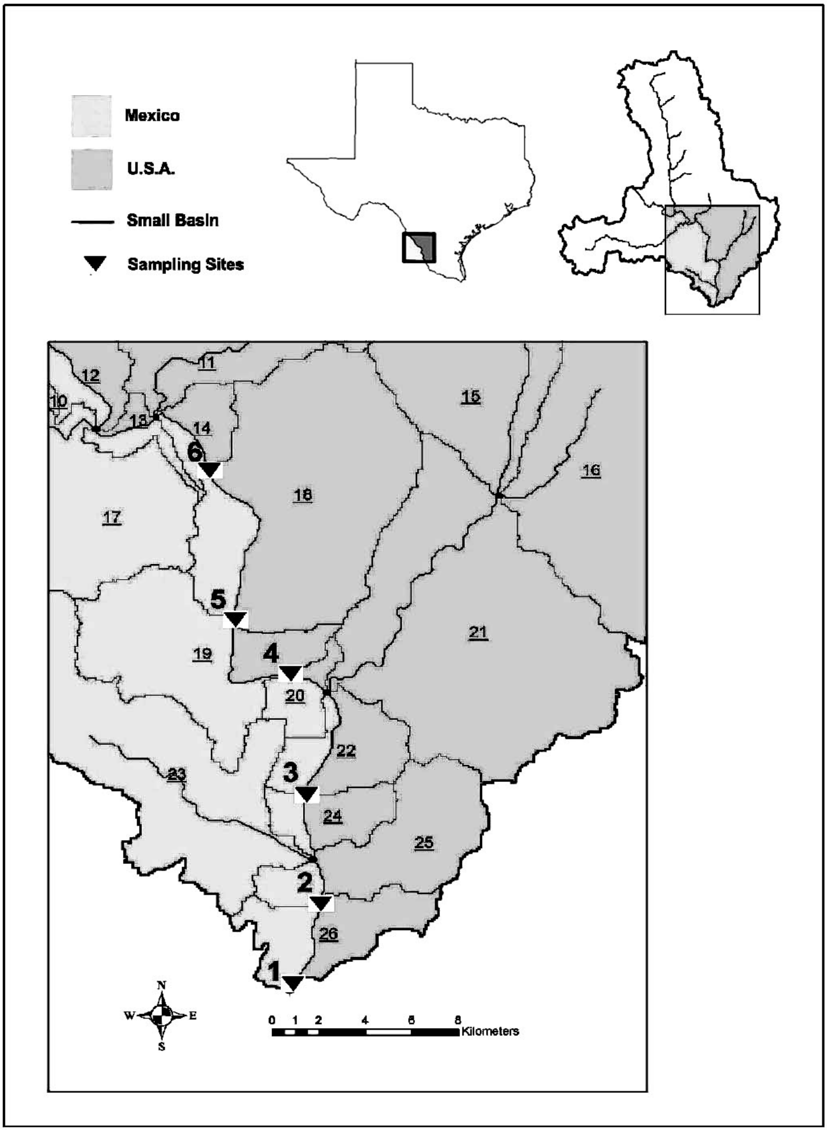


Figure 1: Study watershed. Sampling sites 1-6 within the basin.

South Laredo Wastewater Treatment Plant. No significant inflows from Mexico are present across from site 3.

Upstream of the primary site there are two sampling locations (sites 5-6; fig. 1). Site 5 is located at the Jefferson Water Treatment Plant (drinking water) in Laredo and is 6 km upstream from site 4. Note that there is a major bend in the Rio Grande present between sites 4 and 5. Some turbulent back eddies were noted at site 5. Site 6 is 14 km upstream of site 4 and is located close to the inlet of Manadas Creek; a location noted for heavy metal pollution. Significant riparian areas are noted along both the US and Mexican side of the Rio Grande studied.

The Rio Grande in Texas was regulated upstream of Laredo with the completion of Amistad Dam 300 km north of Laredo, which was finished in November 1969. A large quantity of water was released at Amistad Dam in early July 2010 that resulted in the inundation of cities along the Rio Grande downstream of the dam. At Laredo the river crested on July 8th and 9th (12.94 m, 3170 m^3/sec). Since Amistad Dam was constructed the 2010 flood was second greatest in magnitude with slightly greater flow recorded in 1971 (3260 m^3/sec).

3 Methods

This study examined both observed and simulated bacterial concentrations in the Rio Grande. Observed bacterial values were obtained through the MF method (US EPA Method 1603 [3]) that provided a direct count of *E. coli* in water based on the development of colonies that grew on the surface of a membrane filter.

Simulated bacterial concentrations were determined using the SWAT model. Tobin and Bennett [1] previously modeled the middle Rio Grande Basin, which overlaps with the study area, and this work provided information that facilitated model calibration. The precipitation dataset input into the model was the National Weather Service Multisensor Estimator product (MPE). The model was run from January 1, 2009 to September 30, 2010 covering the July 2010 flood period. The first eight months of the run was used as an initialization period to warm-up the model.

SWAT model results were validated with two metrics, the Nash–Sutcliffe model efficiency coefficient (NS) and the Mass Balance Error (MBE). The Nash–Sutcliffe model efficiency coefficient (NS) was used to evaluate the predictive power of hydrological models.

$$NS = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_s^t)^2}{\sum_{t=1}^{T}(Q_o^t - Q_a^t)^2} \qquad (1)$$

where Q^t_o is the observed bacteria value, Q^t_s is the simulated streamflow (bacteria) value, and Q^t_a is the average observed bacteria value (Nash and Sutcliffe [4]). The Mass Balance Error (MBE) directly compared the totals of simulated and observed bacteria and is defined below.

$$MBE = \frac{\sum_{t=1}^{T}(Q_s^t - Q_o^t)}{\sum_{t=1}^{T}Q_o^t} \qquad (2)$$

Table 2 describes the model performance metrics as suggested by Moriasi *et al.* [5]. If the NS number is between 0.75 and 1.00, or the percent MBE is within ±15%, then the model performance is very good. NS between 0.65 and 0.75 is considered as a good model as well as a percent MBE between ±15% and ±30%. When the NS value falls between 0.50 and 0.65 (or MBE between ± 30% and ±55%), the model performance is considered satisfactory. Any NS result lower than 0.50 or any MBE percent higher than ±55% is considered as an unsatisfactory model performance, where it is recommended to either re-evaluate the parameters used in model, or to discard it completely.

Table 2: Model performance metrics (modified from Moriasi *et al.* [5]).

Performance Rating	**NS**	**MBE**
Very Good	$0.75 < NS \leq 1.00$	$MBE < \pm 15\%$
Good	$0.65 < NS \leq 0.75$	$\pm 15\% \leq MBE < \pm 30\%$
Satisfactory	$0.50 < NS \leq 0.65$	$\pm 30\% \leq MBE < \pm 55\%$
Unsatisfactory	$NS \leq 0.50$	$MBE \geq \pm 55\%$

At the Columbia Bridge inlet persistent bacterial loadings were either assumed to be a constant value (125, 1,250, 12,500 Colony Forming Units or CFU/100 ml) or a variable value based upon the linear regression of streamflow versus observed persistent bacteria values at the closest sampling site (#6) to Columbia Bridge.

Effluent from wastewater treatment plants was present in several of the subbasins that define the examined watershed (fig. 1). Persistent bacterial loading was assumed to be 200 CFU/ 100 ml, which is the legal upper limit for treated wastewater (NTAC [6]; US EPA [7]). Immediately upstream of site 4, within subbasin 19, fifteen conduits on the Mexican side of the river acted as point dischargers for raw sewage. The nominal value for loading of raw sewage is 10,122.9 m^3/day. Additionally, during the July 2010 flood event the City of Laredo documented the release of domestic sewer water localized at the International Bridge II lift station (near site 4) of approximately 30,000 m^3/day.

A total of thirteen SWAT simulations were conducted to account for different possible loadings. Simulations 1 to 4 had bacterial loading at the basin inlet, wastewater treatment plants, and raw sewage dischargers from subbasin 19. Raw sewage had an assumed concentration of persistent bacteria at 10^6 CFU/ 100 ml, which is the median value for this type of effluent (Sturman *et al.* [8]). Simulations 1 to 3 were based on a constant persistent bacterial loading (125, 1,250, 12,500 CFU/ 100 ml). Bacterial loading in simulation 4 was based on a variable value from regression analysis as described above. Simulations 5 to 8 were similar to the above four simulations except without bacterial loading added within subbasin 19. Simulations 9 and 10 were similar to simulation 4 except that the assumed concentration of persistent bacteria was 10^7 and 10^8 CFU/ 100 ml, respectively. Simulations 11 to 13 account for a worst-case scenario where releases of sewage during the second week of the July 2010 flood were assumed to be thirteen times higher than was reported again with assumed persistent bacterial concentrations of 10^6, 10^7 and 10^8 CFU/100 ml.

4 Results

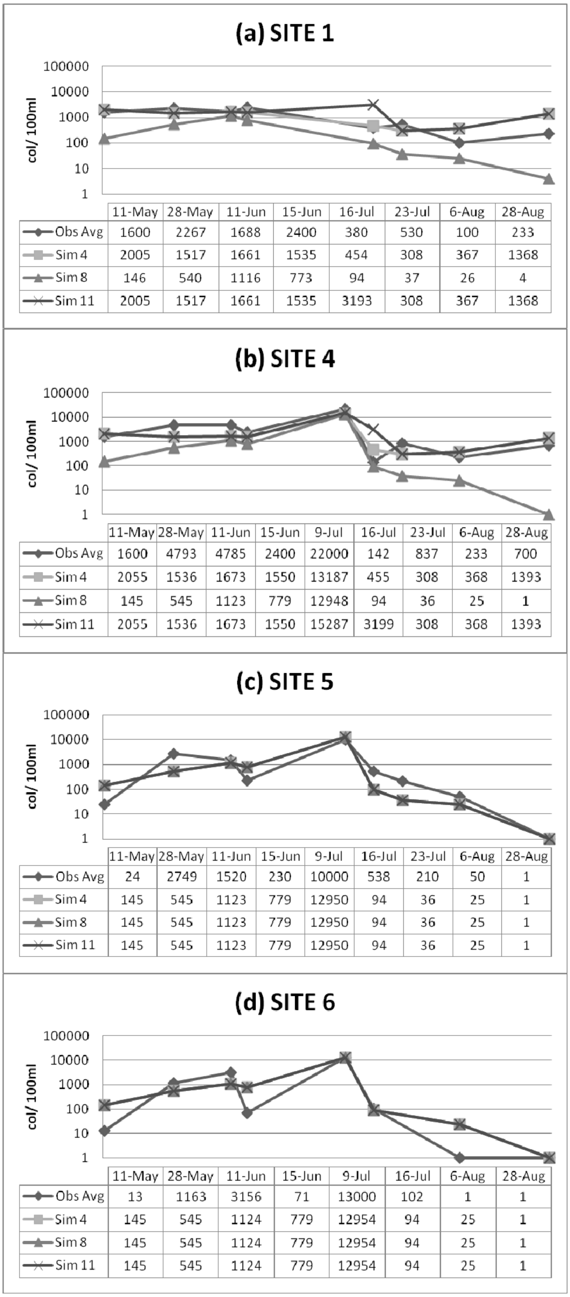
Both observed and simulated bacteria data were measured as CFU and were examined from sites 1, 4, 5, and 6, fig. 1. On July 9 and 23 flood conditions made sites 1 and 6 inaccessible. Relatively high values (generally in the thousands of CFU) were recorded before the main flood event (May-June, 2010), which was a time with above average streamflow and with periods of minor flooding (flow in the range of 100 to 300 m^3/sec). During the flood crest (July 9) extremely high *E. coli* values (in the tens of thousands of CFU) were noted at all examined sites. After the flood crest, in mid-July to late August, *E. coli* the values were much lower, generally < 1,000 CFU, at all sites.

Simulated persistent bacterial values were determined based on several different assumptions about the nature of point source loading in the river. The most fundamental modelling assumption made was the bacterial loading value at the basin inlet. The initial assumption was that bacterial loading was constant and did not change with streamflow (simulations 1, 2, and 3) and this assumption produced unacceptable simulations, based on MSE and NS values, table 3. Conversely, simulation 4 was based on variable bacterial loading at the basin inlet as described in the methodology section. This simulation yielded acceptable MSE and NS values at all sites, table 3, and closely corresponds with the observed average *E. coli* value, fig. 2.

Table 3: Simulated persistent bacterial values (CFU).

	Site 1		**Site 4**		**Site 5**		**Site 6**	
	MBE	**NS**	**MBE**	**NS**	**MBE**	**NS**	**MBE**	**NS**
1	-28%	-0.07	-80%	-0.30	-92%	-0.26	-95%	-0.24
2	71%	-0.65	6%	-0.17	-21%	-0.02	7%	-0.06
3	1100%	-167	220%	-1.95	695%	-12.41	435%	-5.13
4	**-5%**	**0.55**	**-41%**	**0.74**	**19%**	**0.83**	**-8%**	**0.97**
5	-88%	-1.08	-97%	-0.37	-92%	-0.26	-95%	-0.24
6	14%	-0.03	-70%	-0.19	-21%	-0.02	-47%	-0.06
7	1040%	-149	204%	-1.64	695%	-12.41	435%	-5.13
8	-66%	-0.06	-58%	0.69	**19%**	**0.83**	**-8%**	**0.97**
9	542%	-54.4	107%	-0.13	**19%**	**0.83**	**-8%**	**0.97**
10	6017%	-6576	1593%	-139	**19%**	**0.83**	**-8%**	**0.97**
11	31%	-0.78	**-28%**	**0.80**	**19%**	**0.83**	**-8%**	**0.97**
12	903%	-210	239%	-3.02	**19%**	**0.83**	**-8%**	**0.97**
13	9623%	-22372	2909%	-518	**19%**	**0.83**	**-8%**	**0.97**

Numbers in ***bold*** *indicate acceptable simulations.*



(a) SITE 1

	11-May	28-May	11-Jun	15-Jun	16-Jul	23-Jul	6-Aug	28-Aug
Obs Avg	1600	2267	1688	2400	380	530	100	233
Sim 4	2005	1517	1661	1535	454	308	367	1368
Sim 8	146	540	1116	773	94	37	26	4
Sim 11	2005	1517	1661	1535	3193	308	367	1368

(b) SITE 4

	11-May	28-May	11-Jun	15-Jun	9-Jul	16-Jul	23-Jul	6-Aug	28-Aug
Obs Avg	1600	4793	4785	2400	22000	142	837	233	700
Sim 4	2055	1536	1673	1550	13187	455	308	368	1393
Sim 8	145	545	1123	779	12948	94	36	25	1
Sim 11	2055	1536	1673	1550	15287	3199	308	368	1393

(c) SITE 5

	11-May	28-May	11-Jun	15-Jun	9-Jul	16-Jul	23-Jul	6-Aug	28-Aug
Obs Avg	24	2749	1520	230	10000	538	210	50	1
Sim 4	145	545	1123	779	12950	94	36	25	1
Sim 8	145	545	1123	779	12950	94	36	25	1
Sim 11	145	545	1123	779	12950	94	36	25	1

(d) SITE 6

	11-May	28-May	11-Jun	15-Jun	9-Jul	16-Jul	6-Aug	28-Aug
Obs Avg	13	1163	3156	71	13000	102	1	1
Sim 4	145	545	1124	779	12954	94	25	1
Sim 8	145	545	1124	779	12954	94	25	1
Sim 11	145	545	1124	779	12954	94	25	1

Figure 2: *E. coli* CFU – (a) Site 1, (b) Site 4, (c) Site 5, and (d) Site 6.

Simulations 5 to 8 were identical to model runs 1 to 4 except that sewage was not input into subbasin 19 to test the impact that sewage had on the bacterial loading at sites 1 and 4. Not surprisingly, table 3 and fig. 2 show that these simulations had an unacceptable negative bias.

In simulation 4 the median value for CFU in the sewage effluent emitted in subbasin 19 was assumed to be 10^6 CFU/ 100 ml. To test the sensitivity of the assumed CFU value simulations 9 and 10 were ran with values of 10^7 and 10^8 CFU/ 100 ml, respectively. Table 3 shows the extreme positive bias in these simulations validating our initially assumed CFU value of 10^6 CFU/ 100 ml.

During the period of July 9 to 16 the City of Laredo reported releases of untreated wastewater. Simulations 11 to 13 document a worse-case scenario where releases were assumed to be over an order of magnitude higher than was reported. At sites 1 and 4 simulation 11 yielded acceptable MBE and NS values, table 3, which were comparable to both simulation 4 and observed bacterial loading, fig. 3. However at site 1, simulation 11 had an unacceptable NS value indicating that the reported sewage releases were accurate.

5 Discussion

The fundamental question addressed in this paper is whether *E. coli* values can exceed regulatory guidelines during high flow conditions. Results demonstrate that *E. coli* values were underestimated during flood conditions, since the bacterial loading from runoff and floodplain inundation were not taken under consideration; therefore, *E. coli* values exceeded regulatory guidelines during high flow conditions. This study confirmed that bacterial loading could be simulated by the SWAT model potentially informing management decisions associated with extreme weather/flow conditions.

Davies-Colley *et al.* [9] and McKergow and Davis-Colley [10] documented a strong linear correlation between bacterial values and streamflow from small to moderated size watersheds from New Zealand. Our study initially assumed that bacterial loading at the basin inlet was constant; this assumption was the basis for SWAT simulations 1 to 3. Table 3 illustrates the assumption of constant bacterial loading is not valid. To fix this problem, we adopted the approach of Davies-Colley *et al.* [9] by generating variable bacterial loading at the basin inlet, which produced acceptable results (simulation 4; table 3).

Within the examined watershed there were both point and non-point sources for bacterial loading. The most significant permanent point source of bacterial loading along the river was associated with sewage outfalls present in Nuevo Laredo. Transient loading sources present during the July 2010 flood included point sources dischargers of untreated raw sewage from Laredo (Archer [11]) and non-point sources including contributions from overland runoff and flooding of the riparian zone adjacent to the river (Ferguson [12]). Sturman *et al.* [8] indicated that combined sewer overflows have Total Coliforms 10^5–10^7 MPN/100ml. Potential bacterial loading from overland runoff included urban, agricultural and rangeland areas. Runoff from urban sources had variable, but generally lower than sewage, values for bacteria (Sturman *et al.* [8]; Total Coliforms, 10^1–10^8 MPN/100 ml).

During the river flood event, potential bacterial loading from overland runoff in the basin can occur from urban, agricultural, and rangeland areas. Additionally, inundation of floodplains can contribute to bacteria loading. Sites 2, 3, 5 and 6 were situated adjacent to floodplain areas; whereas, sites 1 and 4 were more dominated by urban runoff.

Rangeland areas generate large loads of *E. coli* and faecal bacteria concentrations. Cattle and their manure in soils are the dominant factor affecting the quantity of live bacteria within rangeland areas. Generally, *E. coli* concentrations in dry manure are $4x10^7$ CFU/g (Crane and Moore [13]). Bacterial populations are subject to change with environmental factors, such as temperature, rainfall duration and intensity, and extent of inundated land. These factors may determine whether or not faecal bacteria are transported with overland runoff during a rain event or detached from soil particles during a land inundation event (Khaleel *et al.* [14]; Walker *et al.* [15]). Another consideration is the effect of the die-off rate of microorganisms within overland runoff, which is calculated using the first-order decay relationship expressed as Chick's Law (Moore *et al.* [16]). The same conditions are associated with the inundated riparian zone during flooding, where wildlife excrete faeces with faecal coliforms and *E. coli* that can be directly incorporated into runoff within the river.

To track bacterial loading sources several series of SWAT simulations were performed. Simulation 4 was the default simulation that includes point source loading from Nuevo Laredo with *E. coli* assumed to be CFU 10^6 /100 ml and this simulation yielded acceptable results at all sites, table 3. A series of SWAT simulations (5-8) with inlet loading the same as simulations (1-4) but with no sewage point source loading were executed. At sites 1 and 4, which are downstream of the sewage point source, simulation 8 consistently underestimated *E. coli* values, fig. 2. This result demonstrated that sewage dischargers from Nuevo Laredo contributed significantly to the bacterial loading of the river downstream of the city. Flint [17] has documented that Total Faecal Coliforms including *E. coli* bacteria can survive for prolonged periods in surface water bodies. Therefore, bacterial loading from point sources in subbasin 19 can be attributed to the excess loading noted at, and downstream, of TCEQ station 15814 (site 4).

Simulations 9 and 10 used elevated assumed *E. coli* values (10^7 to 10^8 CFU/100ml). Results from these simulations had extreme positive biases, table 3, indicating that the assumed value of 10^6 CFU/100ml was more realistic. The 10^6 CFU/100ml assumed value is the median value for combined sewer outflows, which is similar to values reported by Sturman *et al.* [8]. Cho *et al.* [18] converted faecal bacteria concentrations from CFU estimates to MPN estimates and found that MPN and CFU estimates are comparable. Additionally, laboratory inspection of bacterial plates indicated that *E. coli* is the dominant type of coliforms in the examined samples.

During the 2010 Rio Grande flood event the stream flow peaked at 3170 m^3/sec and then receded rapidly within one week. From July 8th to July 16th high flow forced wastewater to spill from the Bridge II lift station (Laredo). Unfortunately, site 1 was not accessible during the flood event. Simulations 11 to 13 model the worst case scenario for this incident where the amount of sewage is assumed to be 13 times higher than the official numbers reported from the City of Laredo, which was plausible given the unknown amount of sewage released from Nuevo Laredo at this time. Again these simulations had assumed *E.coli* of 10^6 to 10^8 CFU/100ml with simulation 11, 10^6 CFU/100ml, yielding best results, table 3. However, simulation 11 did not perform as well as the default simulation 4 indicating that sewage releases were not grossly over-reported.

The above SWAT modelling was based on the following assumption. The examined watershed was relatively small (2,589.375 km^2) and the total length of the river from sites 1-6 was only 32 km. Therefore, bacteria die-off and growth was not considered as a major factor, since *E. coli* bacteria loading at site 6 travels to site 1 without significant growth or death. This assumption was justified based on limited travel times of bacteria within the river; less than six hours under normal flow conditions and even less during the flood event. *E.coli* die-off rate in surface runoff is 0.659 day^{-1}, and *E.coli* die-off rate in stream water is 0.990/day^{-1} (Crane and Moore [13]).

Bacterial and nutrient dynamics during pre-flood, flood and post-flood conditions varied significantly. Bacterial contamination during the pre-flood time period was strongly influenced by known point source near Site 4 where there significant raw sewage outfalls. Sites 1 and 4 are considered contaminated by the TCEQ with typical *E. coli* values in excess 10^3 CFU/100ml (Archer [11]). Conversely, sites 5 and 6 typically have *E. coli* concentrations less than the regulatory limit set by the TCEQ of 200 CFU/100ml and commonly can have very low values approaching zero (Archer [11]). However, the period of May and June 2010 had inordinately high rainfall. Consequently, bacterial loading from non-point sources urban, agricultural, and rangeland areas contributed to elevated *E. coli* values, table 3, in even relatively clean sites (5, 6).

During peak flood conditions (July 9), the floodplain adjacent to the river was inundated, facilitating significant non-point source loading with greatly elevated *E. coli* values at all sites, which is consistent with previous research (Davies-Colley *et al.* [9]; McKergow and Davis-Colley [10]). Bacterial mobilization from the flooded riparian zone likely served as a large source for *E. coli,* and nutrients, during this event.

Davies-Colley *et al.* [9]; McKergow and Davis-Colley [10] documented a sharp decrease in bacterial loading in rivers after a flood event. Results from this study are consistent with the above observation. McKergow and Davis-Colley [10] indicates that bacterial stores present in channel and adjacent floodplain sediments are rapidly washed downstream. *E. coli* values during the post-flood period are very low at sites 5 and 6 ($\leq 10^2$ CFU/100ml) indicative of the depleted state of bacteria in the river. Even at sites 1 and 4 *E. coli* values are lower than average ($\leq 10^3$ CFU/100ml).

This study has implications for understanding how bacterial loading varies between normal and high flow conditions. Environmental monitoring of rivers is generally conducted under normal flow conditions when it is safe to be in close proximity to the river. Therefore, existing records of *E. coli* from sources such as the TCEQ, are biased by the omission of high values associated with floods. This conclusion potentially has regulatory significance in that during floods even relatively clean river segments can have *E. coli values* that greatly exceed acceptable standards. The strong correlation between streamflow and *E. coli* can be utilized to predict bacterial loading during future floods without the risk of sampling during non-safe flow conditions. Finally, the SWAT model is capable of accepting many types of precipitation data to support modelling. Use of remotely sensed precipitation products such as from NASA's Tropical Rainfall Measurement Mission can potentially extend the approaches articulated in this study to the developing world where there is an acute need for water quality monitoring.

6 Conclusions

Even so called clean stream reaches can exceed regulatory limits with high *E. coli* values during flooding. This study provides guidelines for users of the SWAT model to predict bacteria fate and transport during future flood events and therefore can potentially assist communities in improving management of their water supplies during periods of hydrometeorological extremes.

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