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Should Contact Recreation Water Quality Standards be Consistent across Hydrological Extremes?

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Abstract: Water quality standards are developed to protect and define when waterbodies support their designated uses including public water supply, recreational use, aquatic life use, and others. Recreational use categories include various activities that typically do not occur under similar hydrologic conditions making protection of all uses challenging. This paper presents a case study where *Escherichia coli* concentrations were grouped by flow rate to demonstrate potential effects of developing use-specific water quality standards for contact recreation. Adopting this approach requires a shift from current water quality policy which applies to all hydrologic conditions; however, it also requires additional data collection on actual usage types and occurrence before it can be implemented. This paper demonstrates that implementing an alternative water quality standards approach can still reasonably protect human health while minimizing taxpayer cost to restore impaired waterbodies.

Keywords: *E. coli, human health, risk*

Safeguarding water quality is essential to protect public health worldwide. Globally, the UN estimates that 780 million people do not have access to clean water, and another 2.5 billion do not have adequate sanitation (UNICEF and WHO 2012). Deficient water treatment and natural phenomena can cause infectious doses of pathogens to be present in surface waters. When consumed, these pathogens can potentially cause water borne illnesses. Pathogen presence estimates commonly use fecal indicator bacteria (FIB) concentrations such as *Escherichia coli* due to cost considerations; however, tools including molecular markers and quantitative microbial risk assessment are evolving and provide additional options for future water quality assessments (Pachepsky et al. 2018). Despite such advances, many locales continue to rely on simple FIB concentrations in water quality standards application.

Escherichia coli and associated pathogens arrive in streams through direct deposition (point sources or defecation into the stream) or indirectly via runoff (nonpoint source pollution). Nonpoint *E. coli* sources undergo various fate and transport processes before arriving in streams (Ferguson et al. 2003), thus affecting *E. coli* and pathogen quantities entering the stream. Regardless of transport mechanism, sediment provides an environmental niche where *E. coli* can persist for extended periods of time (Garzio-Hadzick et al. 2010) and potentially grow (Solo-Gabriele et al. 2000; Stocker et al. 2018). This challenges water managers, as extended persistence and growth can yield *E. coli* populations that may not be associated with recent contamination events (Anderson et al. 2005), thus diminishing potential relationships between *E. coli* concentration and human health risk. It may also lead to impaired waterbody statuses and significant financial investments to correct perceived pollution issues (Wagner et al. 2016).

Known flow rate effects on sediment transport further confound this issue. Research has demonstrated normal and high streamflow induced streambed bacteria releases. In southeast Texas, up to 90% of observed instream *E. coli* load was derived from sediment under baseflow conditions (Brinkmeyer et al. 2015). This deviates from conventional thought that resuspension only occurs during high-flow events (Jamieson et al. 2005). Using artificial floods, Muirhead et al. (2004) and Stocker et al. (2018) demonstrated roughly two order of magnitude increases in *E. coli* concentrations that directly resulted from flow rate induced sediment resuspension. This is not surprising, considering that a literature review by Pachepsky and Shelton (2011) noted that *E. coli* concentrations can be 1 to 2,200 times greater in sediments than in the water column. However, they found that correlations between *E. coli* concentrations in overlying water and sediment are typically very weak. Regardless of correlation, inclusion of high-flow influenced samples in water quality assessments can affect results.

Surface water quality standards are established to protect designated waterbody uses and provide the basis for permitting, compliance, and assessments. Standards include defined designated uses, water quality criteria, and antidegradation policies which largely influence water quality management decisions. Therefore, appropriately developing and applying standards is critical as future management actions and financial resources they require can be significant (Wagner et al. 2016).

Water quality standards established for contact recreation uses based on long-term FIB concentrations aim to protect human health during contact recreation. In work conducted by USEPA (1986) and reaffirmed in 2012 (USEPA 2012), gastrointestinal (GI) illnesses contracted by swimmers at defined bathing beaches were correlated to *E. coli* concentrations. Increased *E. coli* concentrations resulting from recent fecal contamination (point source discharges of treated wastewater effluent) related to a quantified human health risk. Their results formed the basis for development of primary contact recreation standards in many states and countries (Ishii and Sadowsky 2008).

Water quality standards are often applied to flowing water bodies and all flow conditions (TCEQ 2010), although watershed-scale has been reported to effect *E. coli* concentrations (Harmel et al. 2010). Various flow conditions present different inherent risks to engaging in contact recreation. Rational thinking suggests that activities such as swimming, wading by children, and tubing should not occur during high-flows due to increased drowning risks; however, whitewater activities such as kayaking, canoeing, and rafting commonly occur during these conditions. Whitewater recreation is inherently risky and increased flow rates that occur during or shortly after storms greatly increase these recreation opportunities in areas where whitewater streams are not common (Daniel 2004). The existence of these activity types has justified maintaining contact recreation standards at all flow conditions. However, arguments can be made that applying water quality standards at high-flows (floods) is not appropriate due to the natural pollutant flushing that occurs and the inability to effectively manage pollutant sources during these conditions. Further, Dorevitch et al. (2011) found that kayakers typically consume 35-40% less water than swimmers. Thus, an opportunity exists to evaluate other water quality assessment and standards development approaches that could minimize potential financial burdens to society without substantially affecting human health risks. This paper evaluates an admittedly small data set to demonstrate the potential effects of considering *E. coli* samples collected during high-flow events differently in water quality assessment results and discusses policy implications of flow rate and risk-based water quality standards. Results and conclusions are by no means meant to reflect an ubiquitous solution, but rather provide hypothetical evidence that the illness threat to the public may not be considerably different under varying flow regimes and water quality standards if the level and type of use change due to flow condition.

Methods

Site Description

Water quality monitoring was conducted on the Navasota River in east central Texas, USA (Figure 1) from December 12, 2014 through August 30, 2016. The Navasota River spans approximately 200 km from its headwaters to its confluence with the Brazos River. Average annual precipitation in the watershed ranges from 864 to 1,118 mm.

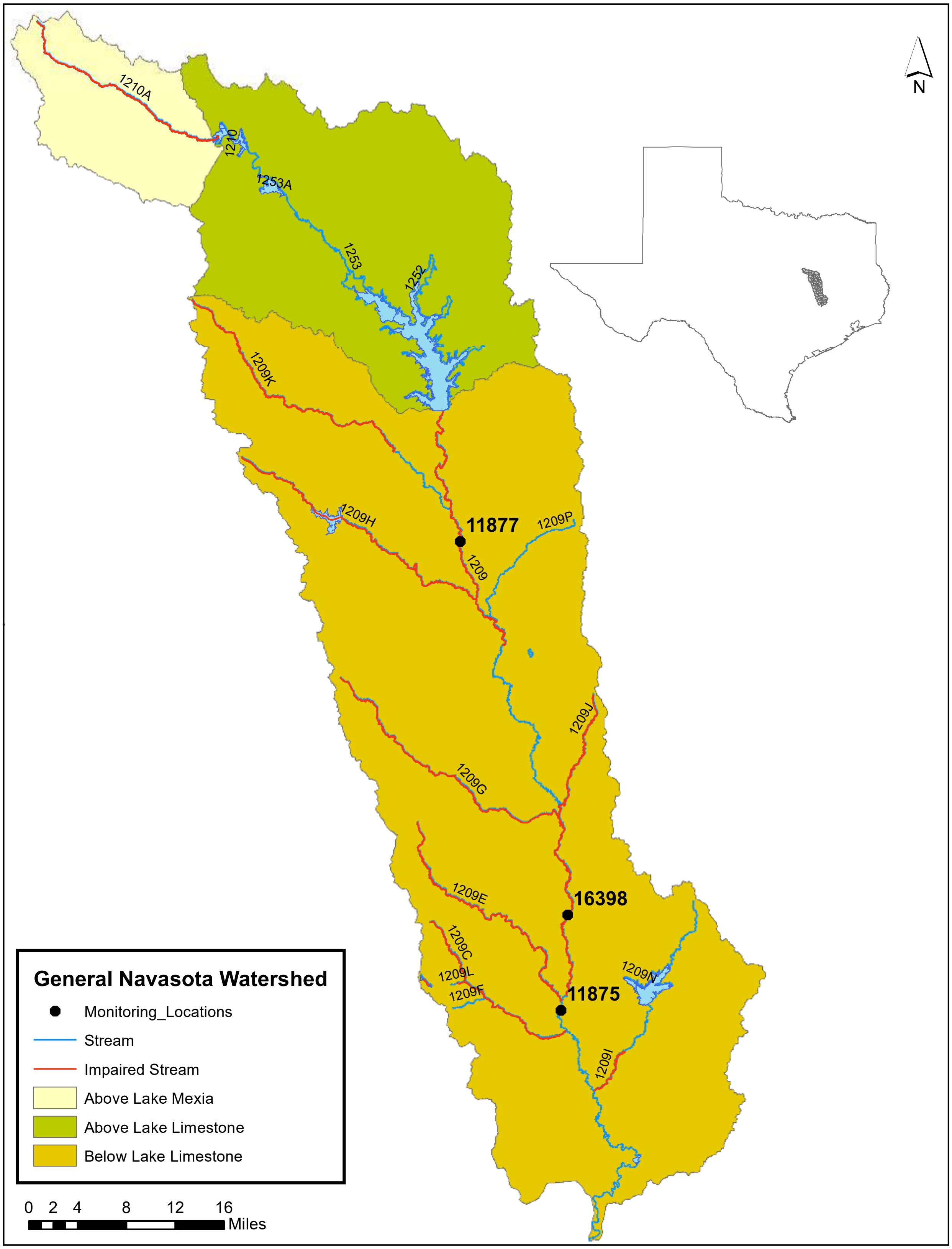

Figure 1. Navasota River Watershed in Central Texas, USA.

Cool, wet winters and hot, dry summers typify local conditions. The watershed is predominantly rural with undeveloped land encompassing >92% of the land area. Grazing land and forests are the dominant land covers. Flood control and water supply are provided by three reservoirs impounding the river in its upper reaches. Lake releases mostly occur in response to rainfall runoff thus making it difficult to distinguish between the effects of dam releases and precipitation/runoff (Gregory et al. 2015).

Three monitoring sites were selected based on geographic location, accessibility, and availability of historic data at each point. For the assessment presented here, only data collected from station 11877 were utilized. This site is located in the upper portion of the river approximately 27.4 km downstream of the largest reservoir. All sites were upstream of urban areas. U.S. Geologic Survey stream gage 08110500 is co-located at this site and records water levels at 15-minute increments. Monitoring occurred biweekly except when high-flows created hazardous sampling conditions or prevented station access. Approximately 25 storm events occurred during the monitoring period. Flow rates above 28.3 m^3/s (bankfull condition) produced hazardous conditions and monitoring was postponed. Missed events were rescheduled as soon as possible. Monitoring techniques followed procedures required by the Texas Commission on Environmental Quality (TCEQ 2012). Large storm events routinely produced discharges of ~300 m^3/s, which are considered major flood events.

Flow volume was recorded using a Sontek ADV (Acoustic Doppler Velocimeter) Flowtracker® or a Sontek RiverSurveyor® M9 Doppler boat. Concurrent pH, water temperature, DO (dissolved oxygen), and specific conductance measurements were recorded with a YSI EXO1 Multiparameter Sonde. Water samples were collected from the centroid of flow at approximately 0.3 m depth and were placed into sterile 200 mL WhirlPak® Thio-Bags®. Samples were transported in ice within six hours to the Soil and Aquatic Microbiology Lab at Texas A&M University for *E. coli* quantification using the EPA 1603 method, a modified thermotolerant membrane filtration approach. Turbidity was determined using a HACH 2100Q field turbidity unit.

Statistical Analysis

Differences in median *E. coli* concentrations between "safe," "unsafe," and "all flow" conditions were evaluated using the non-parametric Mann-Whitney and Kruskal-Wallis tests. Data were non-normally distributed according to Kolmogorov-Smirnov testing. Significance for all analyses was determined using $\alpha=0.05$, thus p values ≤ 0.05 were considered statistically significant. All statistical analyses were conducted using Minitab 17 software (Minitab Inc., State College, PA).

Risk Assessments

Probable human health risks due to potential pathogen exposure during recreational activity was evaluated using two approaches. The first technique applied the linear regression equation developed by Dufour and Ballentine (1986) that was reevaluated and modified for illness type by USEPA (2012) to relate potential swimmer illness rates to *E. coli* geometric mean values. This equation provides the basis of many recreational water quality standards, including those currently applicable in Texas. For this assessment, the below equation was used to estimate expected illness occurrence for differing number of recreators under varying flow conditions.

Illness rate per 1,000 swimmers =

[[Log(E. coli geometric mean) – 1.249]/0.1064]∗4.5

Quantitative microbial risk assessment (QMRA) was performed to estimate human health risks associated with exposure to specific pathogens. Similar approaches have been frequently used in recreational water settings (Schoen and Ashbolt 2010; Soller et al. 2010, 2014, 2015, 2017; McBride et al. 2013; Sunger et al. 2018) and we apply a simple version of these approaches. A point-value QMRA calculation was conducted to provide a rough estimate of the potential human health risks for a GI illness under both safe and unsafe flow conditions and assumed differences in fecal pollution source. FIB concentrations were used to develop a pathogen dose in similar fashion to other assessments in recreational waters (Schoen and Ashbolt 2010; Soller et al. 2010, 2014, 2015; Sunger et al. 2018). Norovirus was selected as the reference pathogen for this "back of the envelope" risk calculation since the pathogen is considered to be the primary agent for GI illnesses in recreational waters (Eftim et al. 2017). The QMRA methodology used in Schoen and Ashbolt (2010) and Soller et al. (2010) was applied for this calculation using the dose equation listed below and assuming input variables presented in Table 1.

Ingested dose of reference pathogen norovirus =

$$\left[\frac{C_{FIB}}{(D_{FIB}*100)}\right]*D_{NoV}*V$$

where C_{FIB} = the concentration of *E. coli* using a culture method in the waterbody (cfu/100mL); D_{FIB} = the density of *E. coli* in wastewater (either raw sewage or treated effluent) (cfu/L); D_{NoV} = the density of norovirus in wastewater (either raw sewage or treated effluent) (genome copies/L); and V = volume of water ingested (mL).

The calculated ingested dose for the reference pathogen is used in a dose-response model to estimate the risk of infection for a specific health endpoint, such as a GI infection. Further, a morbidity ratio can also be used to assess the risk of illness following infection from the pathogen. There are several dose-response models for norovirus in the literature, but the model used (Table 1) assumes viral aggregation of norovirus in the environment and has been recommended for studies assessing health risks in recreational waters (Soller et al. 2017; Van Abel et al. 2017; Sunger et al. 2018).

Table 1. Parameters used in QMRA risk assessment calculation.

Parameter	Use	Value	Units	Assumptions	Reference
E. coli concentration	Safe flow conditions	106.4	cfu/100 mL	Geometric mean	Gregory et al. 2015
	Unsafe flow conditions	510.4	cfu/100 mL	Geometric mean	Gregory et al. 2015
Ingestion rates	Swimming for adults/ children	18.5	mL	Geometric mean (assuming one hour of exposure)	USEPA 2010
	Canoeing/kayaking/ rowing/boating	4.55	mL	Arithmetic mean (includes capsizing during activities and assuming one hour of exposure)	Dorevitch et al. 2011
E. coli density	Secondary treated wastewater	4	log10 cfu/L	Maximum observed value	Rose et al. 2004
	Raw wastewater	8	log10 cfu/L	Maximum observed value	Rose et al. 2004
Norovirus density	Secondary treated wastewater	2.1 log10 removal	log10 GC/L	Average log10 removal for conventional wastewater treatment	Lodder and de Roda Husman 2005; Chaudhry et al. 2017
	Raw wastewater	4.9	log10 GC/L	Upper 95% of the mean; NoV genogroup GII	Eftim et al. 2017
Dose response	Norovirus	P=0.72; μ= 1106	NA	Aggregated; Fractional Poisson (Probability of Illness= P[1-e(-d/μ)])	Messner et al. 2014
	Morbidity ratio	0.6	NA	NA	Soller et al. 2017

Results

In order to recognize instances in which sediment resuspension and nonpoint sources are the likely cause of elevated *E. coli* concentrations, flow events were separated into safe and unsafe conditions for swimming and wading by children (Table 2). Based on recorded flow velocity and stream depths, a discharge of 2.12 m^3/s at the monitoring location was assumed as the upper flow-volume limit that allows for safe swimming and wading (TCEQ 2012). Biweekly monitoring and sampling during the two year study captured *E. coli* concentrations and flow volumes for multiple storm events and baseflow conditions. All data were aggregated into an all flows category for evaluation to represent the current assessment approach.

Statistically, median *E. coli* concentrations were not equal between the safe and unsafe flow categories ($p=0.001$). Between individual categories, safe and unsafe conditions were found to be significantly different ($p<0.001$), but safe conditions and all flows combined were not ($p=0.205$). The presence of several outlier *E. coli* concentrations during high-flow events strongly influenced the median and geometric means in each group (Figure 2), but these could not be excluded as they represent natural occurrences in *E. coli* concentration that sometimes arise from storm events (Figure 3) or unexplained sources that are also commonly observed during baseflow conditions (Muirhead and Meenken 2018). Despite the limited size of the data set, the evaluation suggests that there are potentially different human health risks under safe and unsafe flow conditions. These differing scenarios present an opportunity to create or apply multiple recreation water quality standards on the same waterbody that are based on flow condition and/or the amount and type of recreation that occurs.

Policy Implications

A singular numeric water quality standard for *E. coli* that a waterbody must meet to support recreation uses during all flow conditions may not be practical. In Texas, this was acknowledged and addressed by developing specific standards for different waterbody uses that are as follows:

- Primary contact 1 (126 cfu/100mL): uses presumed to involve a significant water ingestion risk including children wading, swimming, diving, surfing, water skiing, tubing, and whitewater kayaking, canoeing, or rafting.
- Primary contact 2 (206 cfu/100mL): uses are the same as primary contact 1 but are less frequent due to physical limitations of the waterbody and limited access.
- Secondary contact 1 (630 cfu/100mL): common activities with limited body contact including fishing, canoeing, kayaking, rafting, sailing, and motor-boating.
- Secondary contact 2 (1030 cfu/100mL): uses are the same as secondary contact 1 but are less frequent due to physical limitations of the waterbody and limited access.
- Non-contact (2060 cfu/100mL): contact is prohibited by law, or activities with no presumed water ingestion risk including hiking, biking, and birding.

Although this is an improvement from a singular standard, the definition of primary contact recreation includes disparate activities not likely to occur in a waterbody under similar flow conditions. Whitewater sports require much higher flow velocity than swimming, wading by children, or diving. The latter are likely to occur under normal or low-flow conditions, while the former occur during high-flow and flood conditions on all but a few Texas streams that have whitewater year round. Therefore, a logical assumption can be made that water quality may be worse when whitewater sports are likely to occur.

Whitewater sports are inherently dangerous due to adverse hydrologic conditions. Researchers documented whitewater kayaking fatality rates from 3 to 6 deaths per 100,000 kayaking days and injury rates at 4.5 per 1,000 kayaking days. They noted that self-guided paddling trips are significantly more dangerous than commercial trips (Fiore and Houston 2001; Schoen and Stano 2002). Insurance companies also acknowledge the increased risk by routinely increasing policy premiums by \$2 to \$10 per \$1,000 of coverage for frequent extreme sports participants. These persons assume increased risk for bodily harm and

Table 2. *E. coli* concentration descriptive statistics by flow category.

E. coli Concentrations cfu/100mL	N	Median	Standard Deviation	Geometric Mean
Safe flows	32	110	163.1	106.4[a]
Unsafe flows	9	290	1835.7	510.4[a]
All flows	41	124	978.9	150.1[a]

[a] ±36% uncertainty assumed in reported values due to potential influences of sample collection, storage, and analysis for 'good practices' in near surface sampling (Harmel et al. 2016).

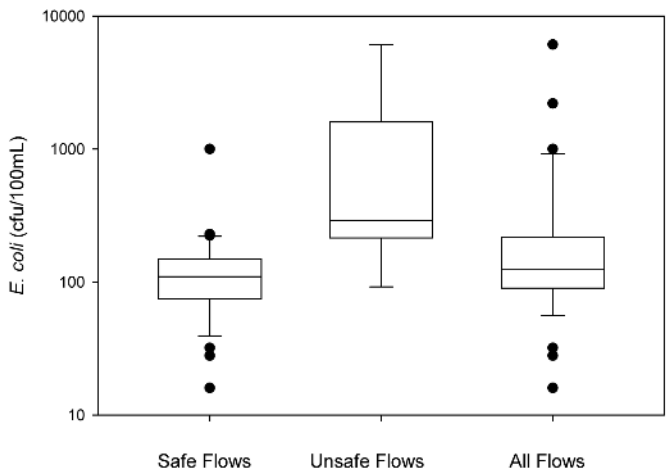

Figure 2. *E. coli* concentrations by flow condition.

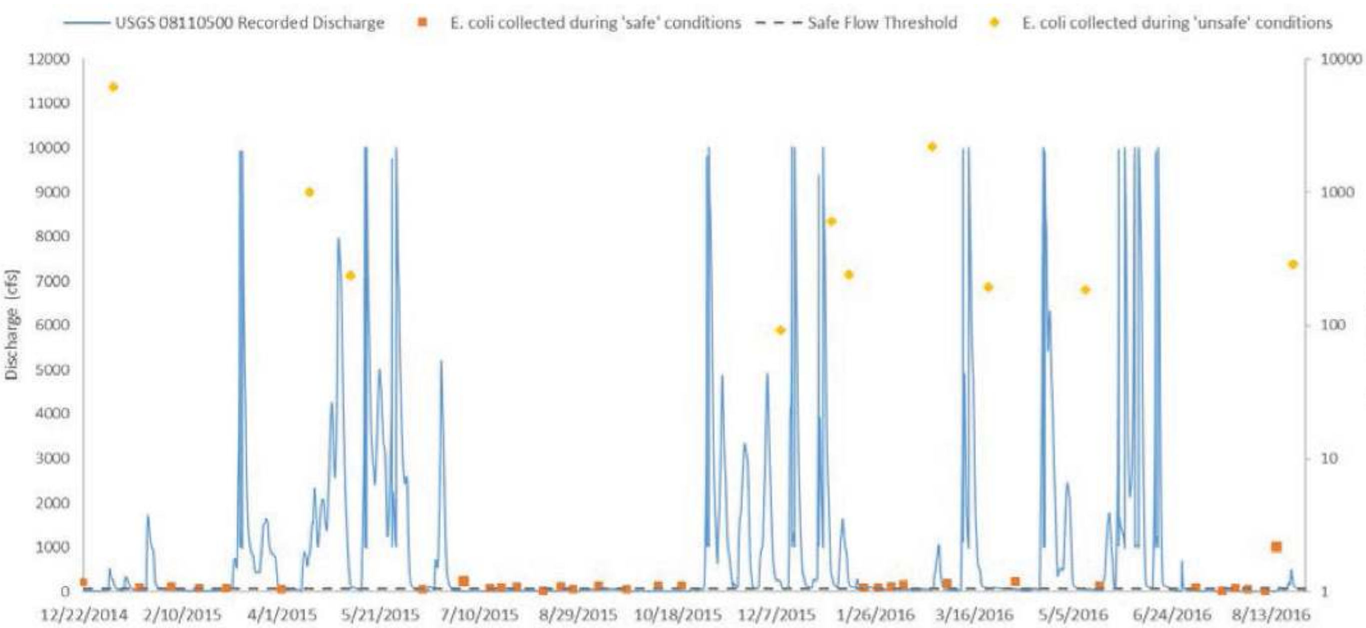

Figure 3. Hydrograph and *E. coli* concentrations at the monitoring station.

death during the activity, thus logic suggests that a slight risk increase for contracting a GI illness is not inappropriate. Implementing less restrictive water quality standards during natural high-flow conditions is likely to adequately protect human health without imparting excessive financial burden to have surface waters meet the most stringent standards under all flow conditions.

A practical option for establishing an alternative contact use category that is applicable for more dangerous flow conditions combines flow rate-based thresholds and risk-based approaches. This will necessitate site-specific criteria establishment but allows more appropriate water quality standards to be selected based on actual use. Utilizing site-specific criteria requires detailed analysis of recreational uses of a waterbody, which is not currently conducted. This is an additional data collection burden required before site-specific criteria could be established or implemented. Waterbodies also change throughout their course, thus it makes sense to evaluate standards at refined scales within streams to ensure that standards are individually relevant and not overly broad. Flow rate-based standards can be used in situations where multiple uses occur at varying flow conditions. Under normal or safe flow conditions, primary contact uses may occur; but under higher flow conditions, these uses become unsafe and are replaced by extreme uses like whitewater sports. Site-specific knowledge can be used to determine a flow threshold where swimming and wading become unsafe. In Texas, surface water quality monitoring procedures prohibit wading in streams where depth multiplied by velocity is ≥ 10 ft^2/s (TCEQ 2012), thus an assumption can be made that flows generating area velocities higher than this threshold are not safe for swimming or wading. Once this threshold is established, the primary contact 1 standard would only apply to water quality samples collected below this flow threshold and excludes values collected above that level. The less restrictive standard applicable for flow conditions supporting extreme water sports should apply for all flow conditions including those above the flow threshold for safe flow conditions. Effectively, this standard applies for all contact recreation uses, but acknowledges the fact that natural hydrologic processes likely result in temporarily reduced water quality.

A risk-based approach to establishing alternative water quality standards can be used to set appropriate risk levels for differing thresholds. This approach considers the number of individual contact recreating on an annual basis. Improvements documenting the quantity of contact uses and the flow conditions when they occur are necessary. For example, if 5,000 individuals swim in a waterbody in a given year under normal flow conditions and only 50 individuals engage in extreme whitewater sports under high-flow conditions, separate standards can be established to allow acceptable *E. coli* concentrations in the waterbody. Current primary contact 1 standards described above predict an illness rate of 36 people per 1,000 individuals.

At the assumed number of swimmers listed above and the primary contact 1 standard, 180 individuals per year may become ill. However, only 1.8 individuals of the extreme sports group may become ill at the same water quality threshold due to the difference in amount of users. Increasing the water quality threshold for high-flow conditions to the secondary contact 1 use standard (630 cfu/100 mL) and applying it to individuals engaged in extreme sports results in 3.27 ill individuals out of the same 50 individuals during this one-year period. Translated to *E. coli* concentrations reported for safe and unsafe flow conditions and assumed number of recreators, the expected number of illnesses are 164 and 3.09, respectively. This is a nominal illness increase relative to the increase in allowable *E. coli* concentrations in all flow conditions.

Similarly, when evaluated using QMRA techniques, the estimated human health risks did not greatly differ between activities and flow conditions when using less stringent water quality standards. QMRA point value estimation provides a broad idea of risks across the assumed recreational scenarios. For primary contact recreation (swimming, wading by children) in safe flow conditions (assuming a geometric mean of 106.4 cfu/100mL) with treated wastewater as the contaminant source, the risk of a GI illness was estimated to be 4.8×10^{-4}. Whitewater type recreation activities occurring during unsafe flow conditions (using a geometric mean of 510.4 cfu/100mL) and primarily raw sewage influent as the contaminant source, the estimated risk for a GI illness would be 7.2×10^{-6}. The risk estimates should only be considered "back of the envelope" and an initial starting point for further risk assessment work that considers safe and unsafe flow conditions and their appropriate activities. Results do suggest that the risk of boating/kayaking/canoeing/rowing (and potentially capsizing) in water that exceeds current water quality standards may not pose as much of a risk for a GI illness as previously considered, especially considering the lower frequency of those uses.

Conclusions

The Navasota River provides a case study representative of many low-use waterbodies. Its water quality is currently impaired under the required primary contact 1 standard. Recent waterbody use assessment indicates that primary contact uses occur, but at low frequencies. No instances of use during high-flow conditions were observed or noted in surveys. Application of risk estimates by flow condition demonstrates that the expected number of individuals potentially becoming ill is considerably smaller for unsafe than safe flow conditions due in part to the smaller number of individuals engaged in recreation.

Grouping water quality data by flow threshold revealed significantly different mean *E. coli* concentrations, which suggests that altering water quality standards application as a result of changes in stream flow may not have a detrimental effect on human health protection. This approach requires more site-specific data collection prior to establishing flow rate-based thresholds and associated numeric criteria; however, it may reduce the number of impaired waterbodies by more accurately characterizing their use and allowing an appropriate standard to be selected. We realize that this is not a simple or perfect process, but it is one that has potential to reduce management and restoration costs in waterbodies where significant primary contact uses do not occur at all flow conditions. This allows natural hydrological processes to occur that would prevent waterbodies from fitting into traditional standards categories based on use without causing water quality impairments.

It is not the intent of this paper to promote water quality standards reductions but instead to propose an alternative application of current standards based on actual uses. Stringent standards are important for protecting public health and conserving natural waters; however, water quality standards should incorporate the best available science and acknowledge different levels and types of use that occur. Implementing variable condition standards will not compromise mandates to protect public health, but will support a targeted and reasonable approach that allows limited restoration resources available to be applied in critical areas.

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