A Systematic Framework to Identify and Prioritize Sources of Bacteria

SWWT Bacteria Working Group
UWM-School of Freshwater Sciences
9-26-17

Many Sources of Contaminants	
Contaminant	**Potential Sources**
Sediment and Floatables	Streets, lawns, driveways, roads, construction activity, atmospheric deposition, drainage channel
Pesticides and Herbicides	Residential Lawns and gardens, roadsides, utility right-of-ways, commercial and industrial landscape areas, soil wash off
Organic Materials	Residential Lawns and gardens, commercial landscaping, animal wastes
Metals	Automobiles, bridges, atmospheric deposition, industrial areas, soil erosion, corroding metal surfaces, combustion processes
Oil and Grease / Hydrocarbons	Roads, driveways, parking lots, vehicle maintenance areas, gas stations, illicit dumping to storm drains
Bacteria and Viruses	Lawns, roads, leaky sanitary sewer lines, sanitary sewer cross-connections, animal waste, septic systems
Nitrogen and Phosphorus	Lawn fertilisers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, detergents

USEPA. 1999

Concentrations of pollutants in stormwater runoff from selected urban source areas

Source	Total Phosphorus (mg/l)	Solids (mg/l)	*E. coli* (cfu/100ml)	Zinc (µg/l)	Cadmium (µg/l)	Copper (µg/l)
Residential	1.31	662	92,000	220	0.8	46
Residential	1.07	326	56,000	339	1.4	56
Commercial	0.47	232	9,600	508	1.8	46
Industrial	1.50	763	8,380	479	3.3	76
Industrial	0.94	690	4,600	575	2.5	74
Residential Roofs	0.15	27	290	149	ND	15
Commercial Roofs	0.20	15	1,117	330	ND	9
Industrial Roofs	0.11	41	144	1,155	ND	6
Residential Lawns	2.67	397	42,000	59	ND	13
Driveways	1.16	173	34,000	107	0.5	17
Commercial Parking	0.19	58	1,758	178	0.6	15
Industrial Parking	0.39	312	2,705	304	1.0	41

Bannerman et al, 1993

Developing a Study Design

1) Collect and examine historical data
2) Identify data gaps and collect additional data as needed
3) Analyze data
4) Identify causes and sources of pollution that need to be controlled
5) Estimate relative contributions
6) Identify solutions
7) Implement remedial measures

Collect & Examine Historical Data

- Comparable data can be combined with future data
  - Dependent on quality/quantity
- Historical data will reveal trends or correlations between the target and the explanatory variables
- Data can guide future assessment needs

Identify Gaps/Collect Additional Data

- A thorough examination of historical data will reveal whether or not critical information is lacking
- An evidentiary, science-based decision is critical to successful mitigation
- Data collected as part of the investigative process can also serve as a baseline from which to benchmark future improvements

Analyze Data

- Relationships between dependent (target) and independent (explanatory) variables
- Rule in and rule out potential sources
- Identifying when/where/how pollution sources adversely impact water quality
  - e.g. wet vs. dry weather mediated
- Relationships do not imply causation but can be used as evidentiary support

Identify Causes/Sources of Pollution

- Data analysis leads to the association of measured parameters or conditions to the dependent variable
  - Typically faecal indicator bacteria concentrations in a receiving water body
- Associations provide clear lines of evidence for one action over another as part of a decision tree approach.

Estimate Relative Contributions

- Examining lines of evidence determines the strongest associations
  - Relative contributions
- Estimating relative contributions at sites with multiple sources will target future or additional monitoring needs
- Direct solutions towards alterations that will have the greatest relative impact

Identify Solutions

- Solutions should be site-specific
- Based on a critical review of historical and recent monitoring data and field assessments
- Take into account how the resource is used
  - cultural convention, finance, and feasibility
- Hard and/or naturalised engineering approaches should be considered and the merit of each explored

Implement Remedial Measures

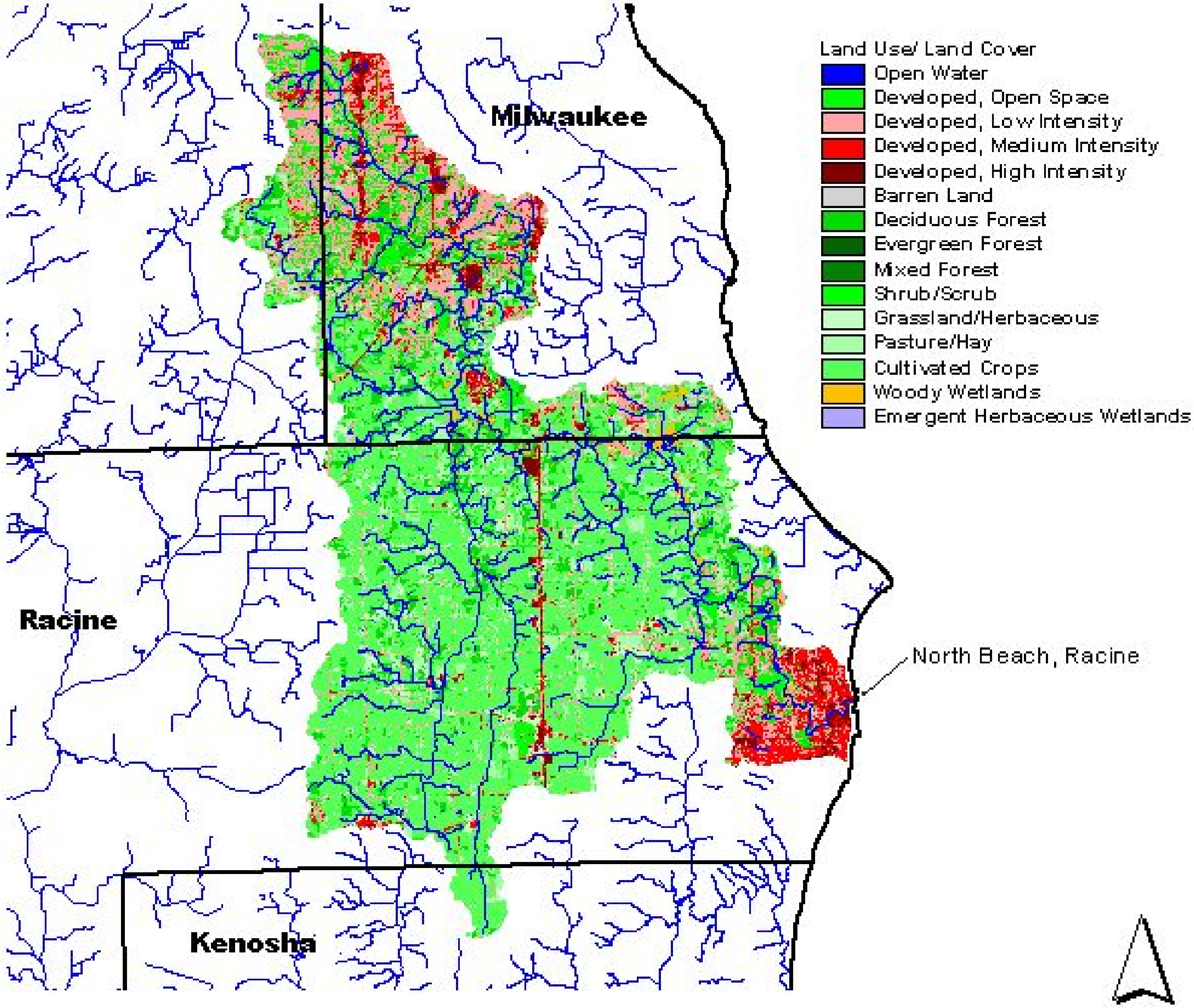
- Once viable solutions have been identified, plans to mitigate identified pollution sources can be developed
- Plans must gain approval in order for implementation to occur
- Revisions to the original plans may be necessary
- Trade offs between the ideal and acceptable solutions may be required

Purpose of Watershed Studies

- Expand upon historic Root River monitoring conducted by the Racine Health Department
- Assemble a comprehensive database of water quality data which could be used as a baseline from which to gauge improvements
- Contribute to the development of a watershed restoration plan
- Provide science-based data to target remediation
- Link Root River water quality to coastal water quality

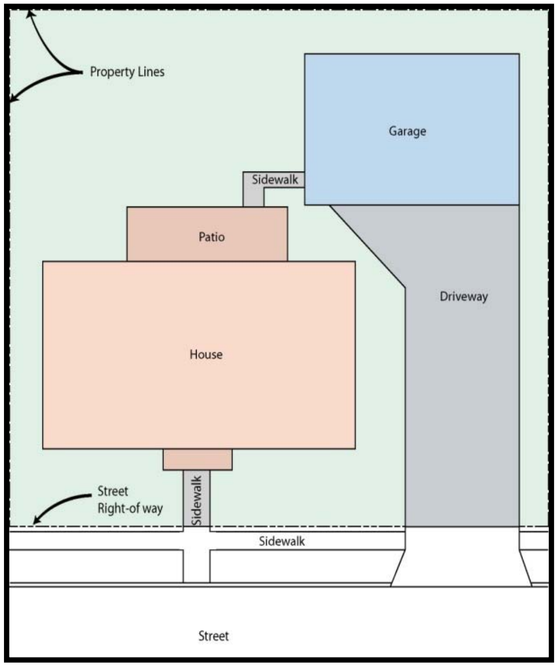
Over 1.6 million residents from Kenosha, Milwaukee, Racine and Waukesha Counties interact with and impact the watershed on a daily basis

Land Use – Root River Watershed



Impacts of Urbanization

Racine Storm Water Utility

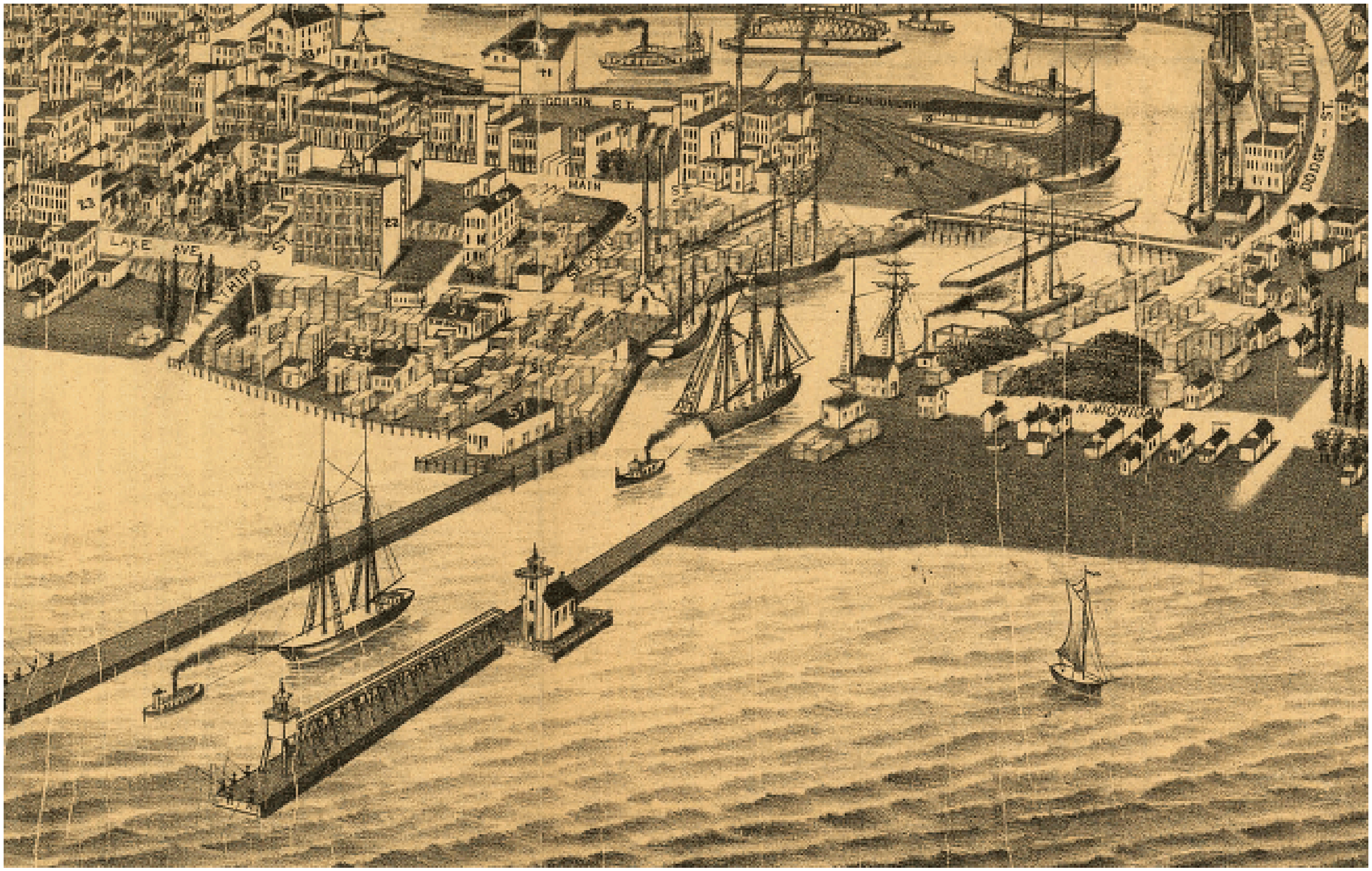


Residential Average Impervious Area = 2,844 square feet (or 1 Equivalent Residential/Runoff Unit (ERU))

Downtown Customer Example

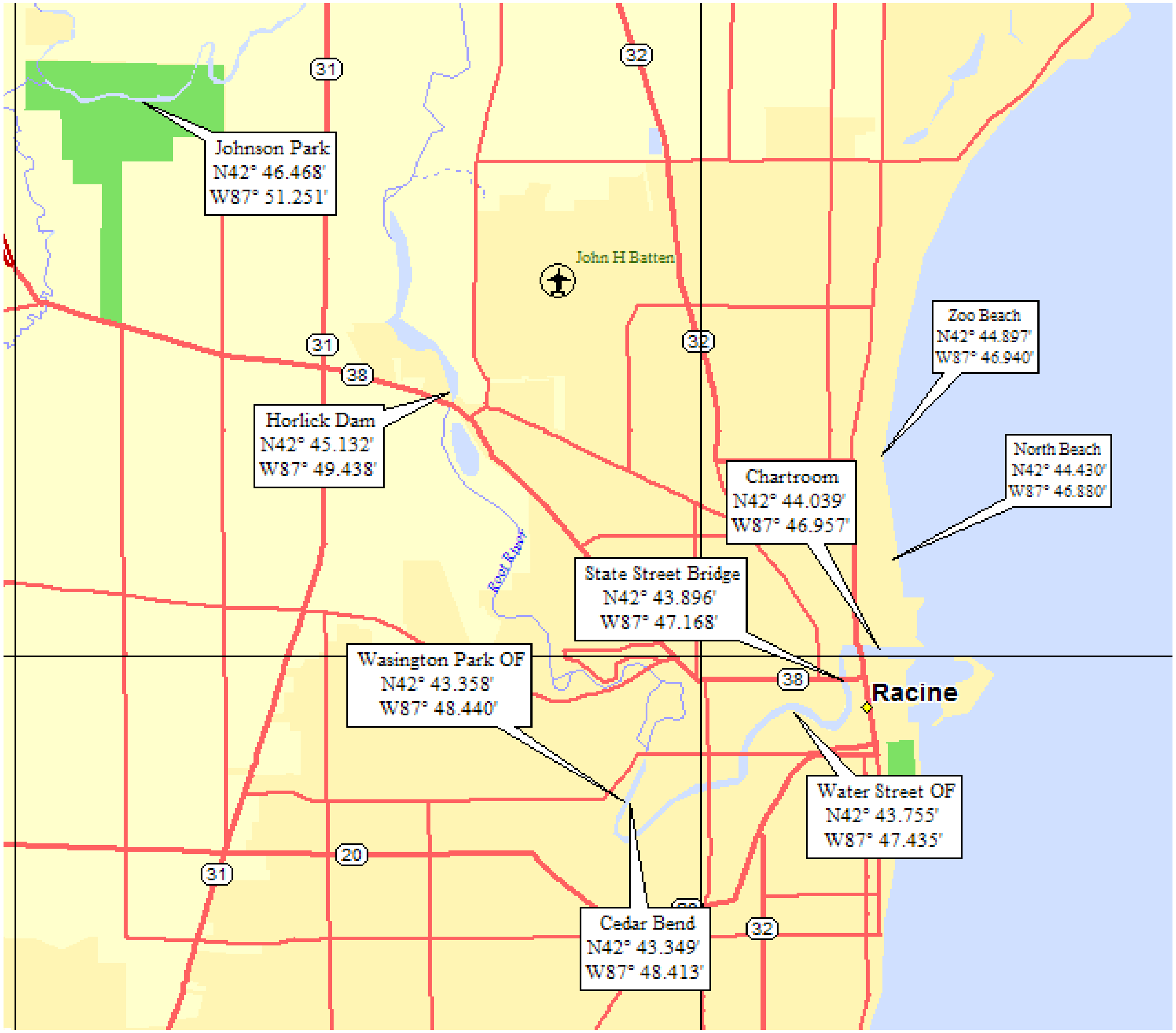
Industrial Customer Example

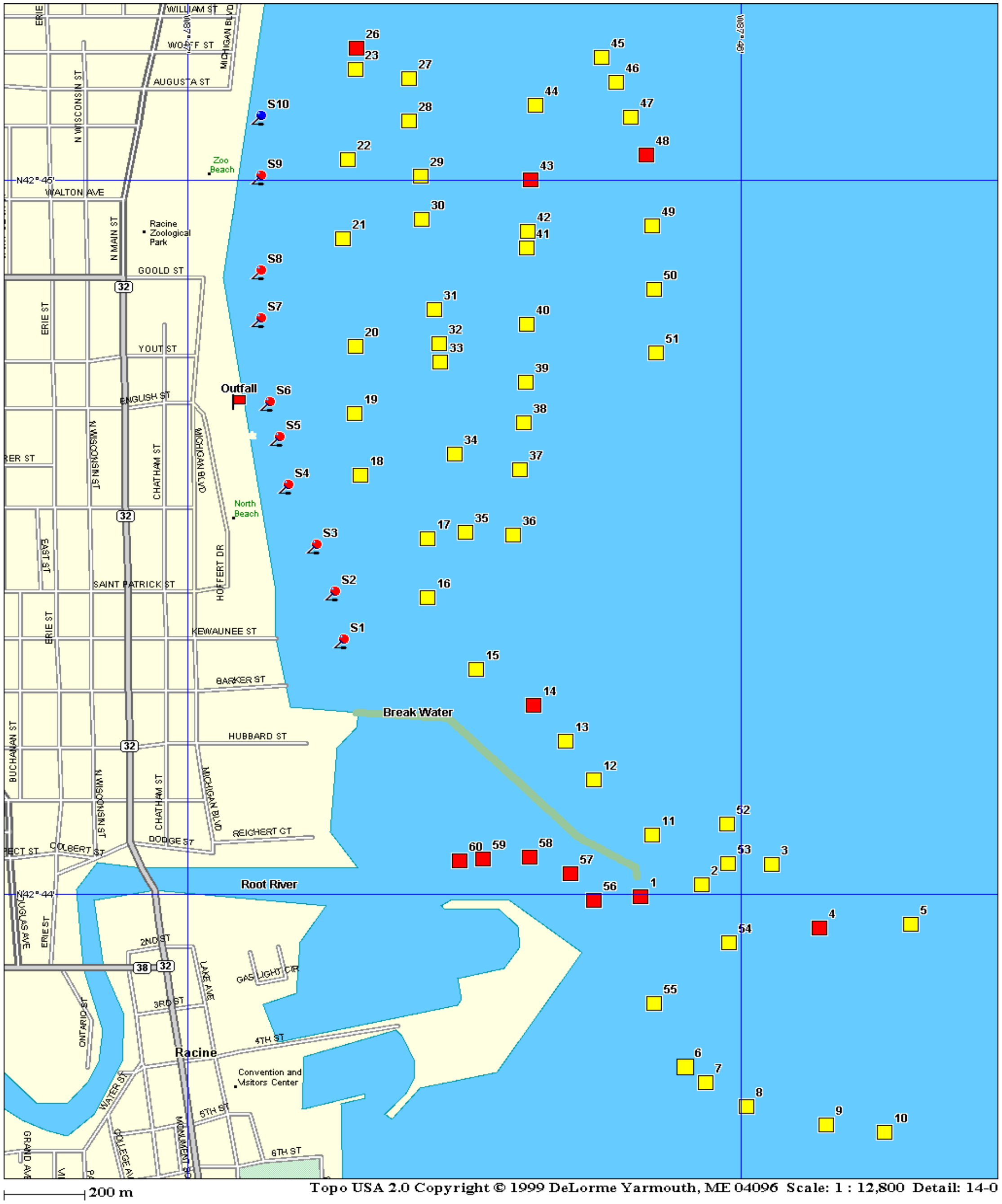
Historic Monitoring



Mouth of Root River c. 1883, Racine Heritage Museum

Racine had 7 Monitoring Stations





<u>2004 Spatial Distribution Study</u>

80 samples by wading or boat

Pre-rainfall, Rainfall, and Post-rainfall samples

Look for elevated levels of *E. coli*

Definite plume from the Root River

Root River *E. coli* Densities – 2004		
SITE	MEAN *E. coli* MPN/100 ml	RANGE
Johnson Park (R1)	1518	10 – 14,136
Horlick Dam (R2)	1431	10 – 12,997
Cedar Bend (R3)	3705	0 – 12,997
Washington Park Storm Outlet (R4)	38,856	0 – 198,628
Water Street Storm Outlet (R5)	18,020	100 – 173,287
State Street Bridge (R6)	1372	63 – 11,199
Chartroom (R7)	1098	20 - 9804

Identifying Sources of Pollution

- Physical Assessments
- Sanitary Surveys (guided data collection)
- Source Tracking

2008 Site Survey

Site: Island Park footbridge behind Racine Lutheran High School

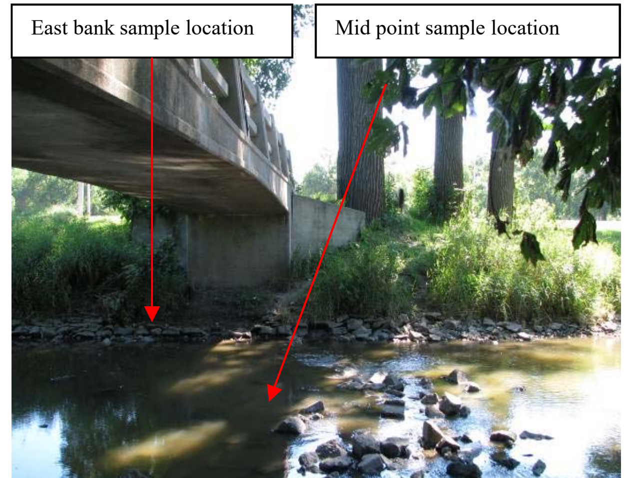
Location and surrounding area:
Located on the western branch of the river which splits around Island Park. Land to the west is residential and to the east is open space/parkland (mainly grass).

Stream bank conditions
Stream banks are in good condition with recent restoration work undertaken on the east bank adjacent to site and approximately 120m u/s (after 2005 Earth Tech stream bank assessment)

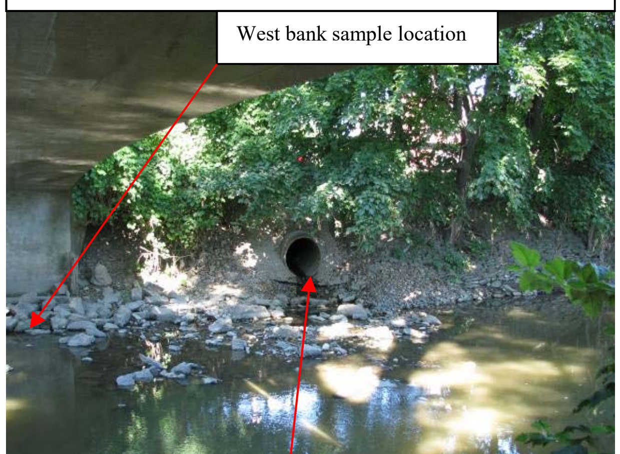
Infrastructure
Outfall (RR17) off Glenn Street adjacent to footbridge and sample locations exhibits a constant DWF.

Other comments:
This outfall is suspected of contributing to the high levels of *E. coli* at the sample site.

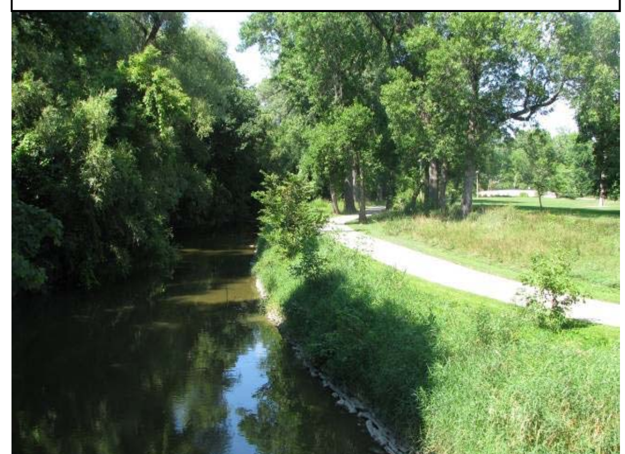
View south, downstream, from the footbridge. Both banks are in good condition.



View from the west bank across to the east bank sample location.



View of the outfall off Glenn Street exhibiting DWF.



View looking north from footbridge at east bank. Conditions = high grass and little sign of erosion.

Looking for Telltale Evidence

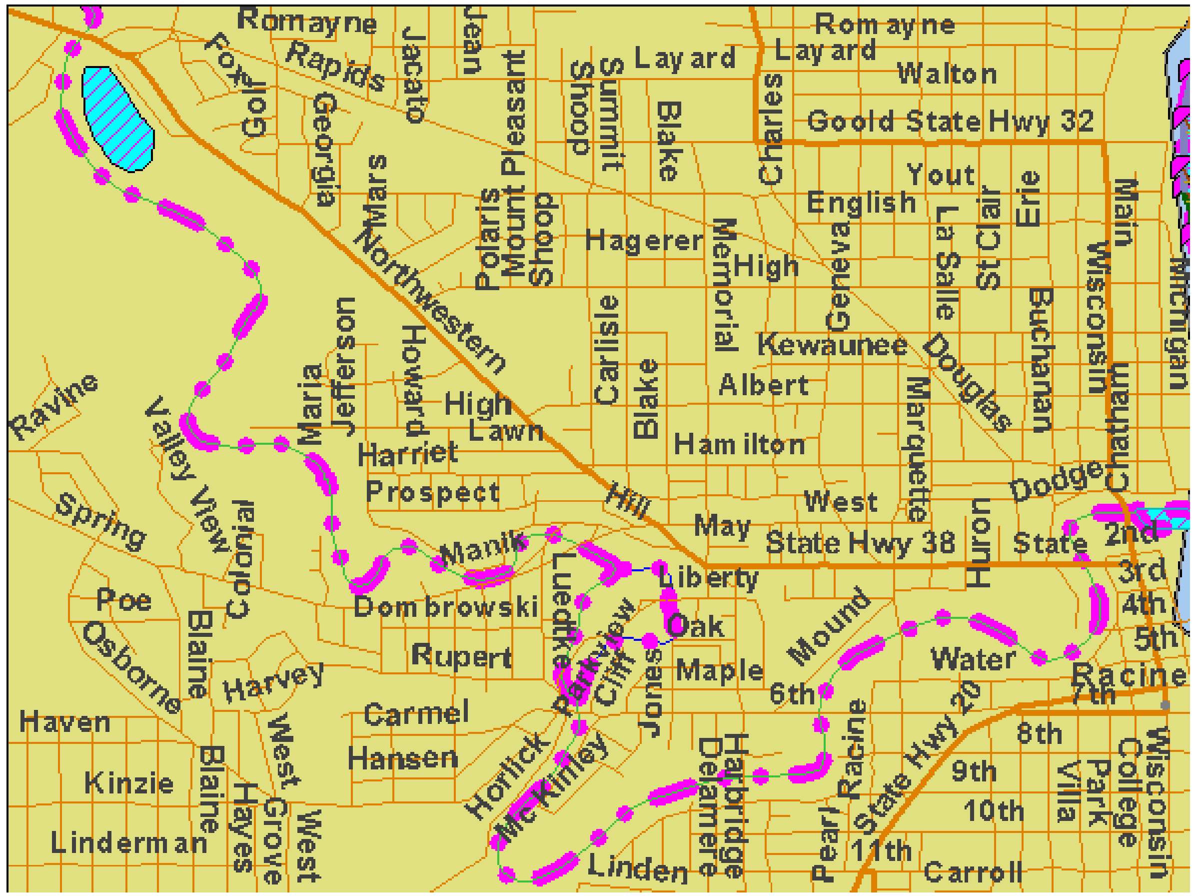
***E. Coli* (MPN/100 ml):**

RR17003 = >241,920
RR17004 (west pipe) = 241,917
RR17002 (north pipe) = 2,780
RR17002 (west pipe) = 30,760
RR17005 = 30,760
Racine Lutheran Outfall = 77,010

Unusual Discharge from SWO

Chemical Indicators

- pH
- Temperature
- Turbidity
- Conductivity
- Detergents
- Chlorine
- Copper
- Phenols
- Nutrients

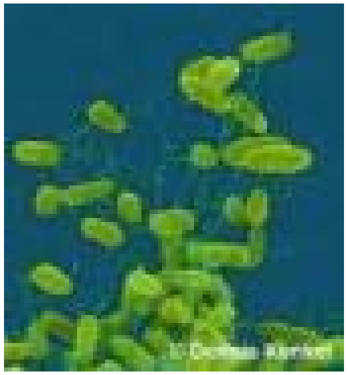


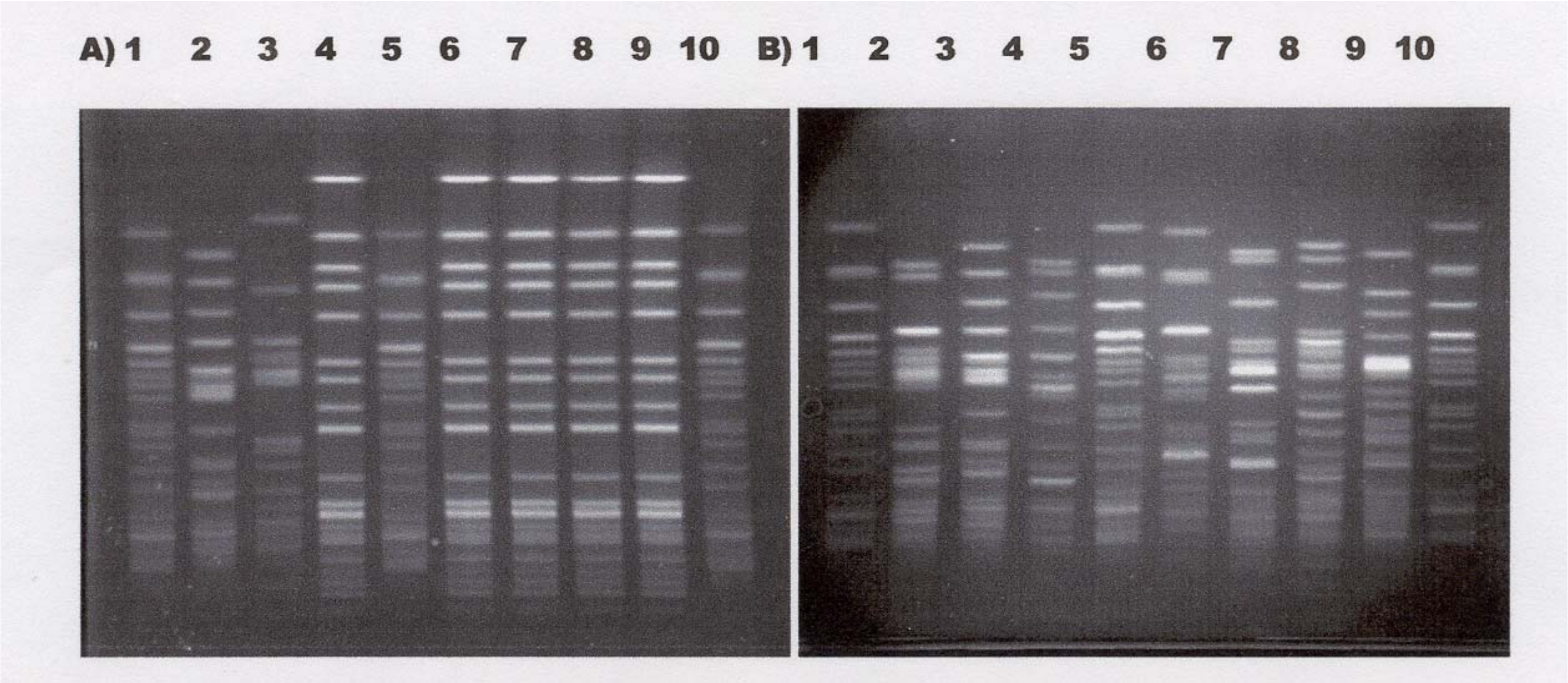
Turbidity vs. Precipitation, 2007-2008						
	Coefficient of determinations [(R^2) left column] and correlation coefficients [(*r*) right column] for combined dry and wet weather data					
PPT	**Group 1 and 2**		**Group 3**		**Group 4**	
24 hr	0.12	0.11	0.56	0.47	0.56	0.75
48 hr	0.28	0.53	0.60	0.44	0.61	0.78

Turbidity vs. Flow Rate, 2007-2008			
	Group 1 and 2	**Group 3**	**Group 4**
R^2	0.65	0.90	0.90
r	0.81	0.95	0.95

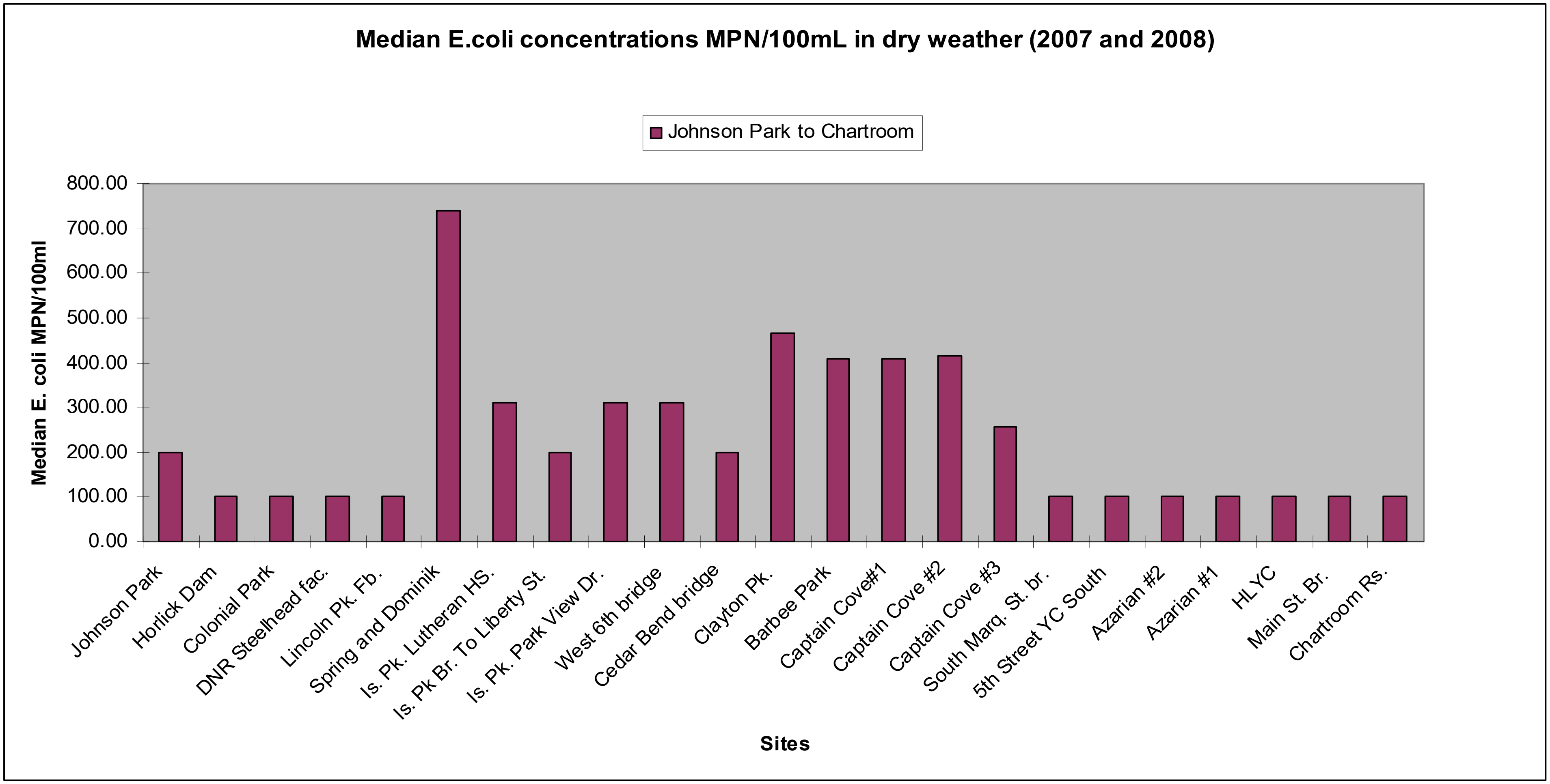
Biological Indicators

- *E. coli*
- Human specific *Bacteroides*
- *Lachnospriaceae*

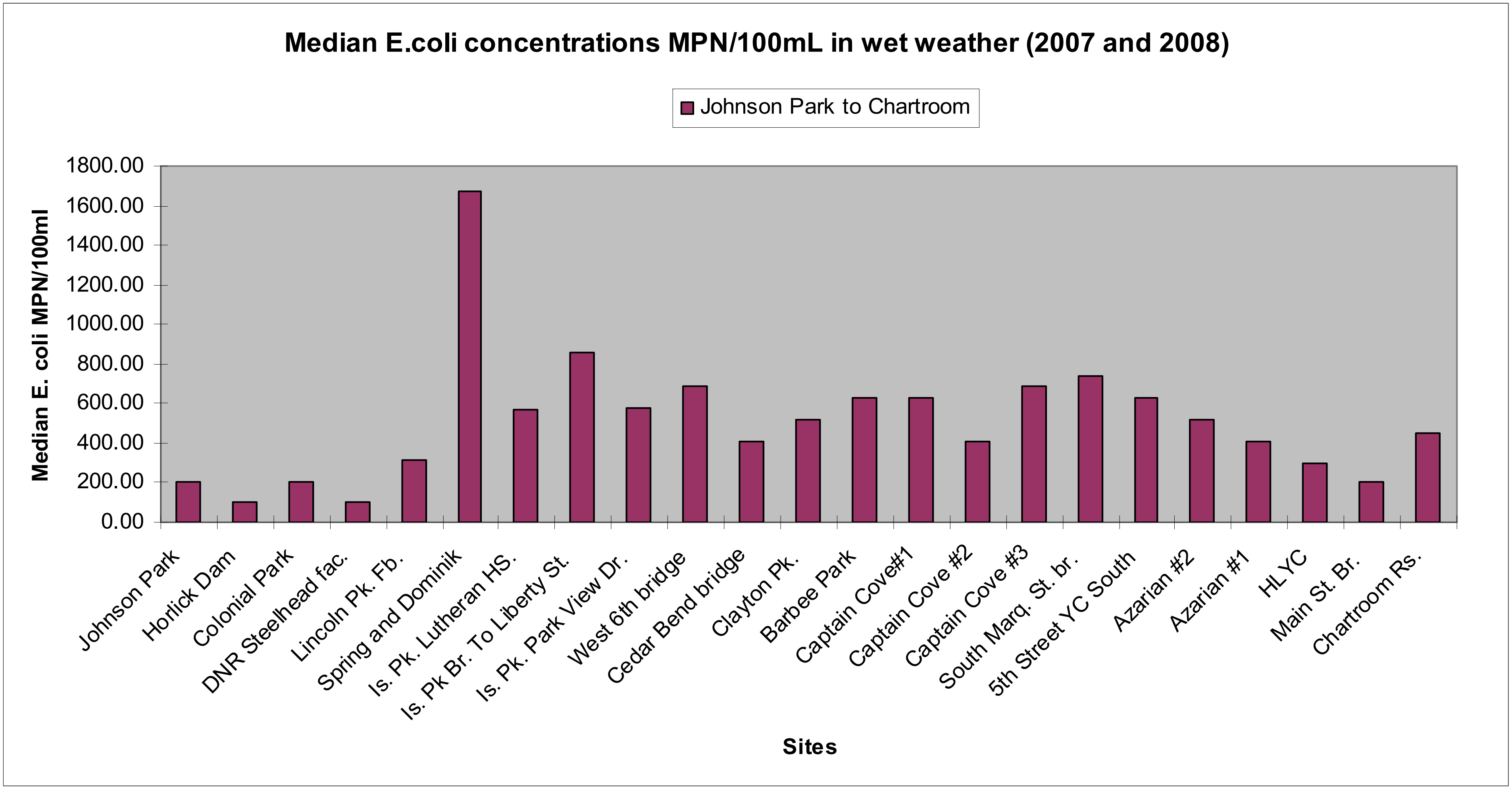


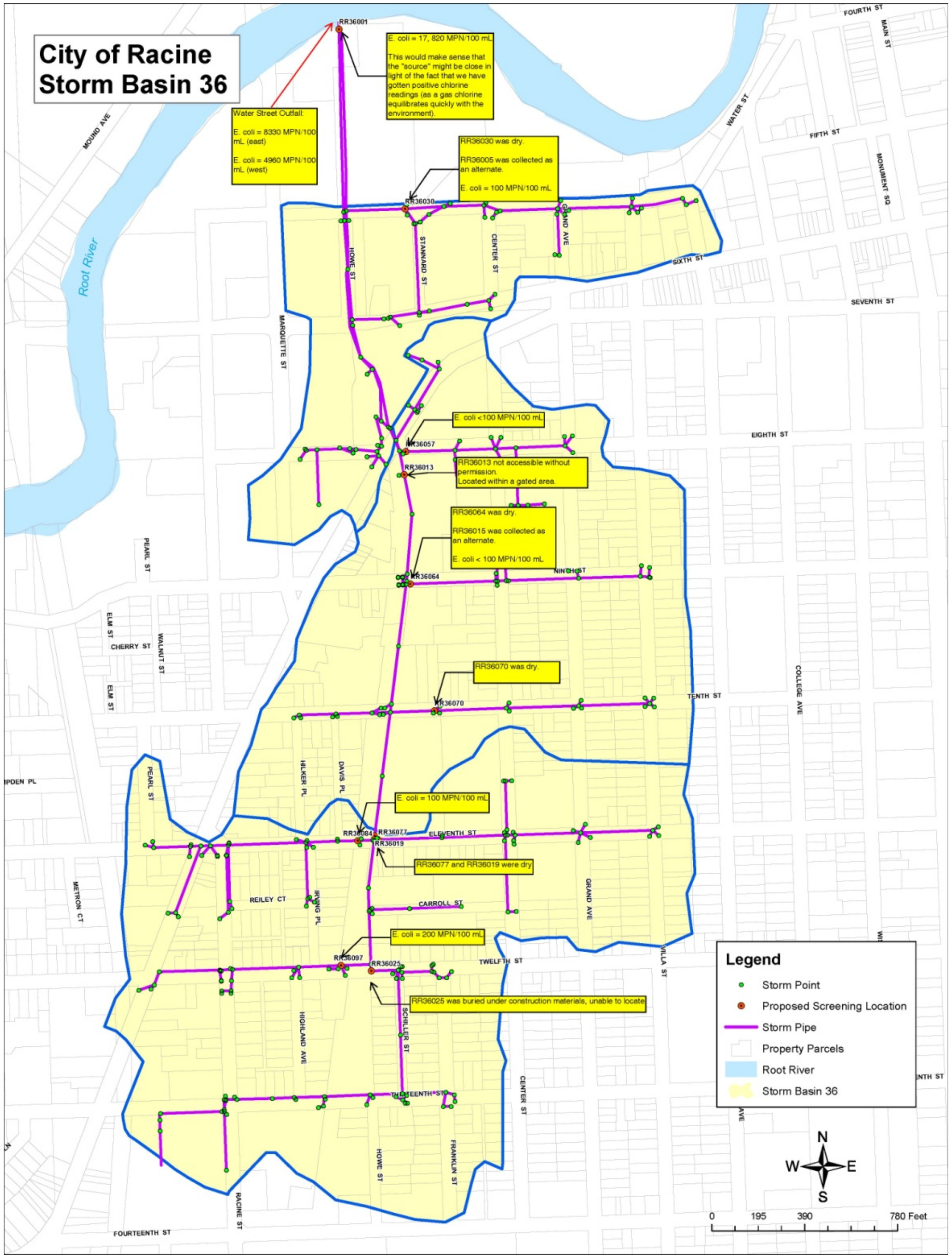


Median *E. coli* (MPN/100ml) upstream to the mouth - dry weather (Root River, 2007 – 2008)



Median *E. coli* (MPN/100ml) upstream to the mouth - wet weather (Root River, 2007 – 2008)



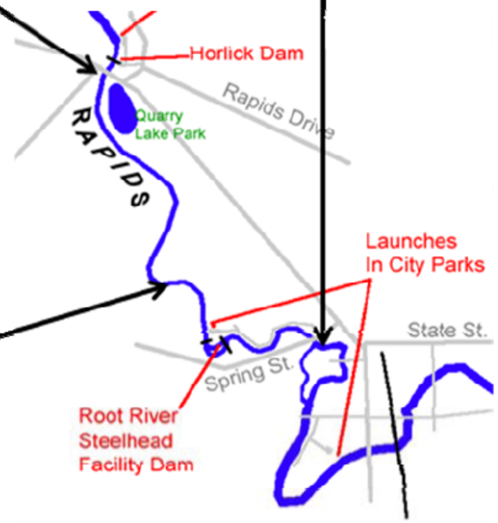


Basin Assessments

Biofilm Assessment

Site 3

Site 1



Site 2

Samples collected from the field demonstrated the presence of *E. coli* DNA in biofilms that developed on sterile surfaces placed in the river. The data from one of the outfalls also indicated the presence of *E. coli* DNA. However, the presence of the *E. coli* DNA in these samples could be from either live or dead cells. The data does suggest that biofilms in the Root River could be a reservoir of *E. coli*. However, more importantly, even though *E. coli* DNA was amplified, no Shiga toxin-producing bacteria were detected in any of the biofilm samples.

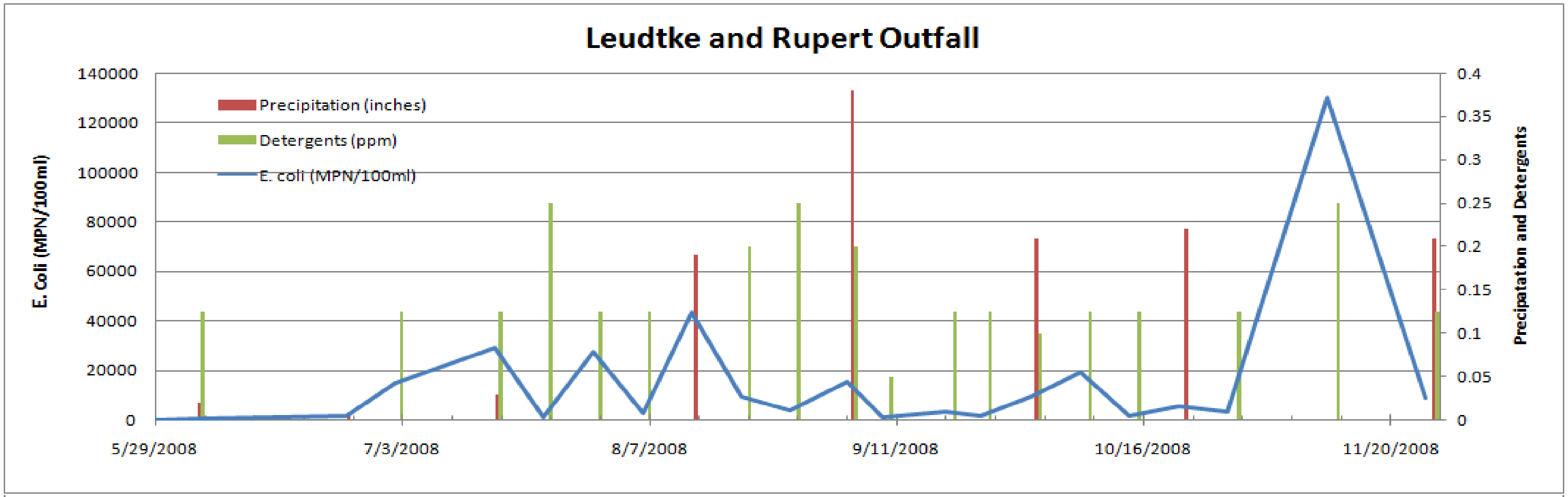
Bacteroides (2010)

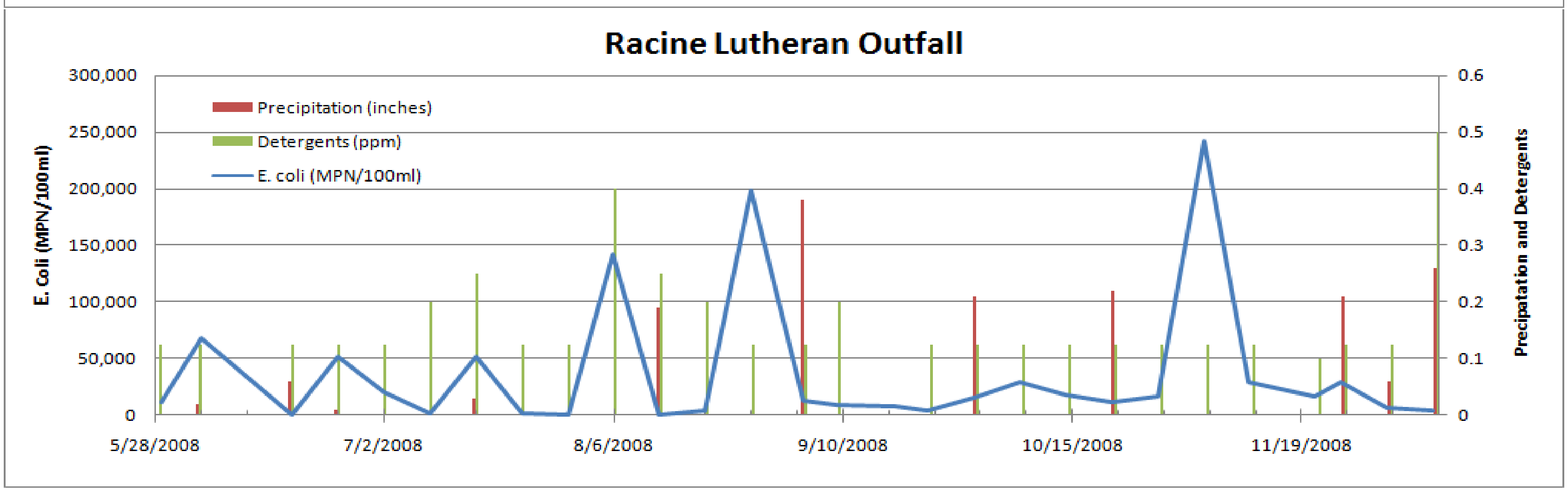
Sample Date	EWS#	Site	Bacteroides Human	Bacteroides Human (CN/100ml)	Total Bacteroides (CN/100ml)	Ratio of Human Bacteroides/Total Bacteroides (%)
5/7/2010	1A	Horlick NW OF	Negative			
5/7/2010	2A	Horlick SW OF	Negative			
5/7/2010	3A	Horlick E OF	Negative			
5/7/2010	4A	Leudtke Off Spring	Negative			
5/7/2010	5A	Racine Lutheran OF	**Positive**	1,855	54,914	3.38%
5/8/2010	1A	Washington Park #2	**Positive**	7,020	67,023	10.47%
5/8/2010	2A	Washington Park #2	**Positive**	2,127	26,032	8.17%
5/8/2010	3A	Washington Park #3	Negative			
5/8/2010	4A	Water St OF W	Negative			
5/8/2010	5A	Water St OF E	Negative			
5/13/2010	IEB	Wetland Outflow	Negative			
5/13/2010	EOF	English St OF	**Positive**	74	20,022	0.37%
6/30/2010	1A	RR16002	**Positive**	4	12,232	0.03%
6/30/2010	2A	RR16005	Negative			
6/30/2010	3A	RR16007	**Positive**	39	17,661	0.22%
6/30/2010	4A	RR16009	**Weak**	7	3,589	0.19%
6/30/2010	5A	RR16012	**Weak**	30	2,375	1.27%
6/30/2010	6A	RR36004	Negative			
6/30/2010	7A	RR36005	**Positive**	386	29,433	1.31%
6/30/2010	8A	RR3601	Negative			
6/30/2010	9A	RR3602	Negative			

The ratio of human bacteroides to total bacteroides in raw sewage is ~2.2 to 8.0 (mean = 5.1) [Dr. Sandra McLellan, UWM WATER Institute]

Summary of storm water outfall results using chemical and microbiological source tracking parameters (2008)

Outfall	Percent exceedance Total samples	Percent exceedance Dry weather	Mean *E. Coli* MPN/100 mL	Max *E. Coli* MPN/100 mL	Mean Chlorine (mg/L)	Mean Detergents (mg/L)
Glen Street	95	52	30,248	141,360	0.002	0.2
Water St. East	93	60	11,611	173,287	0.061	0.2
Leudtke/Domanik	93	52	25,212	241,917	0.006	0.2
Leudtke/Rupert	88	42	14,396	141,360	0.002	0.2
Water St. West	83	45	27,951	241,920	0.098	0.14





Location	Average *E.Coli* (MPN/100ml)	Average Dry Weather *E.Coli* (MPN/100ml)	Average Wet Weather *E. Coli* (MPN/100ml)	Average Detergent concentration (ppm)	Average Dry Weather Detergent Concentration (ppm)	Average Wet Weather Detergent Concentration (ppm)	n_{Dry}	n_{Wet}
Leudtke and Rupert	15200	15700	14300	0.12	0.14	0.08	14	8
Racine Luther Outfall	36200	44500	23400	0.16	0.15	0.18	17	11
Racine Luthern West	2100	1500	3100				18	11
Racine Luthern East	1500	600	3000				18	11

Decision Tree Approach

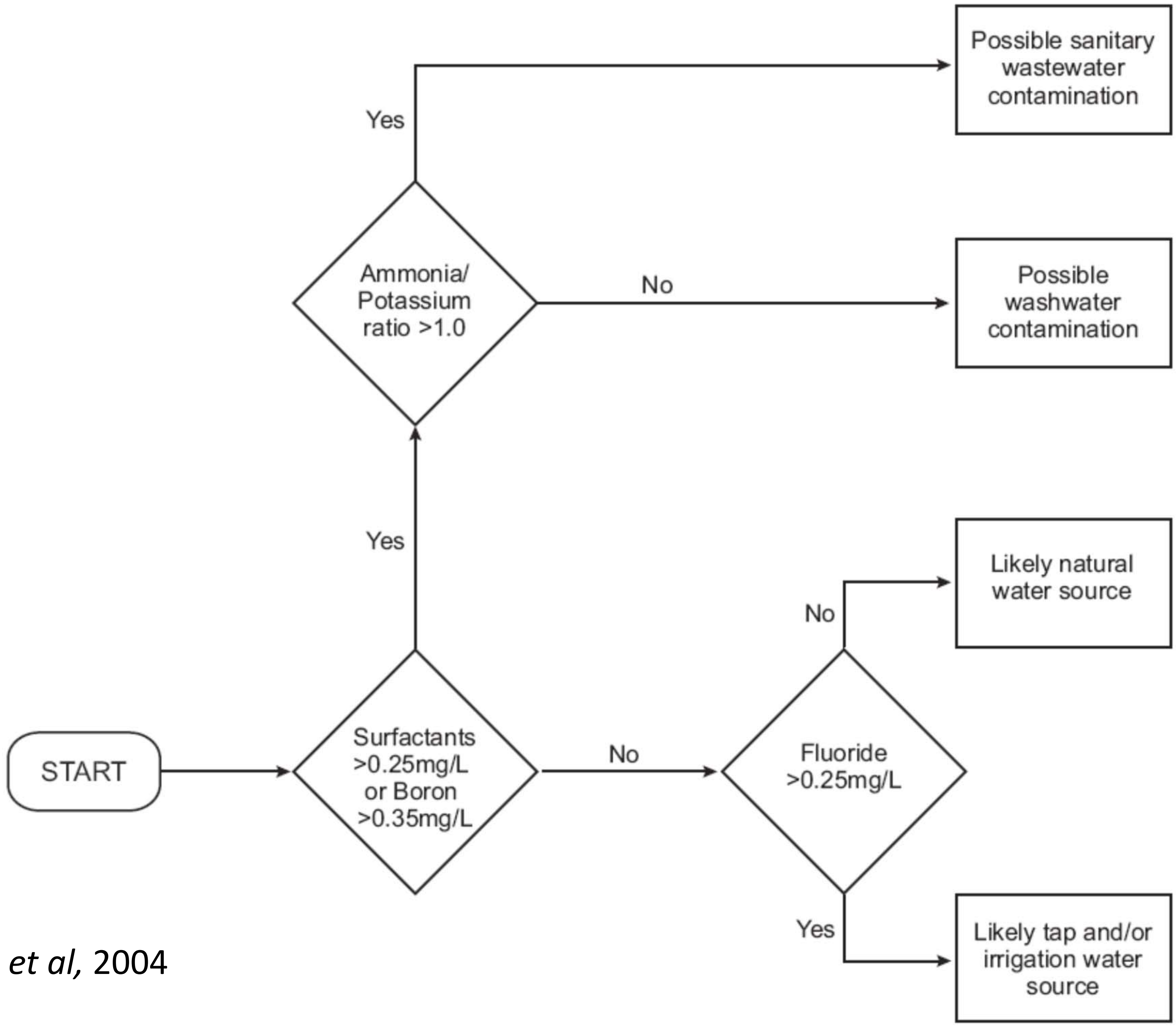
Decision Trees

Decision trees were created by analyzing the physical (extent of stream bank erosion, width of buffer strips, amount of impervious cover, and presence of stormwater infrastructure), microbiological (*E.coli* concentration), and environmental (antecedent precipitation) properties of each sampling location. Each site's path from the root to the leaf was determined by the decision criteria at each node of the decision tree. This method is not as comprehensive as other forms of data analysis; however, it is an informative tool for individuals or communities to begin the process of prioritizing restoration work within the watershed.

Each sampling site was classified as low, medium, medium-high, or high priority for future investigation and/or restoration.

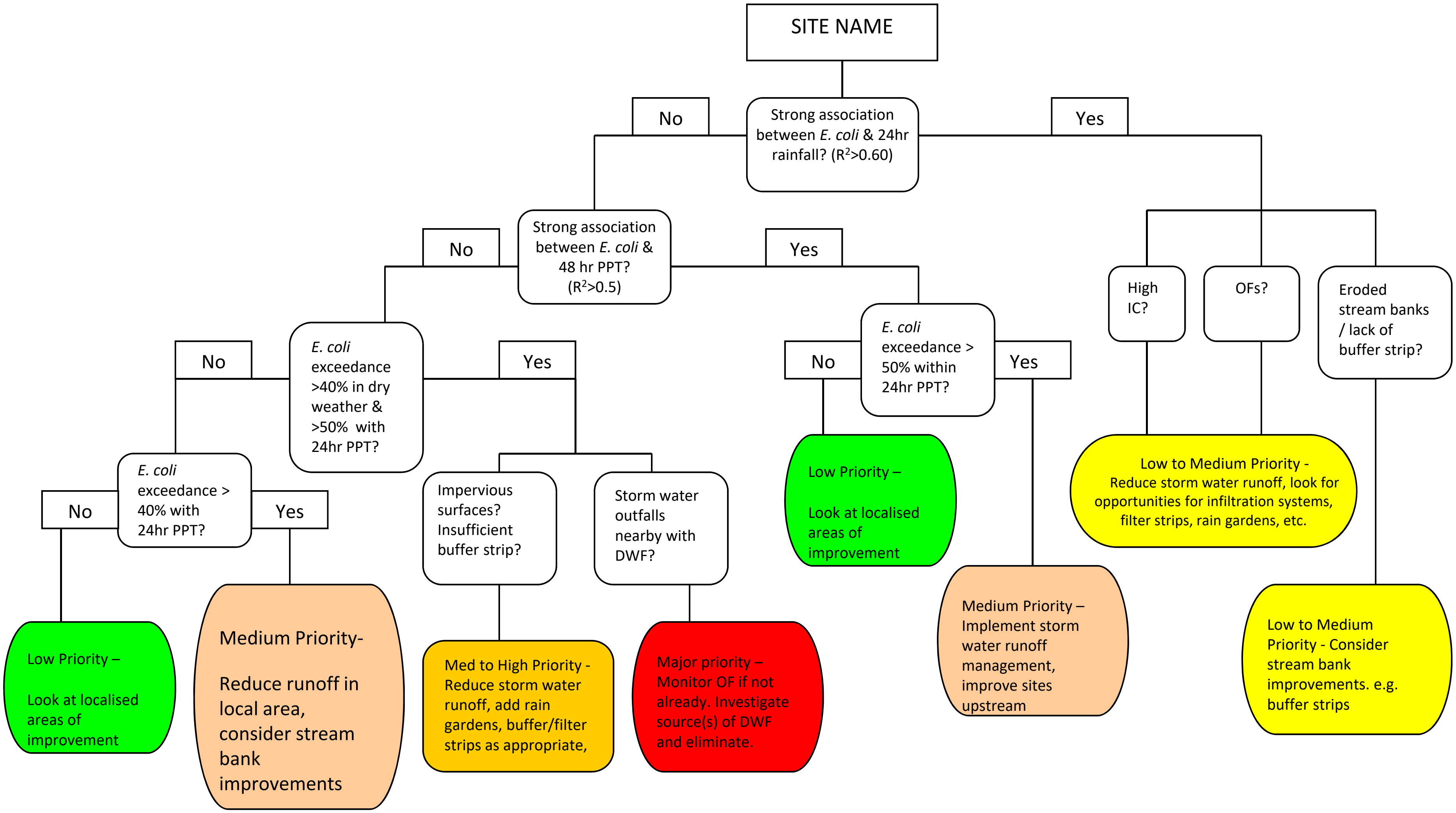
Jozefowski, et al. 2016

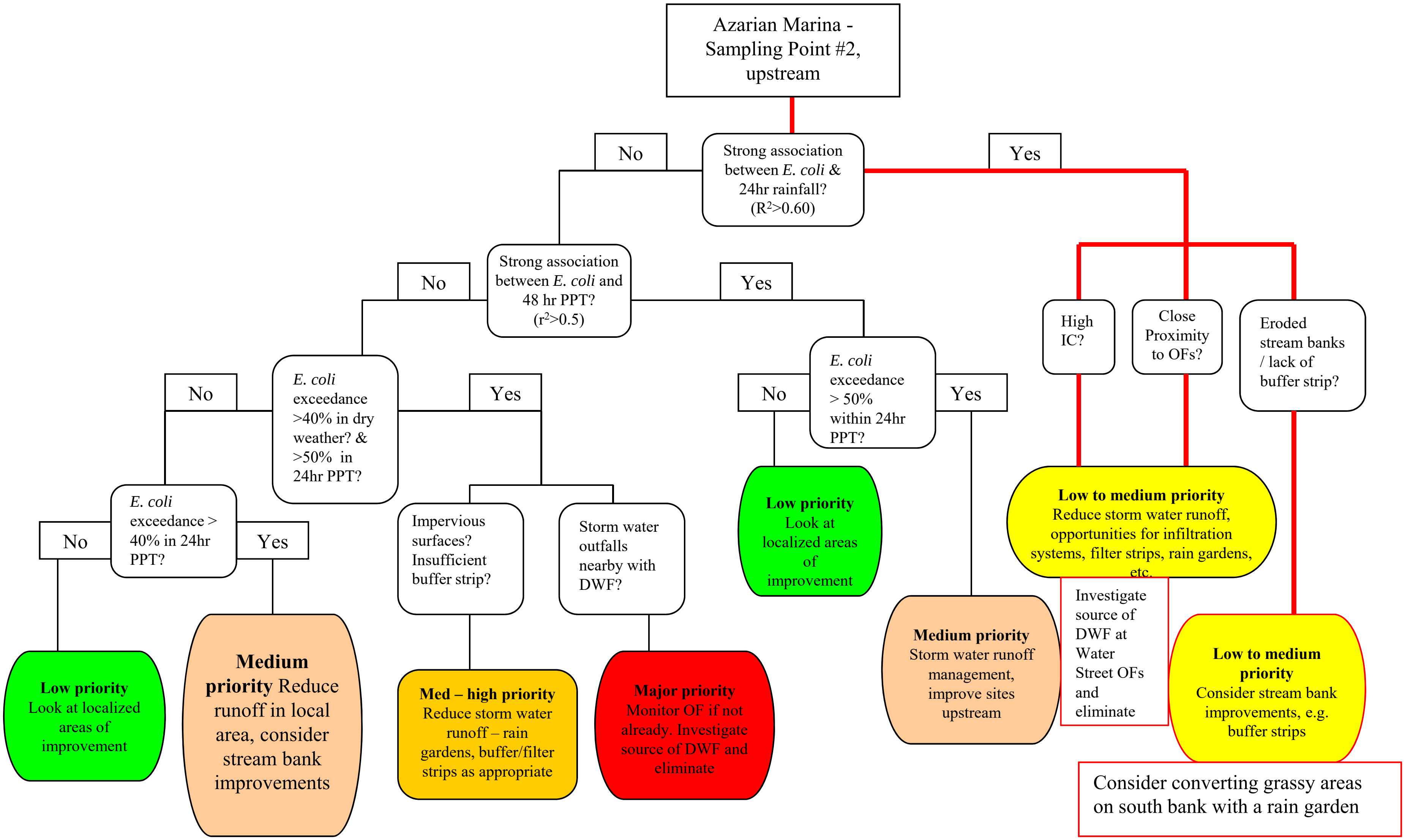
Simplified flow chart to identify significant contaminating sources

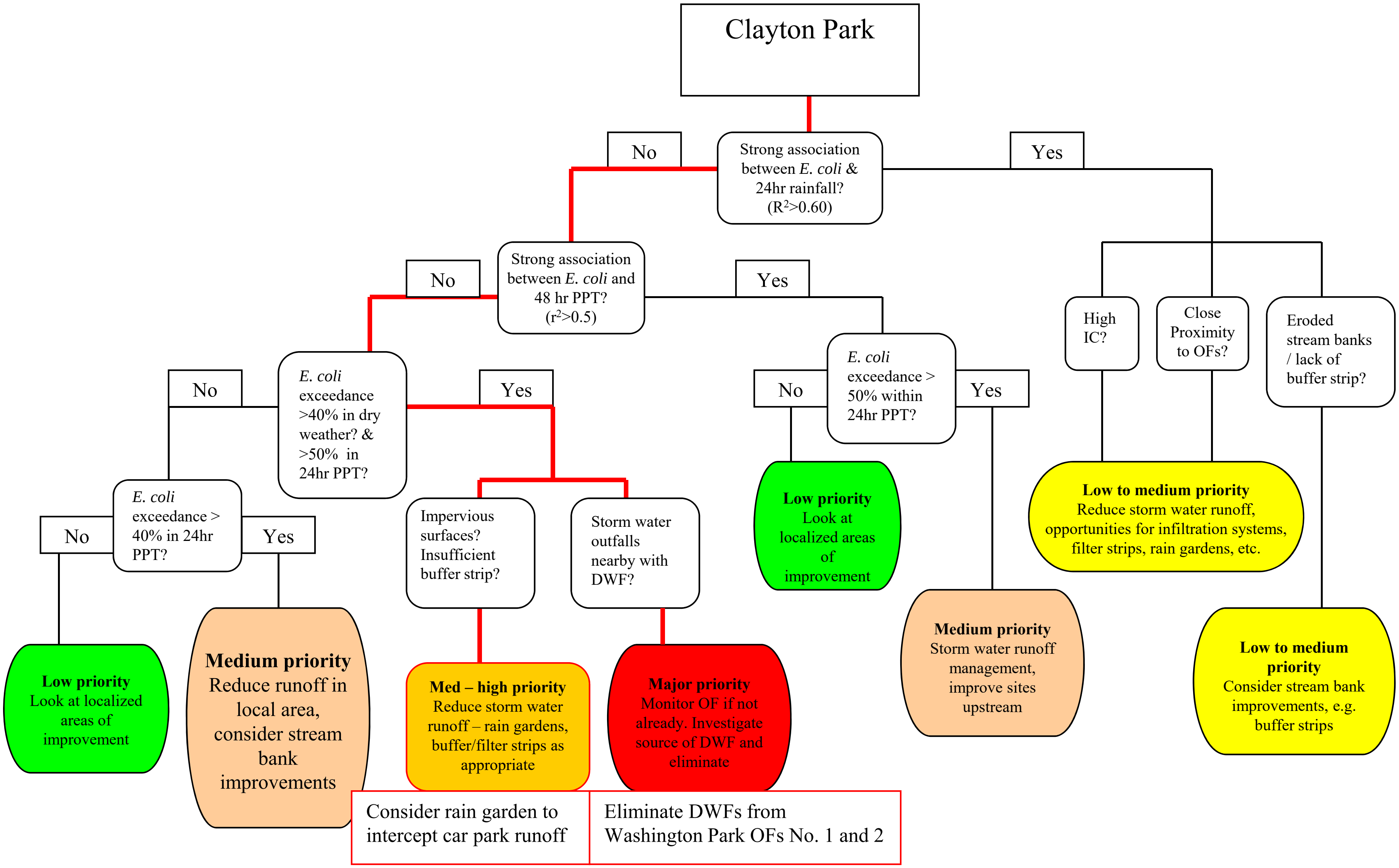


Brown *et al*, 2004

Template decision tree developed from correlation of water quality parameters, environmental parameters and physical assessments

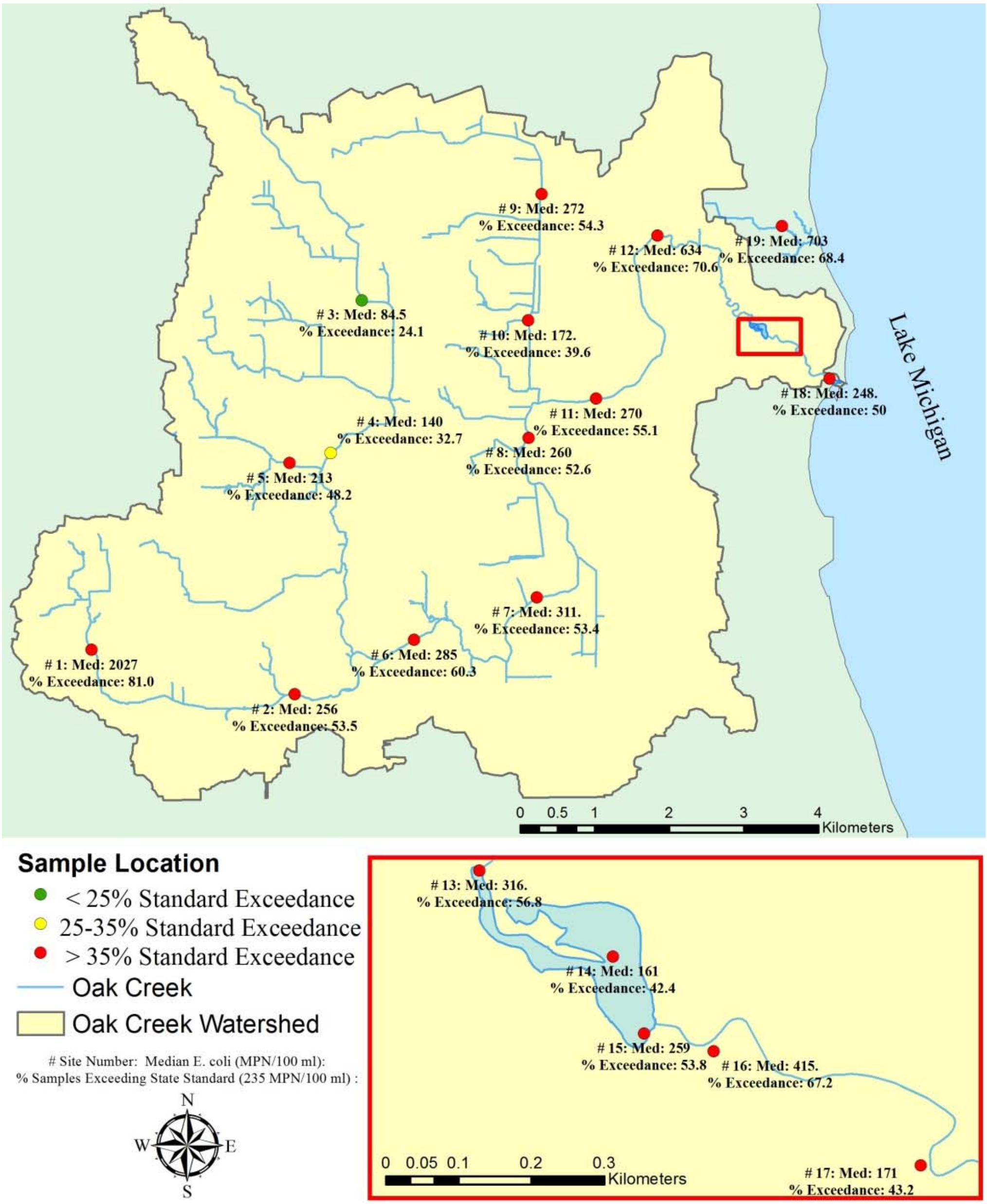



Azarian Marina - Sampling Point #2, upstream
Strong association between E. coli & 24hr rainfall? (R2>0.60)
No
Yes
Strong association between E. coli and 48 hr PPT? (r2>0.5)
No
Yes
E. coli exceedance >40% in dry weather? & >50% in 24hr PPT?
No
Yes
E. coli exceedance > 40% in 24hr PPT?
No
Yes
Low priority Look at localized areas of improvement
Medium priority Reduce runoff in local area, consider stream bank improvements
Impervious surfaces? Insufficient buffer strip?
Storm water outfalls nearby with DWF?
Med – high priority Reduce storm water runoff – rain gardens, buffer/filter strips as appropriate
Major priority Monitor OF if not already. Investigate source of DWF and eliminate
E. coli exceedance > 50% within 24hr PPT?
No
Yes
Low priority Look at localized areas of improvement
Medium priority Storm water runoff management, improve sites upstream
High IC?
Close Proximity to OFs?
Eroded stream banks / lack of buffer strip?
Low to medium priority Reduce storm water runoff, opportunities for infiltration systems, filter strips, rain gardens, etc.
Investigate source of DWF at Water Street OFs and eliminate
Low to medium priority Consider stream bank improvements, e.g. buffer strips
Consider converting grassy areas on south bank with a rain garden


Clayton Park
Strong association between E. coli & 24hr rainfall? (R^2>0.60)
No
Yes
Strong association between E. coli and 48 hr PPT? (r^2>0.5)
No
Yes
High IC?
Close Proximity to OFs?
Eroded stream banks / lack of buffer strip?
E. coli exceedance >40% in dry weather? & >50% in 24hr PPT?
No
Yes
E. coli exceedance > 50% within 24hr PPT?
No
Yes
E. coli exceedance > 40% in 24hr PPT?
No
Yes
Impervious surfaces? Insufficient buffer strip?
Storm water outfalls nearby with DWF?
Low priority Look at localized areas of improvement
Low to medium priority Reduce storm water runoff, opportunities for infiltration systems, filter strips, rain gardens, etc.
Medium priority Storm water runoff management, improve sites upstream
Low to medium priority Consider stream bank improvements, e.g. buffer strips
Low priority Look at localized areas of improvement
Medium priority Reduce runoff in local area, consider stream bank improvements
Med – high priority Reduce storm water runoff – rain gardens, buffer/filter strips as appropriate
Major priority Monitor OF if not already. Investigate source of DWF and eliminate
Consider rain garden to intercept car park runoff
Eliminate DWFs from Washington Park OFs No. 1 and 2

Another Example…

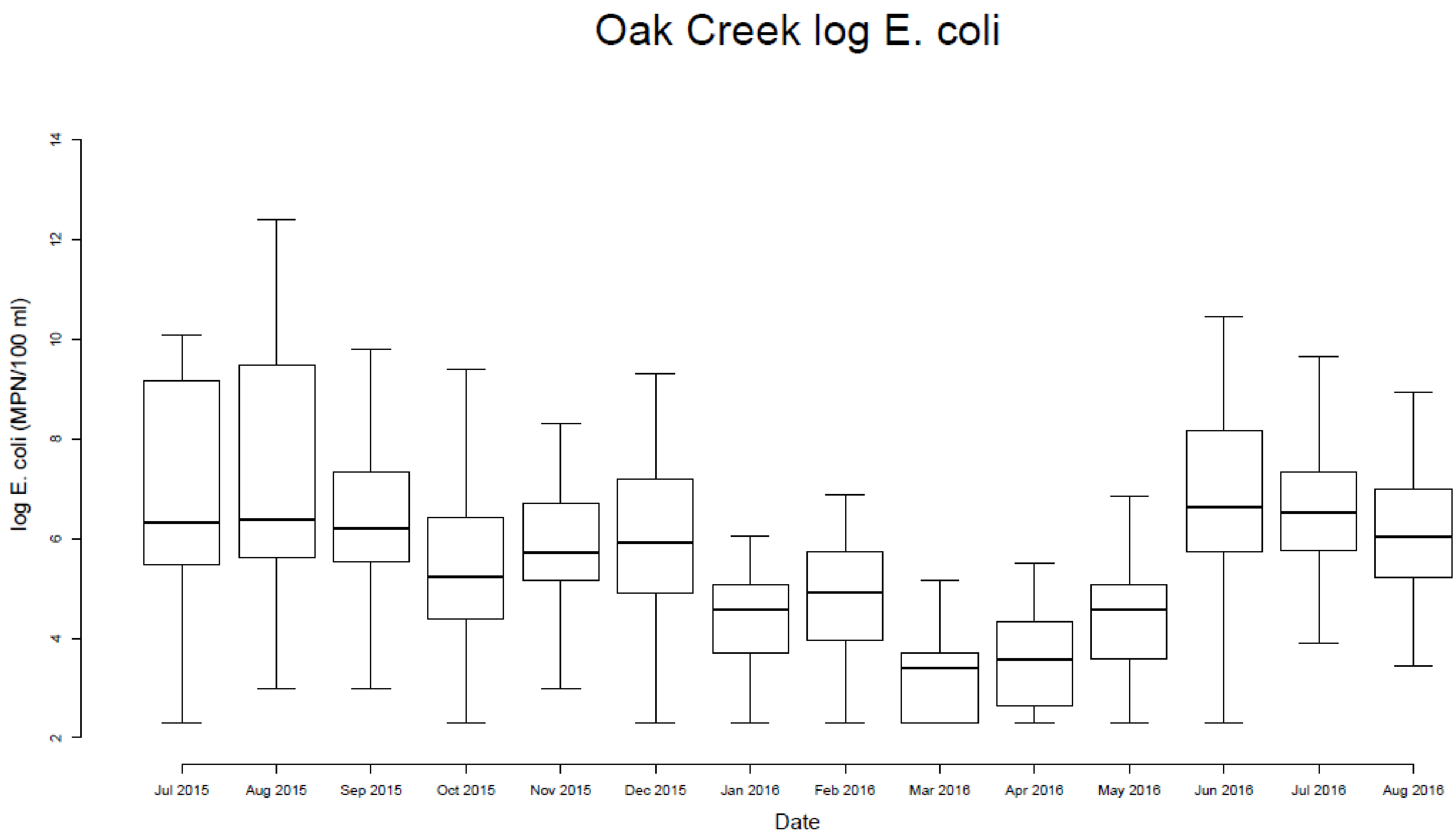
OAK CREEK WATERSHED ASSESSMENT



Spatial Variation of *E. coli* within the Watershed

Correlations											
Precipitation (in)						Water Temperature (◦C)		Volumetric Flow Rate (ft3/sec)		TSS	
24 hr		48 hr		72hr							
r_s	p	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
0.07	0.63	0.19	0.15	0.24	0.07	0.76	0.00	-0.31	0.02	0.62	0.00
0.47	0.00	0.36	0.01	0.37	0.01	0.50	0.00	0.04	0.77	0.52	0.00
0.37	0.00	0.52	0.00	0.49	0.00	0.27	0.04	0.04	0.76	0.43	0.00
0.40	0.00	0.44	0.01	0.46	0.01	0.53	0.00	0.09	0.51	0.28	0.04
0.25	0.05	0.45	0.00	0.47	0.00	0.71	0.00	-0.08	0.56	0.66	0.00
0.39	0.00	0.54	0.00	0.51	0.00	0.63	0.00	0.00	1.00	0.56	0.00
0.40	0.00	0.55	0.00	0.50	0.00	0.64	0.00	-0.18	0.18	0.72	0.00
0.41	0.00	0.52	0.00	0.48	0.00	0.58	0.00	0.05	0.72	0.59	0.00
0.40	0.00	0.47	0.00	0.43	0.00	0.40	0.00	0.03	0.80	0.02	0.90
0.27	0.04	0.48	0.00	0.49	0.00	0.44	0.00	-0.07	0.60	0.30	0.02
0.44	0.00	0.53	0.00	0.55	0.00	0.59	0.00	-0.09	0.52	0.57	0.00
0.36	0.01	0.47	0.00	0.45	0.00	0.49	0.00	-0.20	0.13	0.54	0.00
0.37	0.01	0.48	0.00	0.46	0.00	0.44	0.00	0.10	0.44	0.46	0.00
0.38	0.03	0.55	0.00	0.56	0.00	0.42	0.01	-0.12	0.49	0.38	0.03
0.31	0.03	0.45	0.00	0.50	0.00	0.07	0.65	-0.02	0.89	0.14	0.31
0.33	0.01	0.45	0.00	0.48	0.00	0.40	0.00	-0.06	0.65	0.62	0.00
0.41	0.01	0.64	0.00	0.62	0.00	0.24	0.15	-0.02	0.90	0.64	0.00
0.43	0.00	0.48	0.00	0.51	0.00	0.30	0.02	0.09	0.51	0.57	0.00
0.29	0.03	0.24	0.08	0.29	0.03	0.29	0.03	n/a	n/a	0.27	0.04
r_s = Spearman's rho						Significant p values < 0.05					

Seasonality in *E. coli*



Monthly Geometric Mean*													
Jul 2015	Aug 2015	Sep 2015	Oct 2015	Nov 2015	Dec 2015	Jan 2016	Feb 2016	Mar 2016	Apr 2016	May 2016	Jun 2016	Jul 2016	Aug 2016
6,017	**14,073**	15,157	3,617	**942**	1,144	85	275	68	58	351	**11,418**	7,555	**5,363**
1,048	**399**	269	112	**113**	442	n/a	364	55	57	365	**1,540**	371	**590**
116	**335**	889	120	**95**	179	20	69	13	24	24	**512**	253	**139**
521	**419**	199	75	**107**	142	18	63	10	32	100	**809**	473	**196**
1,524	**1,080**	228	82	**171**	160	27	87	15	27	66	**840**	3,987	**720**
981	**1,065**	374	69	**128**	126	44	292	23	46	349	**808**	701	**647**
1,539	**1,927**	555	134	**175**	187	55	203	21	29	145	**1,264**	575	**315**
841	**1,137**	1,196	46	**230**	217	n/a	254	23	43	174	**968**	662	**409**
752	**537**	540	108	**601**	274	n/a	214	85	10	52	758	489	**599**
506	**792**	834	173	**306**	222	100	70	26	17	50	**1,191**	444	**197**
1,468	**1,024**	643	284	**210**	380	87	159	20	41	97	**721**	960	**321**
3,161	**3,641**	1,722	1,284	**1,466**	803	133	122	10	27	81	**1,437**	1,584	**824**
1,124	**1,805**	986	331	**554**	1,079	116	59	42	33	34	**744**	1,389	**604**
n/a	n/a	n/a	n/a	n/a	1,120	168	109	38	25	34	**742**	994	**591**
335	**1,917**	417	491	**436**	947	n/a	n/a	20	35	32	**449**	242	**350**
1,196	**3,362**	1,707	747	**532**	907	259	76	45	54	61	**915**	809	**511**
n/a	n/a	n/a	n/a	**1,140**	936	178	85	31	42	39	**540**	708	**479**
458	**1,604**	719	171	**576**	913	n/a	60	23	36	73	**813**	1,111	**186**
1,958	**3,250**	7,384	1,439	**1,382**	2,270	n/a	288	25	166	68	**326**	1,499	**391**

Southwood Dr.

Location and Surrounding Area

This site is located on the Upper Mainstem of Oak Creek, in Franklin, WI. Located in a green corridor, the predominant land use upstream of this site is moderate density residential.

Stream Bank Conditions

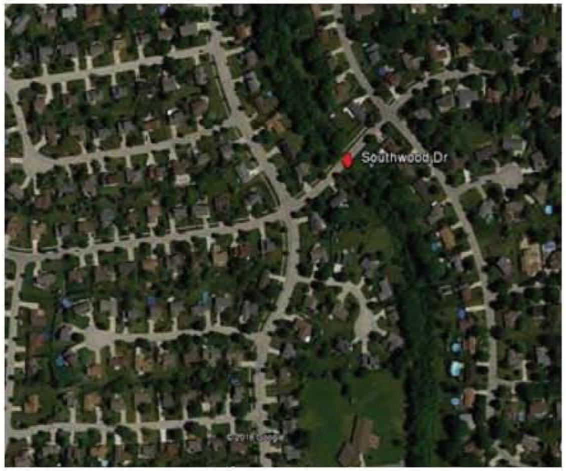
The narrow buffers along the stream bank primarily consist of shrubs and trees, with intermittent reed grass. This stream reach is highly channelized and has minimal streambank erosion.

Infrastructure

A legacy concrete structure extends across the streambed 230 feet upstream from the sampling site. Two stormwater outfalls are located under the bridge (Southwood OF East and Southwood OF West); their pollution potential was relatively low. Outfall 105, located upstream of this sampling site, had exceedances of *E. coli* and positive hits for human specific *Bacteroides* and *Lachnospiraceae*.

Other Comments

The Southwood Drive site has significantly higher *E. coli* concentrations than the other surface water sites included in this study. Outfall 105 is a likely contributor and should be further investigated.



Aerial view of sampling site (red arrow) and surrounding land use.

Concrete legacy structure extends across the stream bed 70 m upstream of site.

Stream reach near sampling site is highly channelized.

Riparian vegetation near sampling site consisting of shrubs, trees and reed grass.

Outfall 105

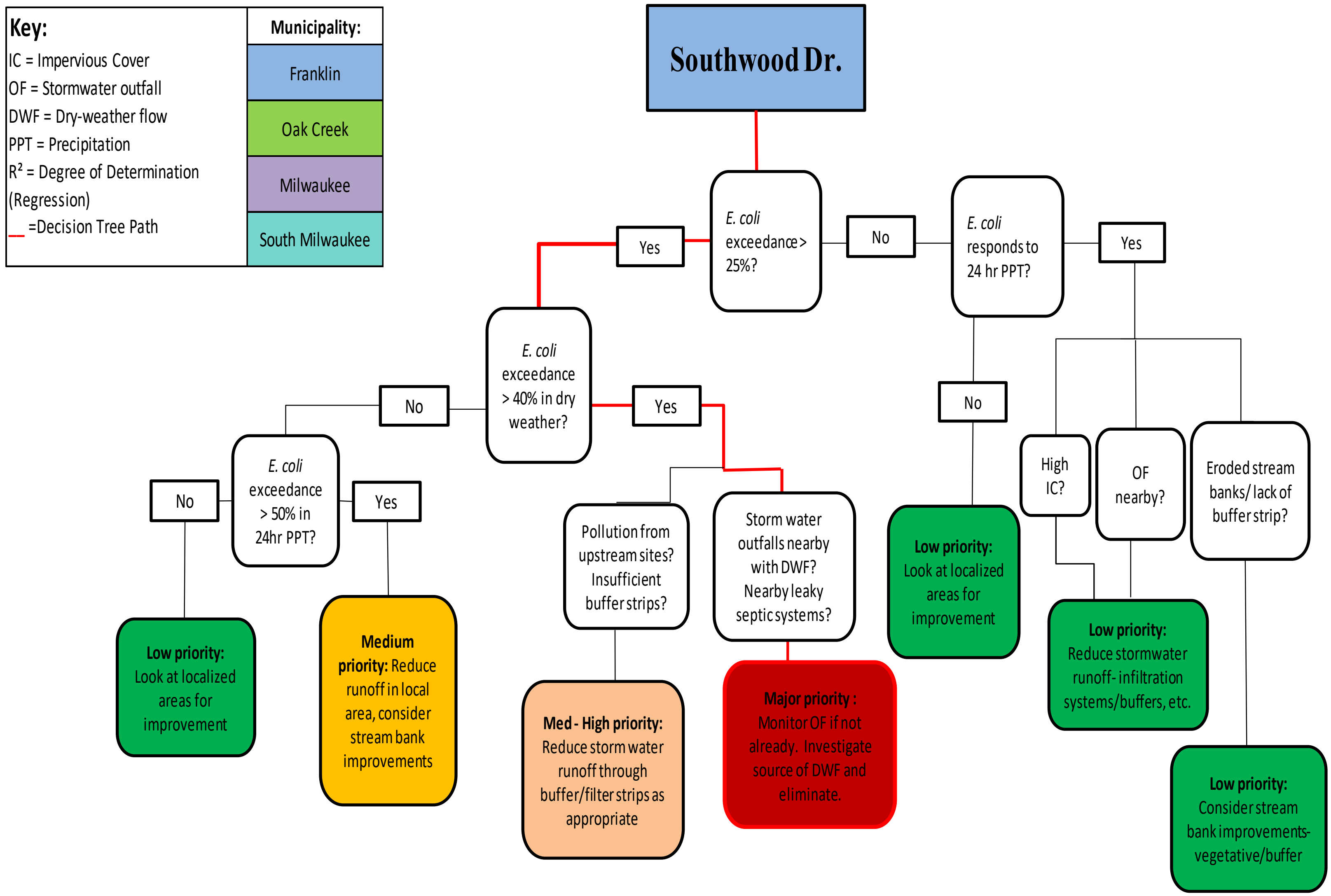
42.87828200°, -87.96668900°

DWF PRESENT

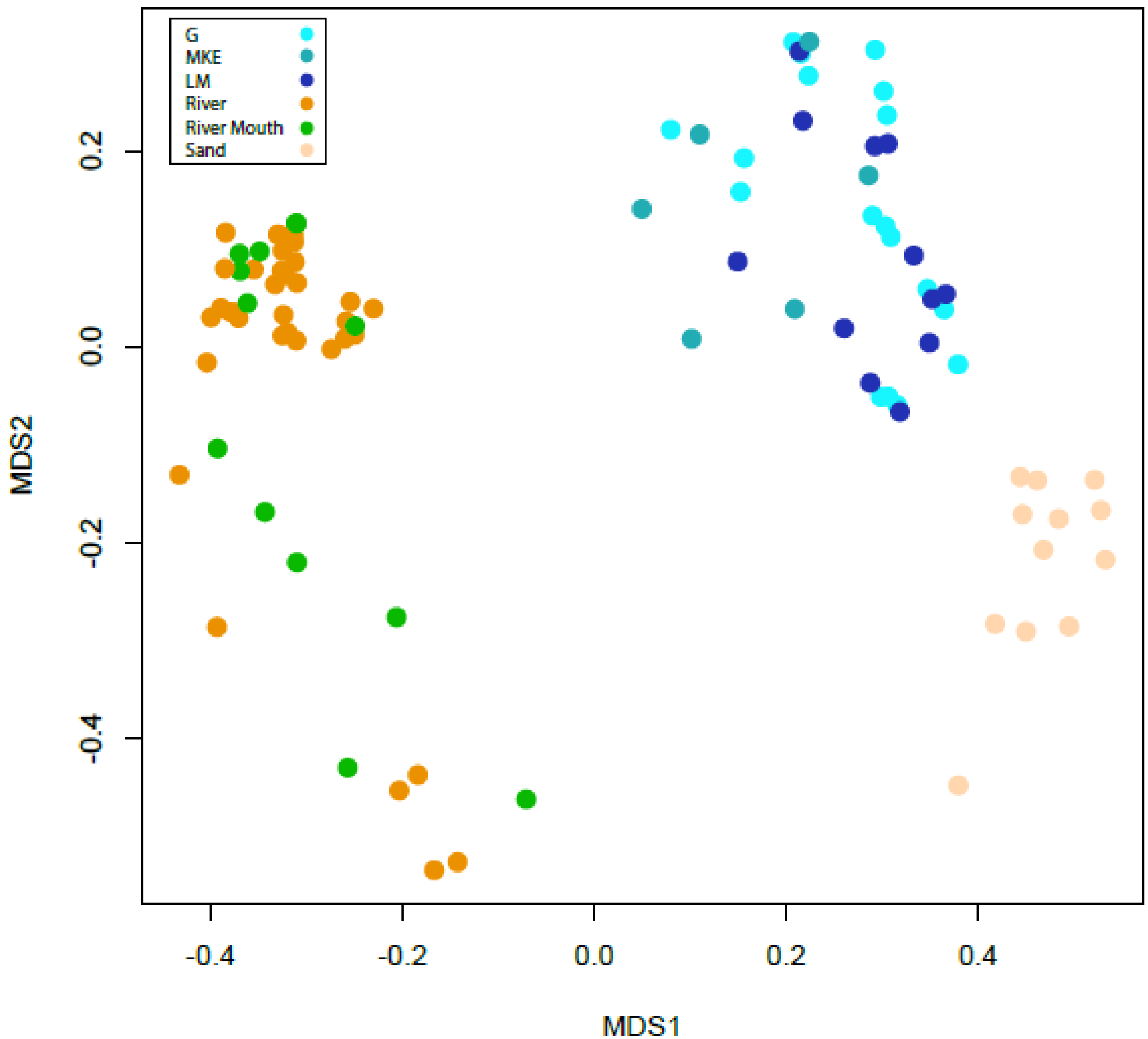
15th Avenue

42.92487000°, -87.87110000°

DWF PRESENT


Key:
IC = Impervious Cover
OF = Stormwater outfall
DWF = Dry-weather flow
PPT = Precipitation
R² = Degree of Determination (Regression)
=Decision Tree Path
Municipality:
Franklin
Oak Creek
Milwaukee
South Milwaukee
Southwood Dr.
E. coli exceedance > 25%?
Yes
No
E. coli responds to 24 hr PPT?
Yes
No
E. coli exceedance > 40% in dry weather?
No
Yes
E. coli exceedance > 50% in 24hr PPT?
No
Yes
Low priority: Look at localized areas for improvement
Medium priority: Reduce runoff in local area, consider stream bank improvements
Pollution from upstream sites? Insufficient buffer strips?
Storm water outfalls nearby with DWF? Nearby leaky septic systems?
Med - High priority: Reduce storm water runoff through buffer/filter strips as appropriate
Major priority : Monitor OF if not already. Investigate source of DWF and eliminate.
Low priority: Look at localized areas for improvement
High IC?
OF nearby?
Eroded stream banks/ lack of buffer strip?
Low priority: Reduce stormwater runoff- infiltration systems/buffers, etc.
Low priority: Consider stream bank improvements- vegetative/buffer

Community Profiling



Stepwise Approach

- Weight of evidence
  - May be no definitive association(s)
    - FIO
    - Alternative or secondary indicators (bacteria, viruses, chemical tracers)
    - MST
    - Sanitary surveys
    - Mathematical modeling
  - Need for exposure interventions still necessary in spite of limitations

Time for a few

QUESTIONS???