Day 3: Forensic Hydrology (where did that contaminating flow come from?)

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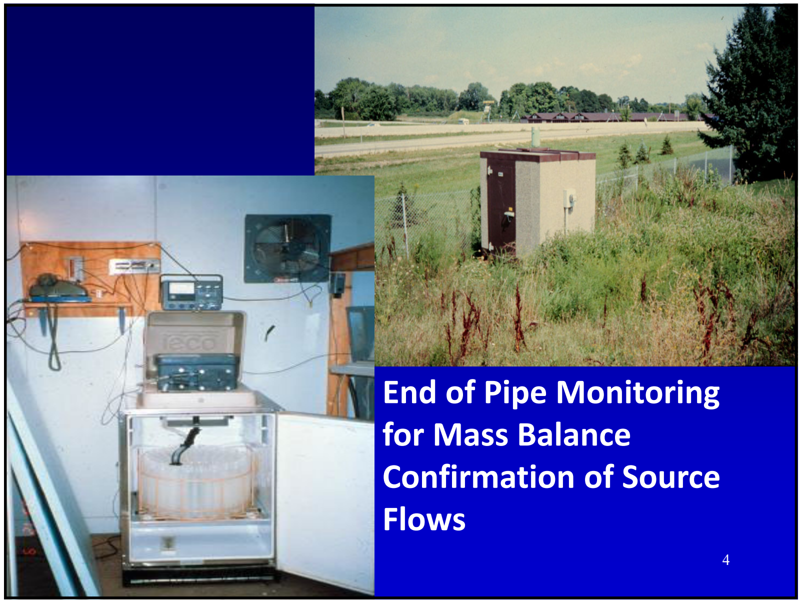
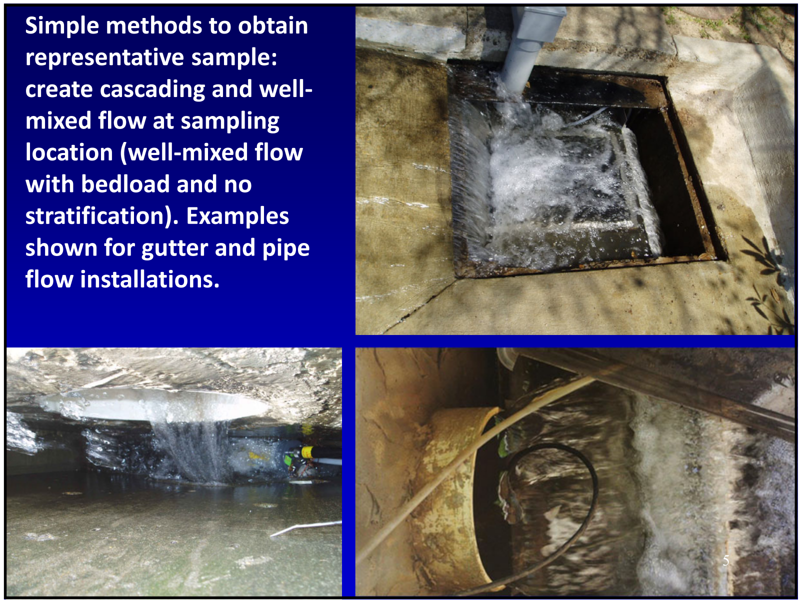
Outline of Presentation

- Examples of stormwater flow measurement setups
- Flow monitoring options with weirs, flumes and the Manning formula
- Inappropriate discharges to stormwater drainage systems using chemical tracers and mass balances

Many stormwater monitoring configurations used over the years



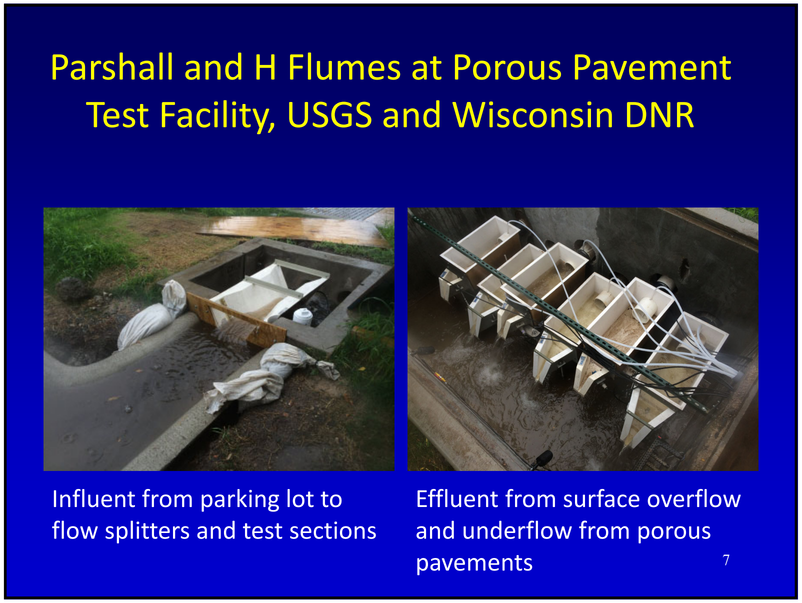
End of Pipe Monitoring for Mass Balance Confirmation of Source Flows



Simple methods to obtain representative sample: create cascading and well-mixed flow at sampling location (well-mixed flow with bedload and no stratification). Examples shown for gutter and pipe flow installations.

1324 76th St. monitoring location, biofilter and adjacent porous concrete sidewalk (one of 10 monitored, plus system)

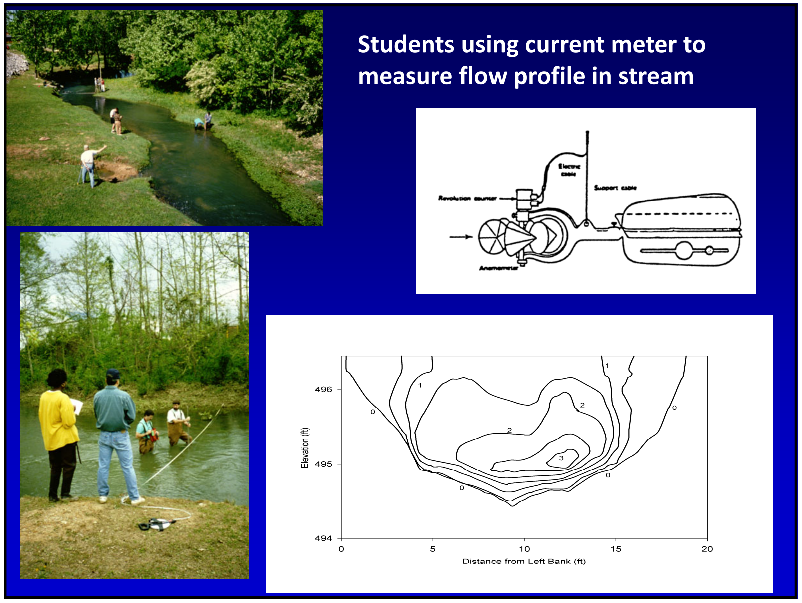
Kansas City, MO, Green Infrastructure Demonstration Project



Parshall and H Flumes at Porous Pavement Test Facility, USGS and Wisconsin DNR

Influent from parking lot to flow splitters and test sections

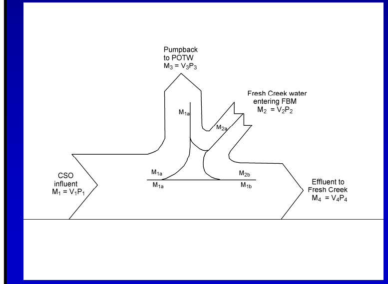
Effluent from surface overflow and underflow from porous pavements



Students using current meter to measure flow profile in stream

Using Tracers to Monitor Flow

- conservative,
- highly soluble under a variety of conditions,
- not amenable to sorption or precipitation or degradation,
- linear with mixing, and
- present in greatly contrasting concentrations in the two water bodies that are mixing.



Mass balance equations to calculate flow sources

Fluorescein dye for sanitary sewer cross-connection identification

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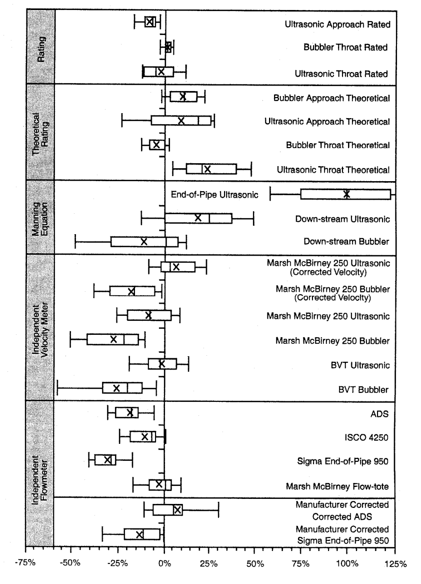


Comparison of different in pipe stormwater flow measurement methods (compared to *in-situ* continuous dye dilution measurements). USGS and WI DNR

"All runoff flow monitoring equipment must be carefully calibrated at the time of installation and periodically re-checked."

Stormwater Flow Monitoring with Weirs, Flumes, and the Manning Equation

Summarized from *Teledyne ISCO Open Channel Flow Measurement Handbook*, 8th Edition. 2017.

Selection of Primary Device for Flow Monitoring

- The selection of a primary device needs to consider:
  - The purpose of the flow measurements
  - The required accuracy
  - Range and duration of flows
  - Possibility of surcharge or reverse flow conditions
  - Costs
- Weir or flume?
- Specific type?
- Exact sizes of the primary device

Common Errors in Flow Monitoring

- Faulty fabrication or construction of the primary device
- Improper gauge or head measurement location
- Incorrect zero setting
- Improper head measurement
- Use of primary device outside it proper range
- Improper installation or maintenance of weirs or flumes
- Turbulence and surges in the approach channel
- Excessive debris and other solids in the flow

Weirs

- Weir edge thickness of 3 to 6 mm (reinforced). Upstream edge must be sharp with right angles (knife edges should not be used as difficult to maintain and rounded edges affect the flow).
- Upstream edge perpendicular to flow. Crest of edge needs to be exactly level.
- Connection of weir to side walls must be waterproof. The weir should be ventilated to prevent vacuum from forming under the nape.
- The height of the weir from the bottom of the channel should be at two times the expected head of the liquid above the crest to lower the approach velocity. The weir height should never be less than 0.3 m.

Weirs (continued)

- The approach section should be straight upstream from the weir for a distance of at least 20 times the maximum height of the liquid over the crest, and have little or no slope.
- The weir crest must be set higher than the maximum downstream elevation of the water surface to prevent backwater conditions.
- Head measurements should be placed upstream at a distance at least three times the maximum expected head and located in a quiet section of the channel.
- The cross-sectional area of the approach channel should be at least eight times that of the nappe at the crest for a distance upstream of 15 to 20 times the head of the crest.

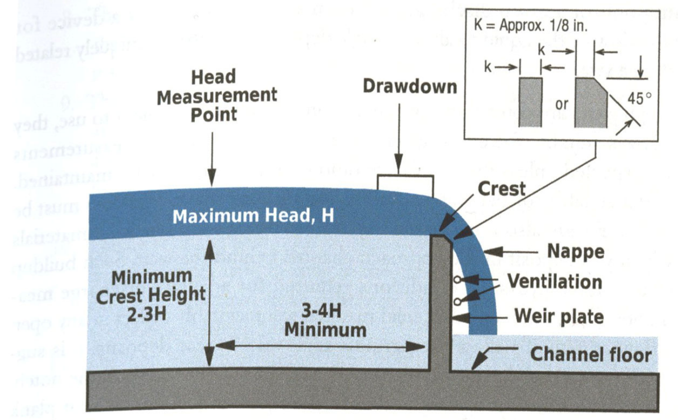
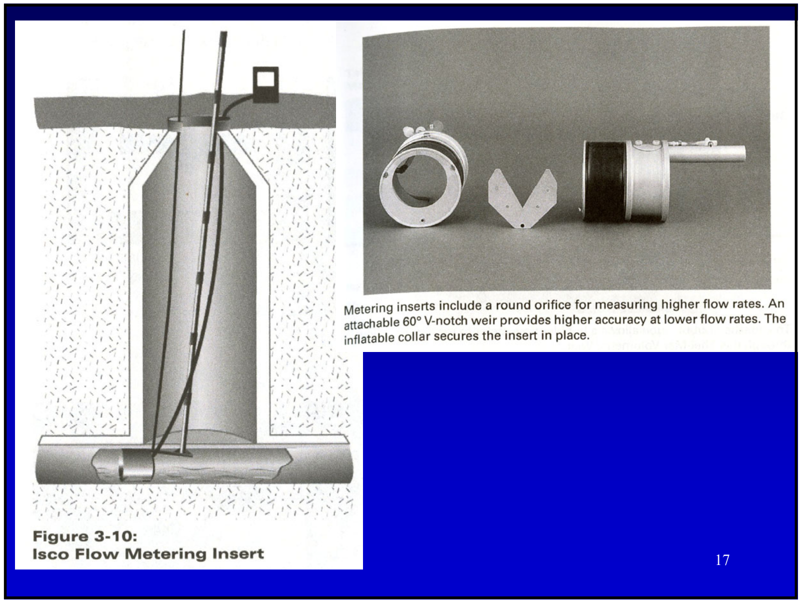
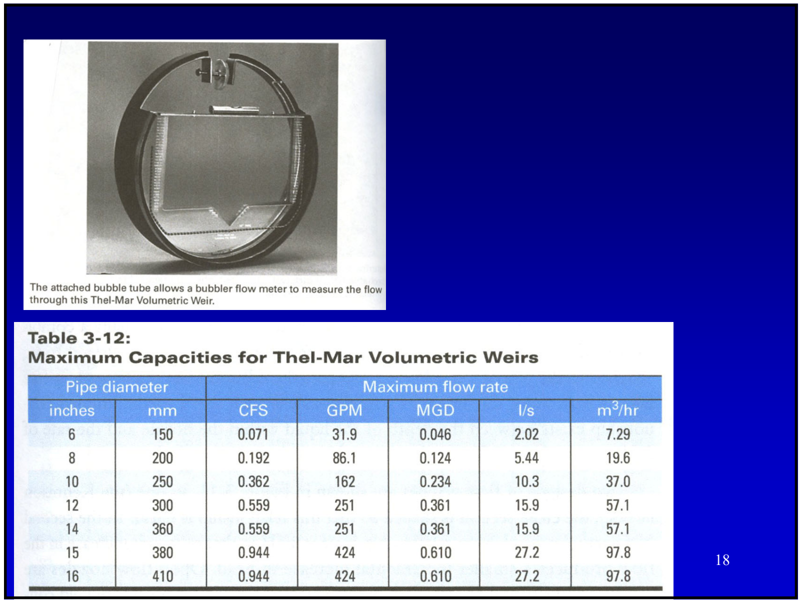


Figure 3-2: Sharp-crested Weir



Metering inserts include a round orifice for measuring higher flow rates. An attachable 60° V-notch weir provides higher accuracy at lower flow rates. The inflatable collar secures the insert in place.

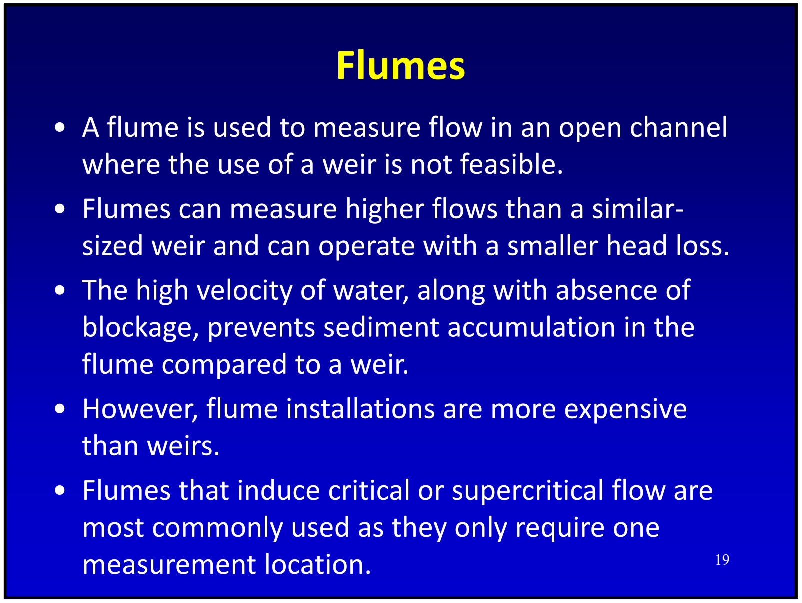
Figure 3-10:
Isco Flow Metering Insert



The attached bubble tube allows a bubbler flow meter to measure the flow through this Thel-Mar Volumetric Weir.

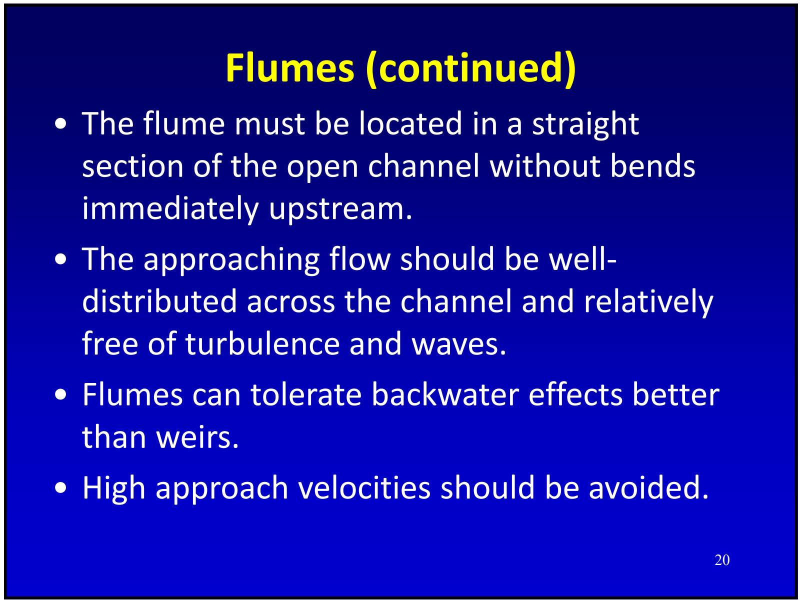
Table 3-12:
Maximum Capacities for Thel-Mar Volumetric Weirs

Pipe diameter		Maximum flow rate				
inches	mm	CFS	GPM	MGD	l/s	m^3/hr
6	150	0.071	31.9	0.046	2.02	7.29
8	200	0.192	86.1	0.124	5.44	19.6
10	250	0.362	162	0.234	10.3	37.0
12	300	0.559	251	0.361	15.9	57.1
14	360	0.559	251	0.361	15.9	57.1
15	380	0.944	424	0.610	27.2	97.8
16	410	0.944	424	0.610	27.2	97.8



Flumes

- A flume is used to measure flow in an open channel where the use of a weir is not feasible.
- Flumes can measure higher flows than a similar-sized weir and can operate with a smaller head loss.
- The high velocity of water, along with absence of blockage, prevents sediment accumulation in the flume compared to a weir.
- However, flume installations are more expensive than weirs.
- Flumes that induce critical or supercritical flow are most commonly used as they only require one measurement location.



Flumes (continued)

- The flume must be located in a straight section of the open channel without bends immediately upstream.
- The approaching flow should be well-distributed across the channel and relatively free of turbulence and waves.
- Flumes can tolerate backwater effects better than weirs.
- High approach velocities should be avoided.

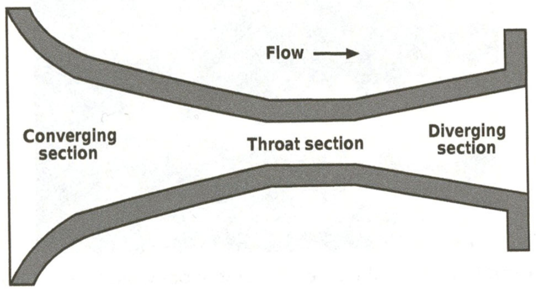


Figure 4-1: General Flume Configuration

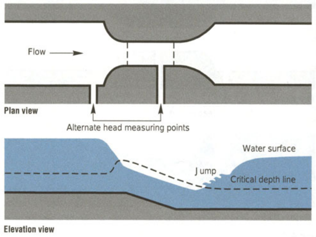


Figure 4-4:
Type V Flume-Supercritical Flow Contraction Obtained by Width Reduction and Drop in Bed Elevation

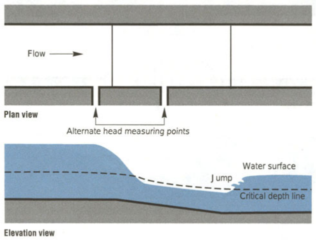


Figure 4-5:
Type VI Flume-Supercritical Flow Contraction Obtained by Steepening Floor

Parshall Flumes

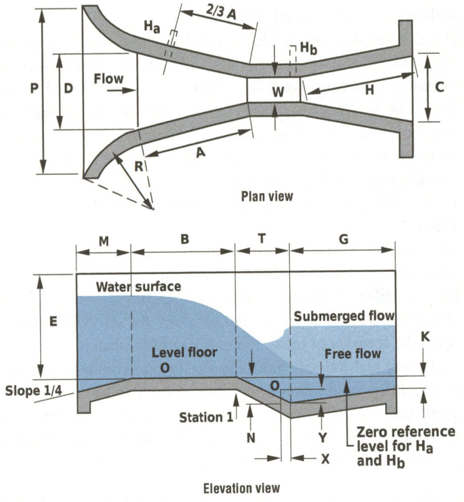


Figure 4-6: Parshall Flume

Main advantages of Parshall flumes are their sell-cleaning ability, low head loss, and ability to operate over a wide range of flows.

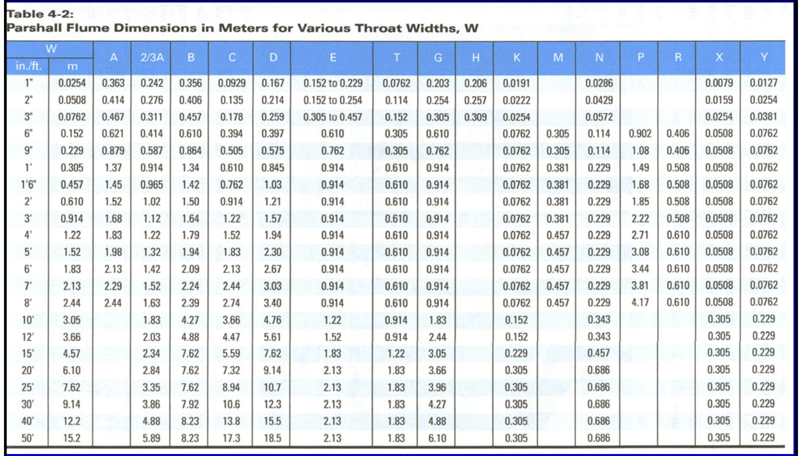


Table 4-2:
Parshall Flume Dimensions in Meters for Various Throat Widths, W

W		A	2/3A	B	C	D	E	T	G	H	K	M	N	P	R	X	Y
in./ft.	m																
1"	0.0254	0.363	0.242	0.356	0.0929	0.167	0.152 to 0.229	0.0762	0.203	0.206	0.0191		0.0286			0.0079	0.0127
2"	0.0508	0.414	0.276	0.406	0.135	0.214	0.152 to 0.254	0.114	0.254	0.257	0.0222		0.0429			0.0159	0.0254
3"	0.0762	0.467	0.311	0.457	0.178	0.259	0.305 to 0.457	0.152	0.305	0.309	0.0254		0.0572			0.0254	0.0381
6"	0.152	0.621	0.414	0.610	0.394	0.397	0.610	0.305	0.610		0.0762	0.305	0.114	0.902	0.406	0.0508	0.0762
9"	0.229	0.879	0.587	0.864	0.505	0.575	0.762	0.305	0.762		0.0762	0.305	0.114	1.08	0.406	0.0508	0.0762
1'	0.305	1.37	0.914	1.34	0.610	0.845	0.914	0.610	0.914		0.0762	0.381	0.229	1.49	0.508	0.0508	0.0762
1'6"	0.457	1.45	0.965	1.42	0.762	1.03	0.914	0.610	0.914		0.0762	0.381	0.229	1.68	0.508	0.0508	0.0762
2'	0.610	1.52	1.02	1.50	0.914	1.21	0.914	0.610	0.914		0.0762	0.381	0.229	1.85	0.508	0.0508	0.0762
3'	0.914	1.68	1.12	1.64	1.22	1.57	0.914	0.610	0.914		0.0762	0.381	0.229	2.22	0.508	0.0508	0.0762
4'	1.22	1.83	1.22	1.79	1.52	1.94	0.914	0.610	0.914		0.0762	0.457	0.229	2.71	0.610	0.0508	0.0762
5'	1.52	1.98	1.32	1.94	1.83	2.30	0.914	0.610	0.914		0.0762	0.457	0.229	3.08	0.610	0.0508	0.0762
6'	1.83	2.13	1.42	2.09	2.13	2.67	0.914	0.610	0.914		0.0762	0.457	0.229	3.44	0.610	0.0508	0.0762
7'	2.13	2.29	1.52	2.24	2.44	3.03	0.914	0.610	0.914		0.0762	0.457	0.229	3.81	0.610	0.0508	0.0762
8'	2.44	2.44	1.63	2.39	2.74	3.40	0.914	0.610	0.914		0.0762	0.457	0.229	4.17	0.610	0.0508	0.0762
10'	3.05		1.83	4.27	3.66	4.76	1.22	0.914	1.83		0.152		0.343			0.305	0.229
12'	3.66		2.03	4.88	4.47	5.61	1.52	0.914	2.44		0.152		0.343			0.305	0.229
15'	4.57		2.34	7.62	5.59	7.62	1.83	1.22	3.05		0.229		0.457			0.305	0.229
20'	6.10		2.84	7.62	7.32	9.14	2.13	1.83	3.66		0.305		0.686			0.305	0.229
25'	7.62		3.35	7.62	8.94	10.7	2.13	1.83	3.96		0.305		0.686			0.305	0.229
30'	9.14		3.86	7.92	10.6	12.3	2.13	1.83	4.27		0.305		0.686			0.305	0.229
40'	12.2		4.88	8.23	13.8	15.5	2.13	1.83	4.88		0.305		0.686			0.305	0.229
50'	15.2		5.89	8.23	17.3	18.5	2.13	1.83	6.10		0.305		0.686			0.305	0.229

Palmer-Bowlus Flumes

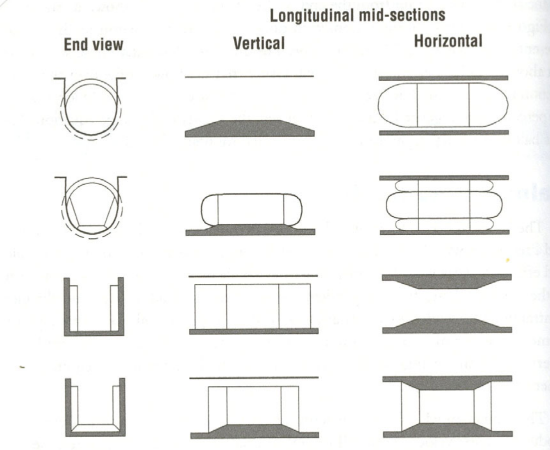


Figure 4-7: Various Cross-sectional Shapes of Palmer-Bowlus Flumes

The Palmer-Bowlus flume was developed as a primary measuring device that could be inserted into an existing conduit (usually a round pipe) with minimal site requirements (beyond a suitable slope).

Most often used in manholes for temporary installations.

Easy to install as it does not require a drop across the flume (as the Parshall flume does), but only useful for a narrow range of flows, with little resolution (small head changes for large flow changes).

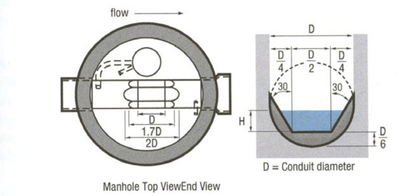


Figure 4-8: Dimensional Configuration of Standardized Palmer-Bowlus Flume-Trapezoidal Throat Cross-section

Table 4-8:
Minimum and Maximum Recommended Flow Rates for Free Flow through Plasti-Fab Palmer-Bowlus Flumes with Head in Meters

Flume size		Maximum upstream slope, percent	Min. head, meters	Minimum flow rate		Max. head, meters	Maximum flow rate	
inches	meters			l/s	m^3/hr		l/s	m^3/hr
4	0.102	2.2	0.020	0.285	1.03	0.075	3.34	12.0
6	0.152	2.2	0.020	0.398	1.43	0.105	8.11	29.2
8	0.203	2.0	0.025	0.742	2.67	0.150	19.0	68.3
10	0.254	1.8	0.035	1.58	5.70	0.180	30.8	111
12	0.305	1.6	0.035	1.83	6.58	0.215	48.1	173
15	0.381	1.5	0.045	3.36	12.1	0.275	87.7	316
18	0.457	1.4	0.050	4.60	16.6	0.320	131	470
21	0.533	1.4	0.055	6.32	22.7	0.380	198	714
24	0.610	1.3	0.060	8.10	29.1	0.425	266	957
27	0.686	1.3	0.065	10.2	36.5	0.490	374	1350
30	0.762	1.3	0.075	14.2	51.3	0.535	470	1690

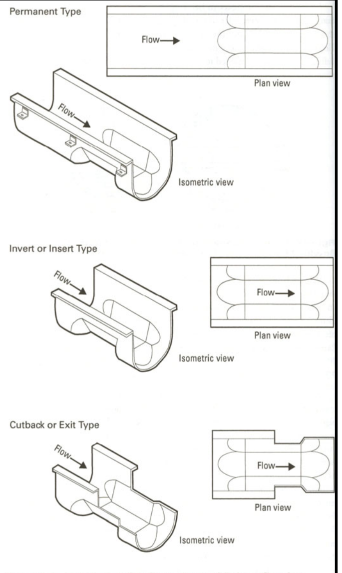


Figure 4-9: Installation Configurations of Palmer-Bowlus Flumes

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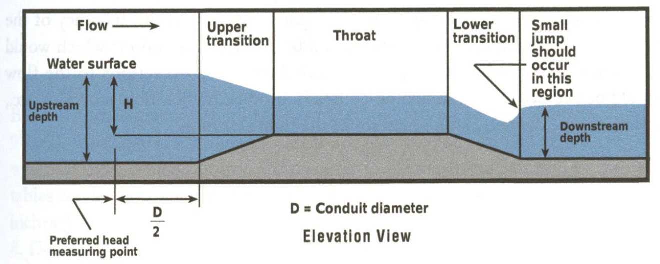
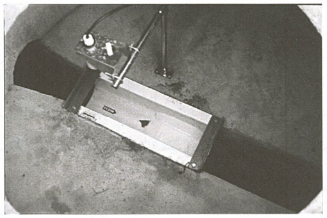


Figure 4-10: Free Flowing Palmer-Bowlus Flume



An ultrasonic sensor installed above a Palmer-Bowlus flume in a manhole.

HS, H, and HL Flumes (More accurately termed "Open Channel Flow Nozzles")

- We have used these small flumes to measure flows from curb-cuts entering adjacent bioretention facilities.
- H flumes are capable of monitoring flow over a wide range with reasonable accuracy.
- Combine the sensitivity and accuracy of sharp-crested weirs with the self-cleaning features of flumes.
- Preferred installation has a rectangular approach channel the same width of the H flume. The approach channel should be 3 to 5 times the depth of the flume.
- H flumes should have their exiting water unimpeded (free discharge with no backwater), however 50% submergence may only have a few percent effect on the flow.

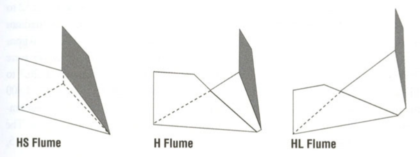
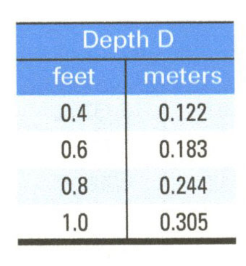


Figure 4-13: HS, H, and HL Flumes



Depth D	
feet	meters
0.4	0.122
0.6	0.183
0.8	0.244
1.0	0.305

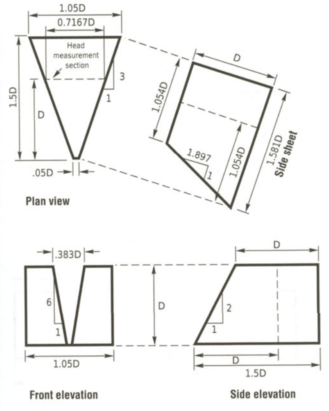
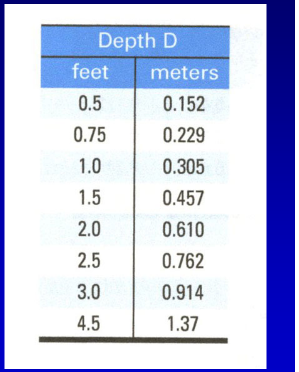


Figure 4-14: HS Flume Dimensions



Depth D	
feet	meters
0.5	0.152
0.75	0.229
1.0	0.305
1.5	0.457
2.0	0.610
2.5	0.762
3.0	0.914
4.5	1.37

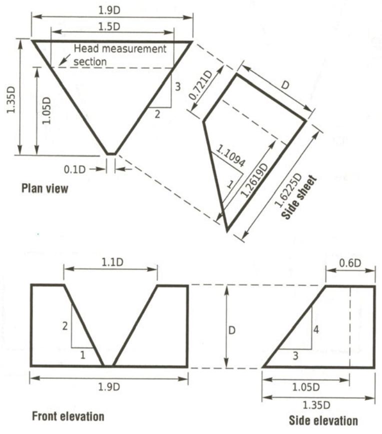


Figure 4-15: H Flume Dimensions

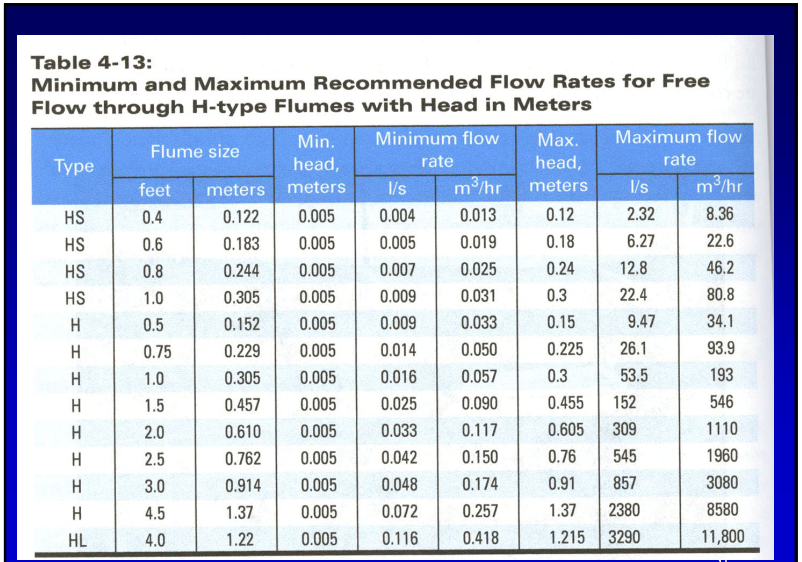


Table 4-13:
Minimum and Maximum Recommended Flow Rates for Free Flow through H-type Flumes with Head in Meters

Type	Flume size		Min. head, meters	Minimum flow rate		Max. head, meters	Maximum flow rate	
	feet	meters		l/s	m^3/hr		l/s	m^3/hr
HS	0.4	0.122	0.005	0.004	0.013	0.12	2.32	8.36
HS	0.6	0.183	0.005	0.005	0.019	0.18	6.27	22.6
HS	0.8	0.244	0.005	0.007	0.025	0.24	12.8	46.2
HS	1.0	0.305	0.005	0.009	0.031	0.3	22.4	80.8
H	0.5	0.152	0.005	0.009	0.033	0.15	9.47	34.1
H	0.75	0.229	0.005	0.014	0.050	0.225	26.1	93.9
H	1.0	0.305	0.005	0.016	0.057	0.3	53.5	193
H	1.5	0.457	0.005	0.025	0.090	0.455	152	546
H	2.0	0.610	0.005	0.033	0.117	0.605	309	1110
H	2.5	0.762	0.005	0.042	0.150	0.76	545	1960
H	3.0	0.914	0.005	0.048	0.174	0.91	857	3080
H	4.5	1.37	0.005	0.072	0.257	1.37	2380	8580
HL	4.0	1.22	0.005	0.116	0.418	1.215	3290	11,800

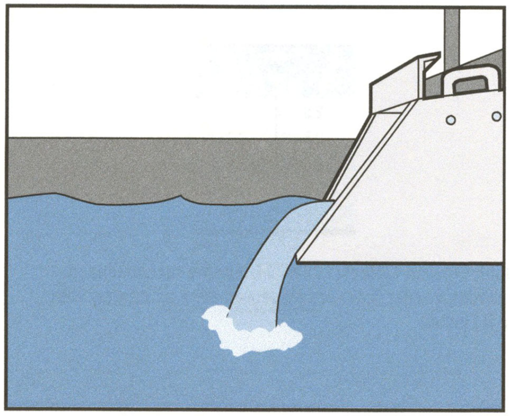


Figure 4-17: Discharge from H-type Flumes

The Manning Formula

- Used to measure gravity flow in open channel conditions (channels or pipes).
- Historically, the Manning formula has been used to measure flow where it is impractical to install a hydraulic structure (flume or weir).
- The Manning formula assumes uniform flow and the driving force is the hydraulic gradient (friction slope).
- A straight course of channel of a least 200 ft (60 m), preferably up to 1,000 ft (300 m), upstream of the point of depth measurement is desired.
- The channel should be nearly constant in slope, cross section, and roughness, and free of rapids, sudden contractions or expansions and tributary flows.
- Under these ideal conditions, the Manning formula would have an accuracy of +/- 10 to 20%.
- Area-velocity measurements are now considered more accurate as they can be used in more typical field conditions (and the flow sensors, usually using Doppler or other acoustic methods, can measure negative flow directions). Very low velocities are still a problem though.

Problems with the use of the Manning Formula in Manholes

- Manning formula often used to calculate flow through round pipes in manholes.
- Measurement location does not approximate the shape of the round pipe (can use a flume insert as a primary device in manholes)
- There may be an abrupt change in flow direction or tributary flows near the measurement location
- The flow may not be straight
- There are extreme variables in conditions (roughness and shape)

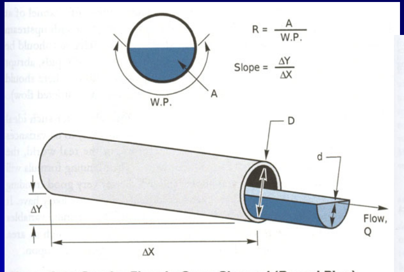
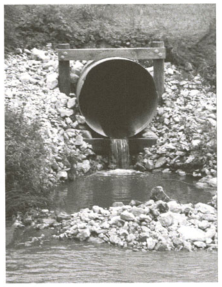


Figure 6-1: Gravity Flow in Open Channel (Round Pipe)

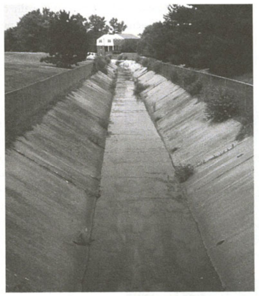
$$Q = \frac{K\,A\,R^{2/3}\,S^{1/2}}{n}$$

where:

Q = flow rate
A = cross sectional area of flow
R = hydraulic radius (cross sectional area divided by the wetted perimeter)
S = slope of the hydraulic gradient
n = Manning coefficient of roughness dependent upon material of conduit
K = constant dependent upon units

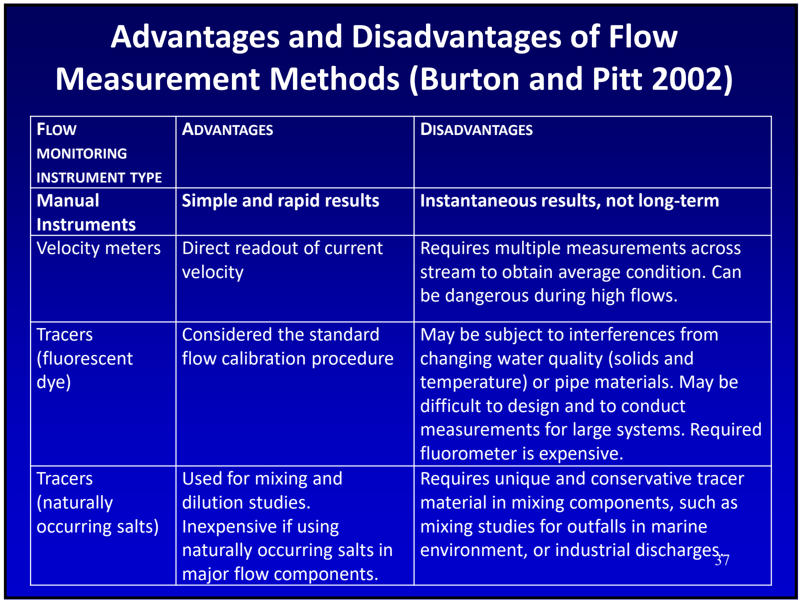


The Manning formula determines flow rate based on the depth of flow, and the size, shape, slope, and roughness of the channel.



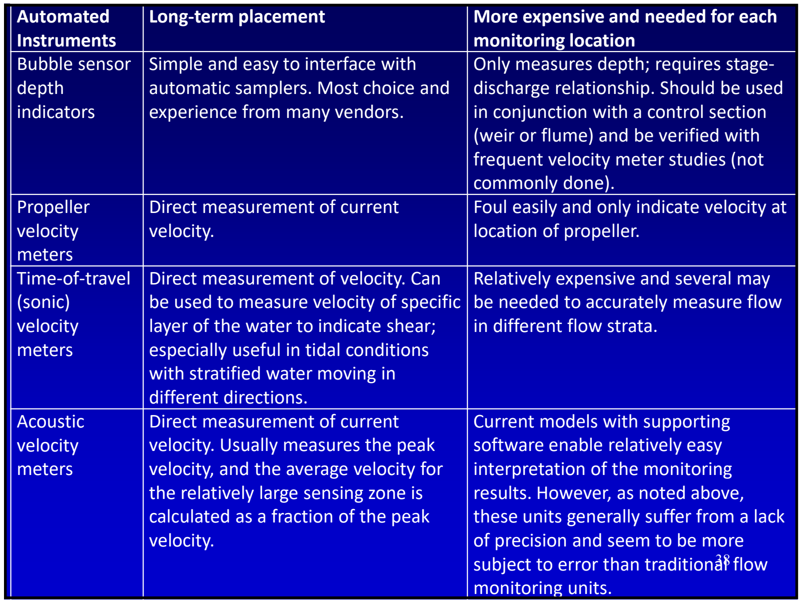
The Manning formula can be used to measure flow in conduits of any cross section, such as this trapezoidal channel that carries storm water runoff from a residential area.

The roughness coefficient of this natural channel will vary as the vegetation in the channel grows.

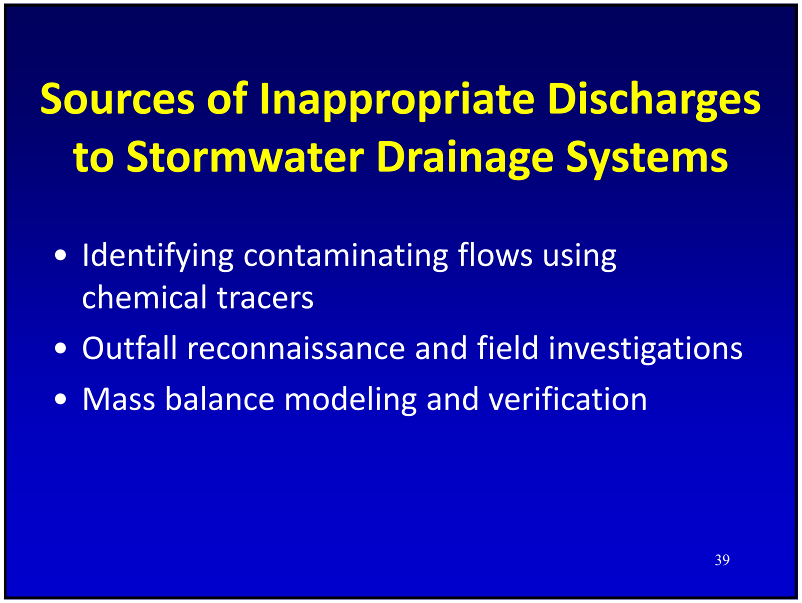


Advantages and Disadvantages of Flow Measurement Methods (Burton and Pitt 2002)

FLOW MONITORING INSTRUMENT TYPE	ADVANTAGES	DISADVANTAGES
Manual Instruments	**Simple and rapid results**	**Instantaneous results, not long-term**
Velocity meters	Direct readout of current velocity	Requires multiple measurements across stream to obtain average condition. Can be dangerous during high flows.
Tracers (fluorescent dye)	Considered the standard flow calibration procedure	May be subject to interferences from changing water quality (solids and temperature) or pipe materials. May be difficult to design and to conduct measurements for large systems. Required fluorometer is expensive.
Tracers (naturally occurring salts)	Used for mixing and dilution studies. Inexpensive if using naturally occurring salts in major flow components.	Requires unique and conservative tracer material in mixing components, such as mixing studies for outfalls in marine environment, or industrial discharges.



Automated Instruments	**Long-term placement**	**More expensive and needed for each monitoring location**
Bubble sensor depth indicators	Simple and easy to interface with automatic samplers. Most choice and experience from many vendors.	Only measures depth; requires stage-discharge relationship. Should be used in conjunction with a control section (weir or flume) and be verified with frequent velocity meter studies (not commonly done).
Propeller velocity meters	Direct measurement of current velocity.	Foul easily and only indicate velocity at location of propeller.
Time-of-travel (sonic) velocity meters	Direct measurement of velocity. Can be used to measure velocity of specific layer of the water to indicate shear; especially useful in tidal conditions with stratified water moving in different directions.	Relatively expensive and several may be needed to accurately measure flow in different flow strata.
Acoustic velocity meters	Direct measurement of current velocity. Usually measures the peak velocity, and the average velocity for the relatively large sensing zone is calculated as a fraction of the peak velocity.	Current models with supporting software enable relatively easy interpretation of the monitoring results. However, as noted above, these units generally suffer from a lack of precision and seem to be more subject to error than traditional flow monitoring units.



Sources of Inappropriate Discharges to Stormwater Drainage Systems

- Identifying contaminating flows using chemical tracers
- Outfall reconnaissance and field investigations
- Mass balance modeling and verification

Source Categories of Inappropriate Discharges

- Pathogenic & toxic pollutant sources
  - Sanitary wastewater
  - Commercial & Industrial discharges
- Nuisance & aquatic life threatening pollutant sources
  - Landscaped irrigation runoff
  - Construction site dewatering
  - Automobile washing
  - Laundry wastes
- Unpolluted water sources
  - Infiltrating groundwater
  - Natural springs
  - Domestic water line leaks

Development and Testing of Methods for Interpreting Field Screening Data

- Physical indicators of contamination
- Detergents as indicators of contamination
- Flow chart for most significant flow component identification
- Chemical mass balance at outfall to quantify flow sources

Physical Indicators of Gross Contamination (presence of any of these should indicate a problem)

- **Odor** (sewage, sulfide, oil, gasoline, rancid-sour)
- **Color** (yellow, brown, green, red, gray)
- **Turbidity** (cloudy, opaque)
- **Floatables** (petroleum sheen, sewage, food products, foam)
- **Deposits/stains** (sediment, oily)
- **Unusual vegetation conditions** (excessive growth, inhibited growth)
- **Damage to outfall structures** (concrete cracking, concrete spalling, metal corrosion)

Initial Approach: Tracers to Identify Sources of Contamination

- **Purpose: Identify toxic/ pathogenic sources of water, typically raw sewage/industrial wastewaters, discharged to storm drain system.**
- **Ideal tracer to identify major flow sources has the following characteristics:**
  - **Significant difference in concentrations between possible pollutant sources;**
  - **Small variations in concentrations within each likely pollutant source category;**
  - **Conservative behavior (i.e., no significant concentration change due to physical, chemical or biological processes);**
  - **Ease of measurement with adequate detection limits, good sensitivity and repeatability.**

Source Area Chlorine Values

	Shallow Groundwater	Sewage	Tap water	Irrigation water
	0.04	0.01	1.50	0.03
	0.00	0.03	1.26	0.05
	0.08	0.03	1.24	0.08
	0.02	0.01	0.40	0.02
	0.00	0.02	1.38	0.03
	0.01	0.00	0.19	0.00
	Cont.	Cont.	Cont.	Cont.
Average	0.02	0.01	0.88	0.03
Std. dev.	0.03	0.02	0.60	0.03
Coef. of var.	1.50	2.00	0.68	1.00

Source Area Potassium Values

	Tap Water	Sewage	Car Wash
	1.48	5.25	22.0
	1.55	4.79	22.0
	1.46	3.44	78.4
	1.50	3.09	40.7
	1.66	4.51	47.7
	1.58	5.88	35.4
	Cont.	Cont.	Cont.
Average	1.55	5.97	42.7
Standard dev.	0.06	1.36	15.9
Coef. of variation	0.04	0.23	0.37

Source Area Ammonia/Potassium Ratios

Source of Water	NH_3/K mean	NH_3/K range
Shallow groundwater	0.16	0.05 – 0.41
Springs	0.01	0.00 – 0.07
Household tap	0.02	0.01 – 0.03
Landscaping runoff	0.07	0.03 – 0.17
Laundry	0.24	0.18 – 0.34
Car Washes	0.01	0.00 – 0.01
Radiator flushing	0.01	0.00 – 0.04
Plating operations	0.16	0.00 – 0.65
Sewage	1.69	0.97 – 2.89
Septic tank discharge	5.18	3.19 – 15.4

Detergents to Indicate Contamination

Water Source	Detergent, mean (mg/L)	Detergent, range (mg/L)
Shallow groundwater	0.00	All < 0.01
Springs	0.00	All < 0.01
Household tap	0.00	All < 0.01
Landscape runoff	0.00	All < 0.01
Sewage	1.50	0.48 – 4.40
Septic tank discharge	3.27	0.15 – 12.00
Laundry	26.9	17.0 – 37.0
Car washes	49.0	38.0 – 56.7
Radiator flushing	15.0	13.5 – 18.3
Plating wastes	6.81	1.45 – 15.0

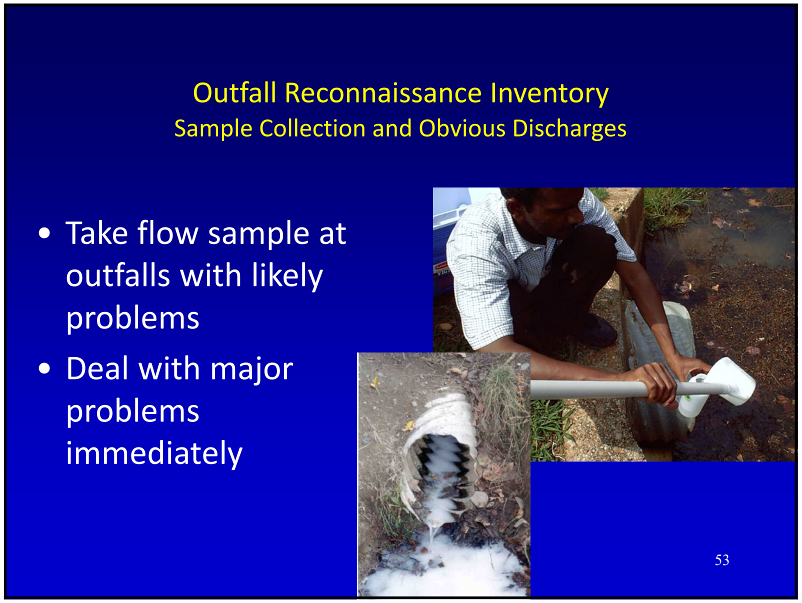
Field Screening Method Verification

- Completely developed 4,500 acre urban watershed (Village Creek) in Birmingham, AL.
- 83 stormwater outfalls, with samples collected during at least 8 visits over 30 months.

	Outfalls from large subwatersheds	Outfalls from creek-side businesses	Total
Always flowing	17%	11%	16%
Intermittently flowing	9%	33%	14%
Always dry	74%	56%	70%

Outfall Reconnaissance Inventory
Simple Monitoring at Flowing Outfalls

- pH (rapid test)
- Temperature (rapid test)
- Ammonia (lengthy test)



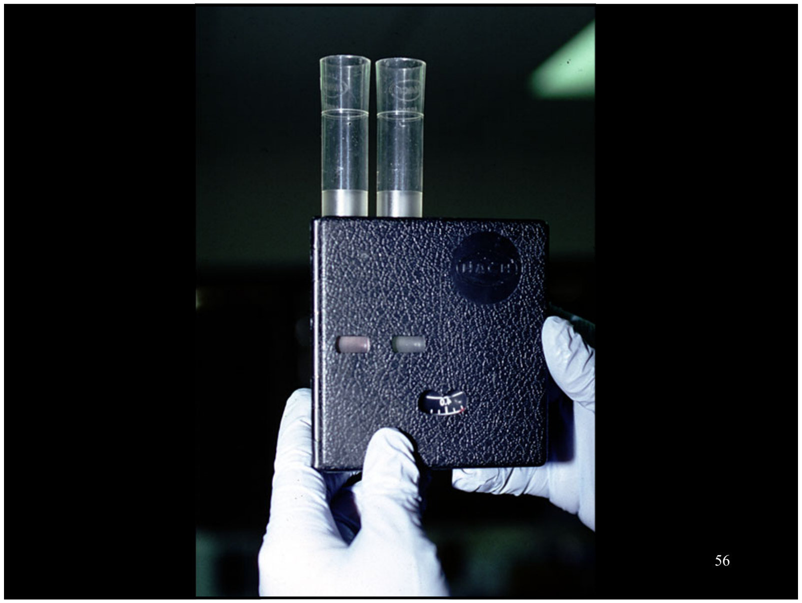
Outfall Reconnaissance Inventory

Sample Collection and Obvious Discharges

- Take flow sample at outfalls with likely problems
- Deal with major problems immediately

Simple and Inexpensive Analytical Methods (can be used in the field, but usually much easier, safer, and more efficient in lab)

- Comparative colorimetric methods (apparent color, detergents after extraction)
- Simple probes (pH, conductivity, ion selective potassium)
- Spectrophotometric (fluoride, ammonia, boron)

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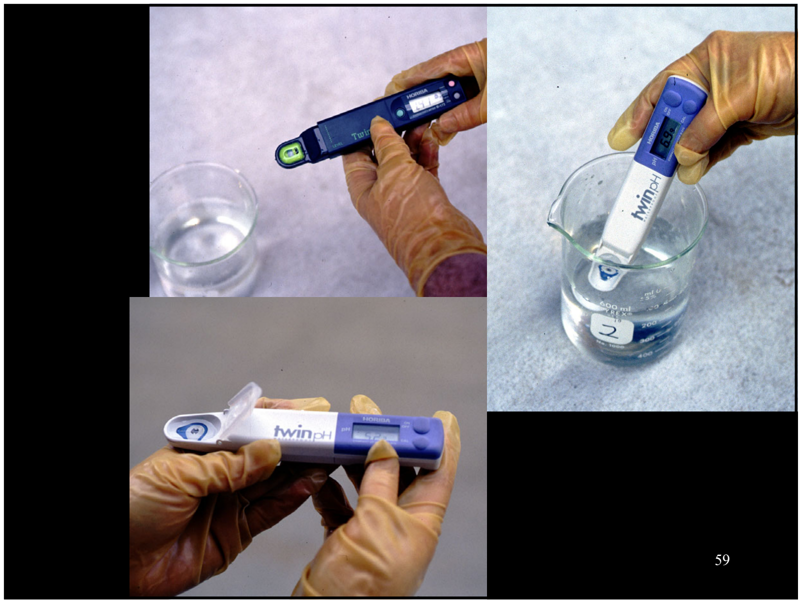
HORIBA
twinpH
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59


HORIBA
7
K
ppm
CARDY
K+
60

60

Results of Field Verification Tests

Drainage areas for 10 outfalls were studied in detail in order to verify actual sources of contamination.

Data analysis method	**Information obtained**	**Percentage of false negatives**	**Percentage of false positives**
Physical indicators	Some contaminated outfalls missed and some uncontaminated outfalls falsely accused.	20%	10%
Detergents	All contaminated outfalls correctly identified!	0	0
Flow chart	All major contaminating sources identified correctly!	0	0
Chemical mass balance	All contaminated outfalls correctly identified, and most sources correctly identified and reasonably well quantified!	0	0

Verification of Inappropriate Sources in Drainage System

- Know what to look for based on outfall screening surveys
- Flow and chemical analyses in upstream drainage system to locate affected section/reach
- Video evaluations to locate specific entry points
- Dye tracer studies of candidate connections

Summary of Follow-up Evaluations

- **Initially developed methods used to identify sources of contaminants in storm drainage systems.**
- **Reviewed emerging techniques that may also be useful.**
- **The initial methods, along with selected new procedures, were tested using almost 700 stormwater samples collected from telecommunication manholes from throughout the U.S.**

Additional Technologies for Inappropriate Discharge Investigations

- Fecal Sterol Compounds
- Caffeine
- Detergent Compounds
- Pharmaceuticals
- DNA Analyses
- Stable Isotope Analyses

Coprostanol and Other Fecal Sterol Compounds

What they are:

- Fecal sterols, such as coprostanol and epicoprostanol, analyzed using GC/MSD.
- Highly persistent in the environment
- Discharged in feces from carnivores.

Coprostanol and Other Fecal Sterol Compounds

Have been successfully used to trace sanitary sewage during historical studies:

- New York bight sediments for mapping sewage sludge disposal areas (Eaganhouse, *et al*. 1988).
- Particulates and sediments collected from coastal areas in Spain and Cuba (Grimalt, *et al*. 1990).
- Sediment cores from Santa Monica Basin, CA, and effluent from two local municipal wastewater discharges (Venkatesan and Kaplan 1990).

Coprostanol and Other Fecal Sterol Compounds

Where successfully used to trace sanitary sewage (historical studies, cont.):

- Sediments and mussels in Venice, Italy (Sherwin, *et al*. 1993).
- CSOs, stormwater, and receiving waters in King County, WA, along with caffeine and heavy metals (Shuman and Strand 1996).
- Stormwater and the sea-surface microlayer (Nichols, *et al.* 1996).

Coprostanol and Other Fecal Sterol Compounds

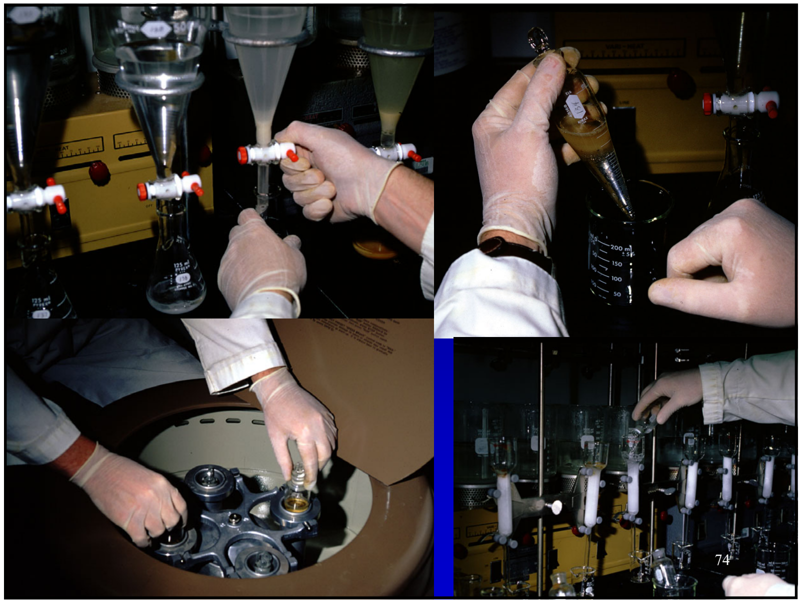
Where successfully used to trace sanitary sewage (historical studies, cont.):

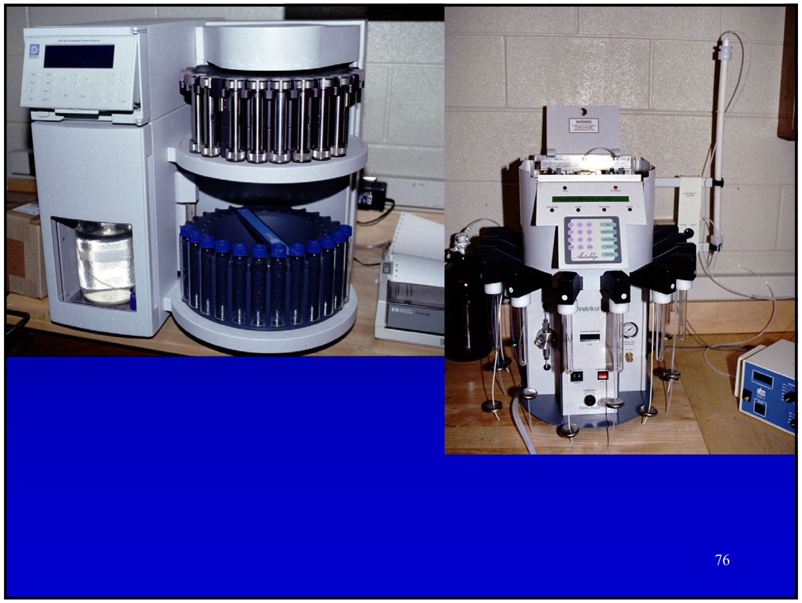
- Estrogenic chemicals recognized using TIE approach and then specifically identified with GC/MSD (Routledge, *et al.* 1998; Desbrow, *et al.* 1998).
- Water, particulate, and sediment samples near the Cocoa, FL, domestic wastewater treatment plant analyzed for saturated hydrocarbons with 16-18 carbons, and saturated hydrocarbons with 16-21 carbons, in addition to coprostanol (Holm, *et al.* 1990).

Coprostanol and Other Fecal Sterol Compounds

Problems:

- Not specific to humans.
- Long lasting (confuses recent contamination with historical or intermittent contamination).
- Commonly available analytical methods are expensive and time consuming, but not very sensitive.
- Best used for particulate-bound material and sediments, not water column measurements.





Coprostanol and Other Fecal Sterol Compounds

Suggestions for better use for tracing inappropriate discharges:

- Utilize more sensitive instrumentation (research grade MS/MS).
- Concentrate particulates from water column.
- Use in conjunction with other indicators (such as total sterols, some saturated hydrocarbons, caffeine, and heavy metals) to separate background levels and for plume tracing.

Caffeine

What it is:

- Caffeine has been used as an indicator of sewage contamination by several investigators (caffeine content of regular coffee about 700 mg/L).

Where successfully used to trace sanitary sewage (historical studies):

- Caffeine (representing dissolved CSO constituents) and coprostanol (representing particulate bound CSO constituents), along with heavy metals and conventional analyses (representing stormwater), used to identify contributions to the Duwamish River and Elliott Bay, King County, WA (Shuman and Strand 1996).
- Caffeine (7 μg/L) found in Boston Harbor *US Water News* (1998).

Caffeine

Problems:

- Very low concentrations.
- Requires expensive and time consuming analytical methods.

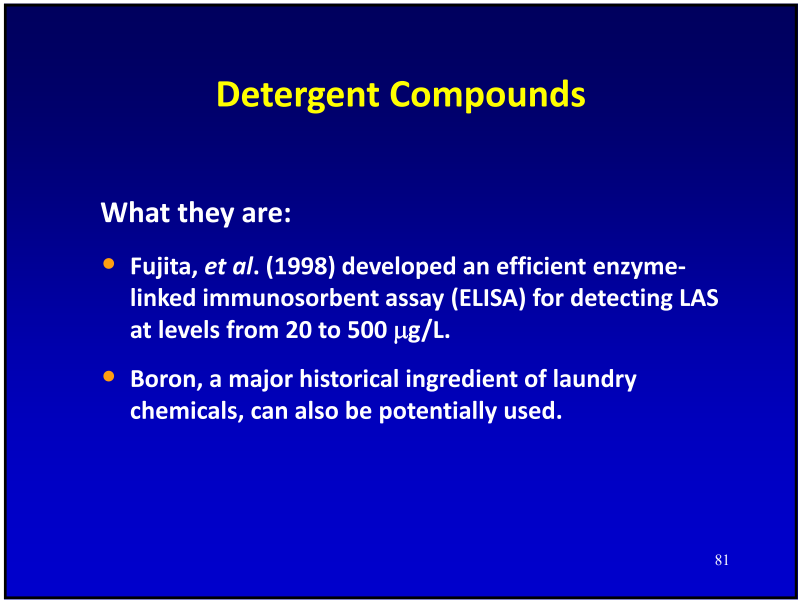
Suggestions for better use for tracing inappropriate discharges:

- Possible confirmation for the presence of sewage, when used in conjunction with other tracers.

Detergent Compounds

What they are:

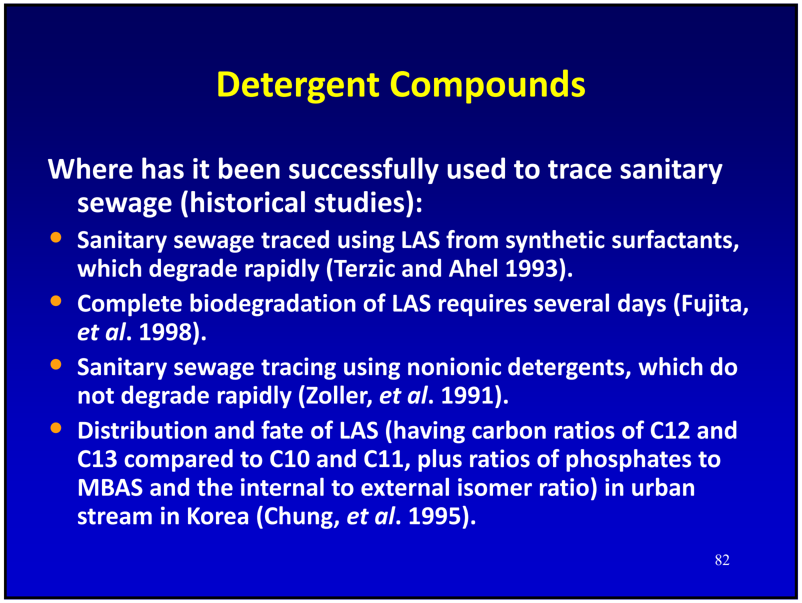
- Detergents (using MBAS tests) most successful individual tracer to indicate contaminated water in storm sewer dry-weather flows (Pitt, *et al*. 1993; Lalor 1994).
- Linear alkylbenzene sulphonates (LAS) and linear alkylbenzenes (LAB) have been used to indicate sewage.
- LAS can be measured using HPLC with fluorescent detection (after solid phase extraction) to very low levels.



Detergent Compounds

What they are:

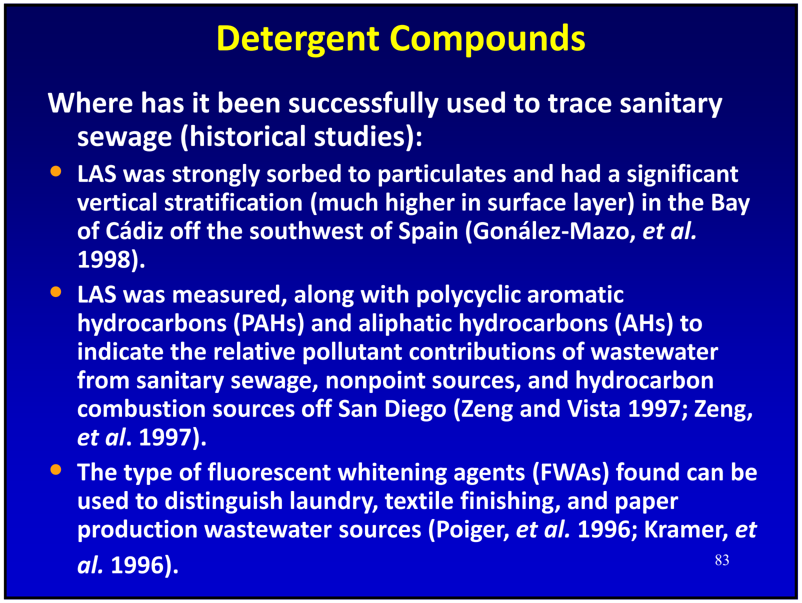
- Fujita, *et al*. (1998) developed an efficient enzyme-linked immunosorbent assay (ELISA) for detecting LAS at levels from 20 to 500 μg/L.
- Boron, a major historical ingredient of laundry chemicals, can also be potentially used.



Detergent Compounds

Where has it been successfully used to trace sanitary sewage (historical studies):

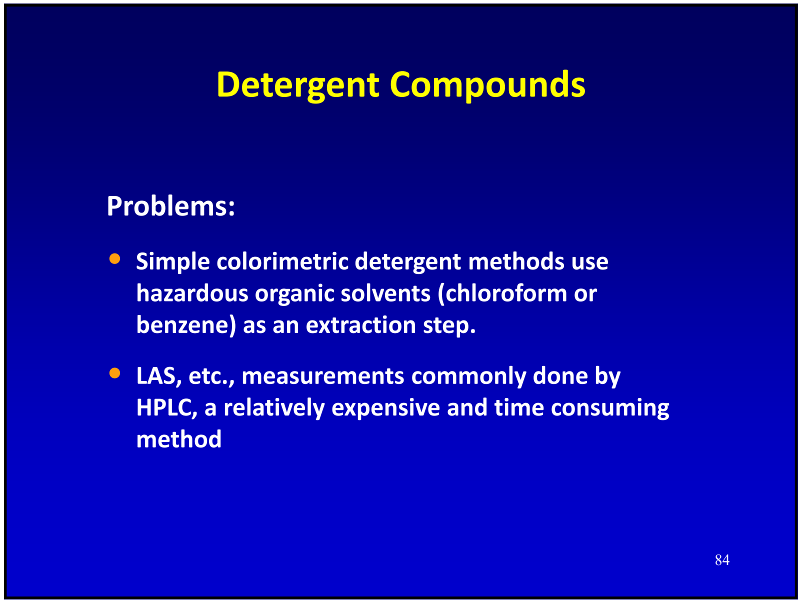
- Sanitary sewage traced using LAS from synthetic surfactants, which degrade rapidly (Terzic and Ahel 1993).
- Complete biodegradation of LAS requires several days (Fujita, *et al*. 1998).
- Sanitary sewage tracing using nonionic detergents, which do not degrade rapidly (Zoller, *et al*. 1991).
- Distribution and fate of LAS (having carbon ratios of C12 and C13 compared to C10 and C11, plus ratios of phosphates to MBAS and the internal to external isomer ratio) in urban stream in Korea (Chung, *et al*. 1995).



Detergent Compounds

Where has it been successfully used to trace sanitary sewage (historical studies):

- LAS was strongly sorbed to particulates and had a significant vertical stratification (much higher in surface layer) in the Bay of Cádiz off the southwest of Spain (Gonález-Mazo, *et al.* 1998).
- LAS was measured, along with polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons (AHs) to indicate the relative pollutant contributions of wastewater from sanitary sewage, nonpoint sources, and hydrocarbon combustion sources off San Diego (Zeng and Vista 1997; Zeng, *et al*. 1997).
- The type of fluorescent whitening agents (FWAs) found can be used to distinguish laundry, textile finishing, and paper production wastewater sources (Poiger, *et al.* 1996; Kramer, *et al.* 1996).



Detergent Compounds

Problems:

- Simple colorimetric detergent methods use hazardous organic solvents (chloroform or benzene) as an extraction step.
- LAS, etc., measurements commonly done by HPLC, a relatively expensive and time consuming method

Detergent Compounds

Suggestions for better use for tracing inappropriate discharges:

- Boron has the advantage of being relatively easy to analyze, while LAS requires chromatographic equipment.
- Fluorescent analyses can perform very sensitive measurements of detergent “brighteners,” can also be done rapidly in the field in real time, but require expensive instrument.

Pharmaceuticals

What they are:

- Various pharmaceutical substances have been found in receiving waters and in public water supplies originating from sanitary sewage discharges and these anthropogenic substances have been suggested as a sewage tracer.

Where has it been successfully used to trace sanitary sewage (historical study):

- Numerous pharmaceutical substances (such as clofibric acid, aspirin, and ibuprofen) in sewage effluents and in receiving waters in Berlin (Halling-Sørensen, *et al.* 1998).

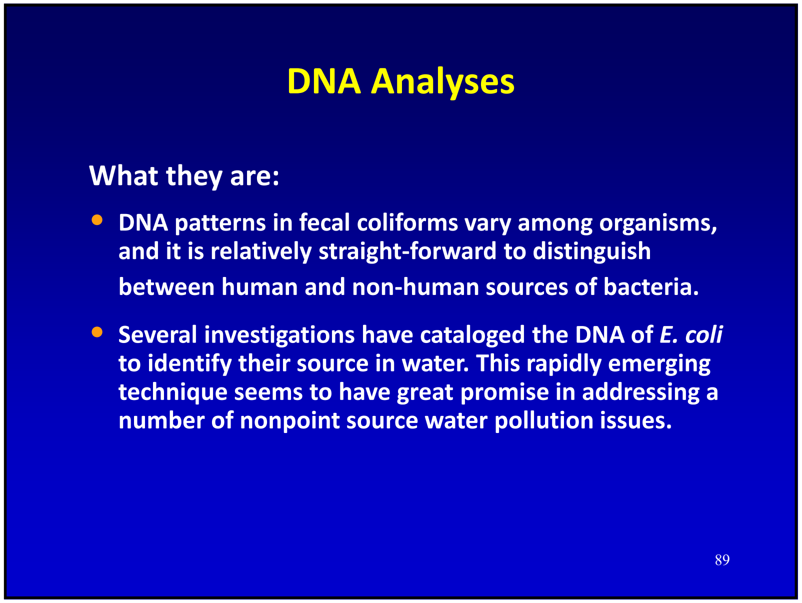
Pharmaceuticals

Problems:

- Expensive and time consuming laboratory analyses required.
- FDA guidance mandates that the maximum concentration of a pharmaceutical substance, or its active metabolites, at the point of entry into the aquatic environment be less than 1 μg/L (Hun 1998).

Suggestions for better use for tracing inappropriate discharges:

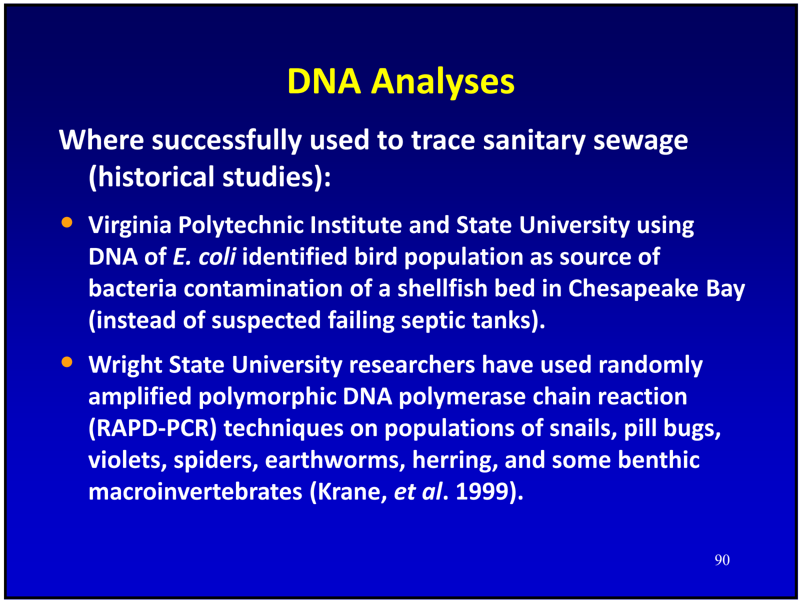
- Possible use for confirmation in conjunction with other sewage tracers that are easier to detect.



DNA Analyses

What they are:

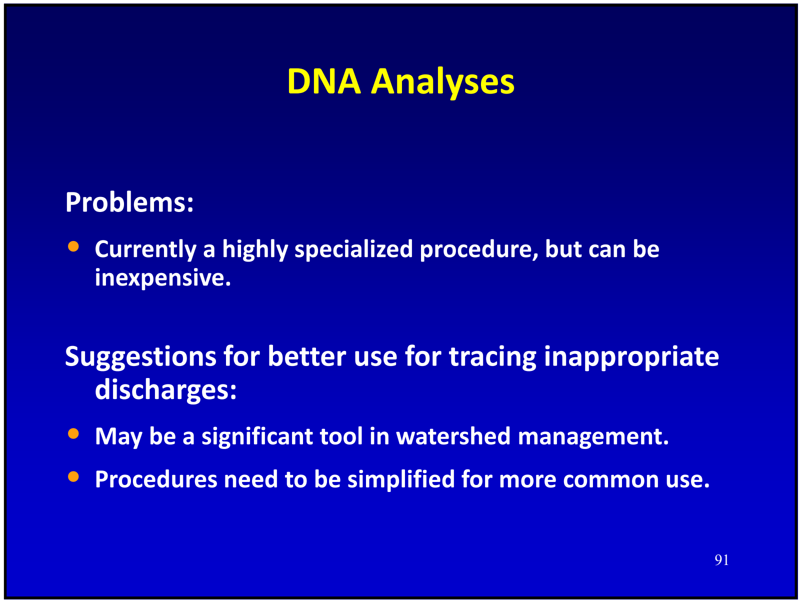
- DNA patterns in fecal coliforms vary among organisms, and it is relatively straight-forward to distinguish between human and non-human sources of bacteria.
- Several investigations have cataloged the DNA of *E. coli* to identify their source in water. This rapidly emerging technique seems to have great promise in addressing a number of nonpoint source water pollution issues.



DNA Analyses

Where successfully used to trace sanitary sewage (historical studies):

- Virginia Polytechnic Institute and State University using DNA of *E. coli* identified bird population as source of bacteria contamination of a shellfish bed in Chesapeake Bay (instead of suspected failing septic tanks).
- Wright State University researchers have used randomly amplified polymorphic DNA polymerase chain reaction (RAPD-PCR) techniques on populations of snails, pill bugs, violets, spiders, earthworms, herring, and some benthic macroinvertebrates (Krane, *et al*. 1999).



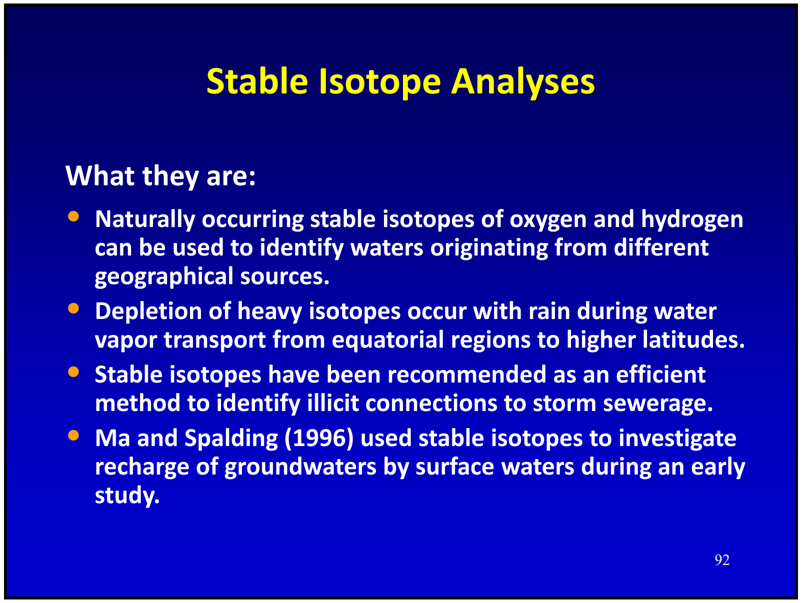
DNA Analyses

Problems:

- Currently a highly specialized procedure, but can be inexpensive.

Suggestions for better use for tracing inappropriate discharges:

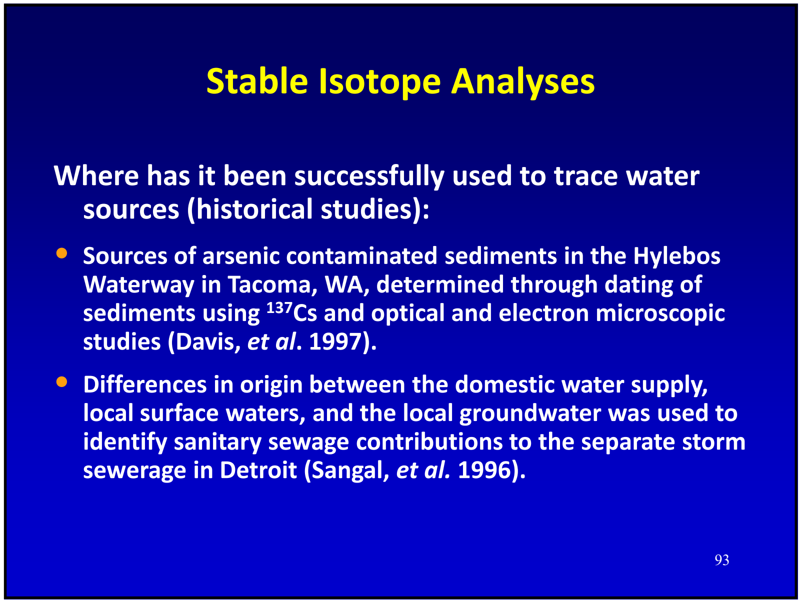
- May be a significant tool in watershed management.
- Procedures need to be simplified for more common use.



Stable Isotope Analyses

What they are:

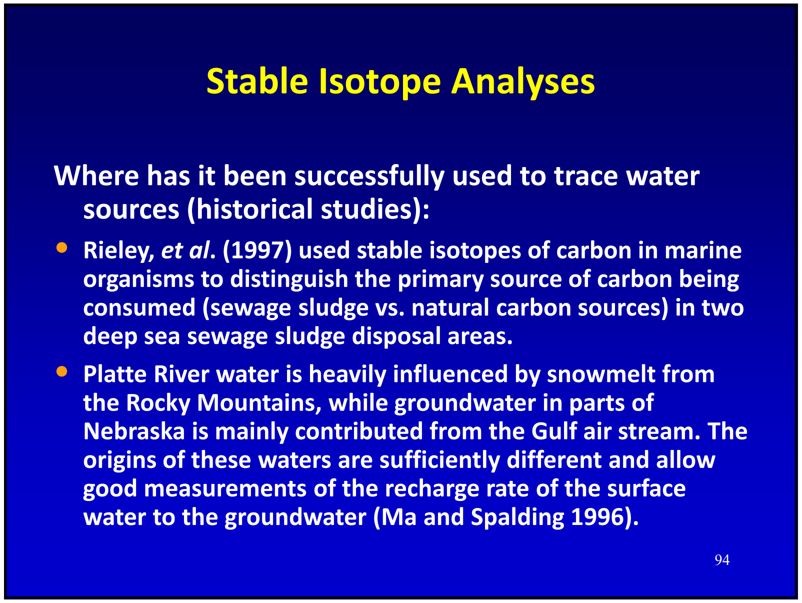
- Naturally occurring stable isotopes of oxygen and hydrogen can be used to identify waters originating from different geographical sources.
- Depletion of heavy isotopes occur with rain during water vapor transport from equatorial regions to higher latitudes.
- Stable isotopes have been recommended as an efficient method to identify illicit connections to storm sewerage.
- Ma and Spalding (1996) used stable isotopes to investigate recharge of groundwaters by surface waters during an early study.



Stable Isotope Analyses

Where has it been successfully used to trace water sources (historical studies):

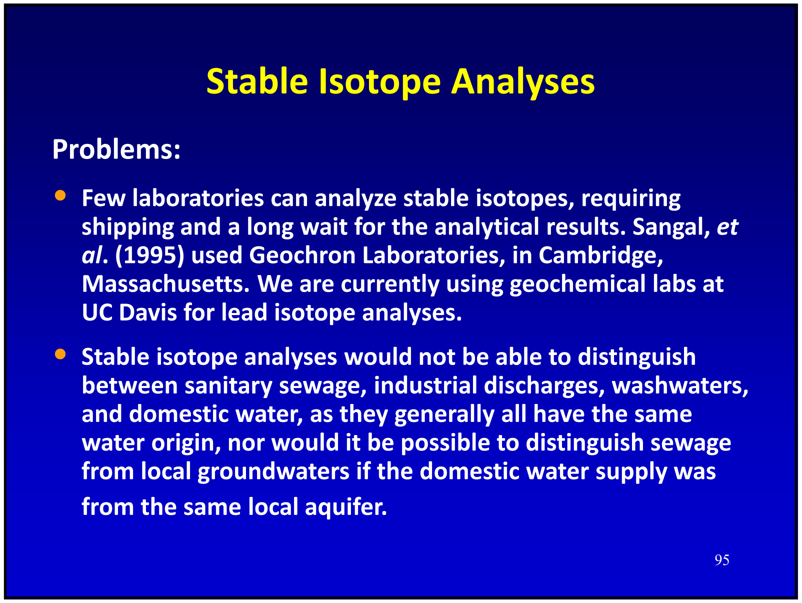
- Sources of arsenic contaminated sediments in the Hylebos Waterway in Tacoma, WA, determined through dating of sediments using ^{137}Cs and optical and electron microscopic studies (Davis, *et al*. 1997).
- Differences in origin between the domestic water supply, local surface waters, and the local groundwater was used to identify sanitary sewage contributions to the separate storm sewerage in Detroit (Sangal, *et al.* 1996).



Stable Isotope Analyses

Where has it been successfully used to trace water sources (historical studies):

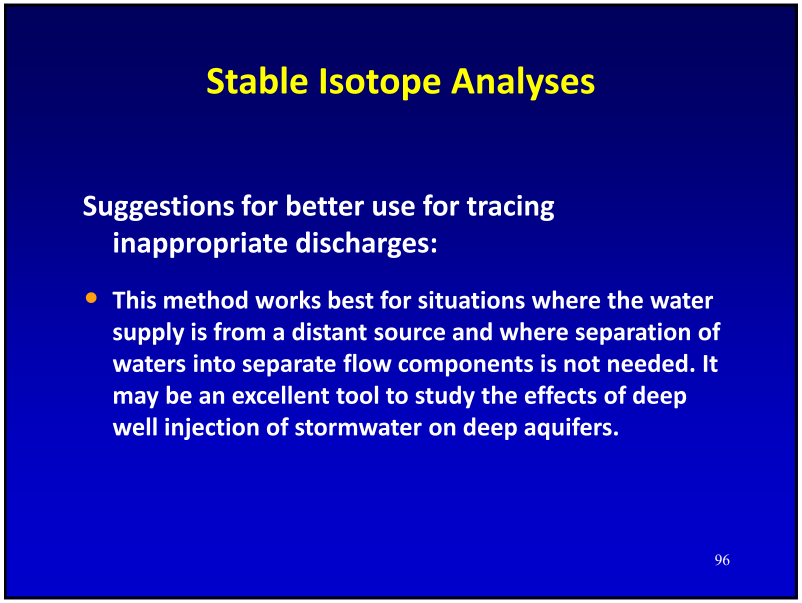
- Rieley, *et al*. (1997) used stable isotopes of carbon in marine organisms to distinguish the primary source of carbon being consumed (sewage sludge vs. natural carbon sources) in two deep sea sewage sludge disposal areas.
- Platte River water is heavily influenced by snowmelt from the Rocky Mountains, while groundwater in parts of Nebraska is mainly contributed from the Gulf air stream. The origins of these waters are sufficiently different and allow good measurements of the recharge rate of the surface water to the groundwater (Ma and Spalding 1996).



Stable Isotope Analyses

Problems:

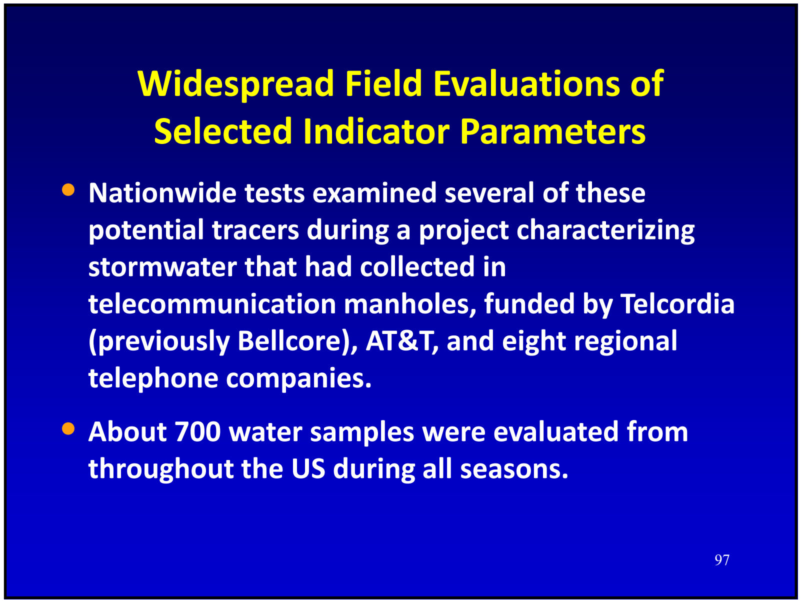
- Few laboratories can analyze stable isotopes, requiring shipping and a long wait for the analytical results. Sangal, *et al*. (1995) used Geochron Laboratories, in Cambridge, Massachusetts. We are currently using geochemical labs at UC Davis for lead isotope analyses.
- Stable isotope analyses would not be able to distinguish between sanitary sewage, industrial discharges, washwaters, and domestic water, as they generally all have the same water origin, nor would it be possible to distinguish sewage from local groundwaters if the domestic water supply was from the same local aquifer.



Stable Isotope Analyses

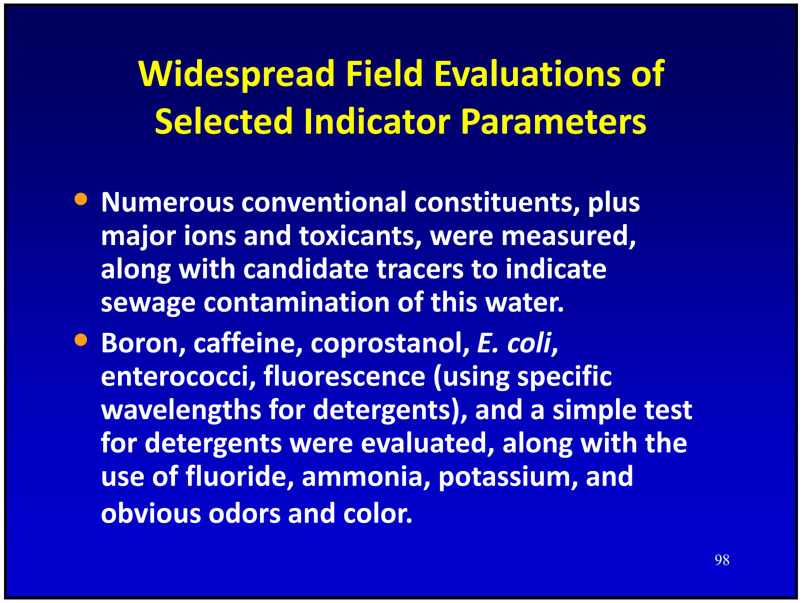
Suggestions for better use for tracing inappropriate discharges:

- This method works best for situations where the water supply is from a distant source and where separation of waters into separate flow components is not needed. It may be an excellent tool to study the effects of deep well injection of stormwater on deep aquifers.



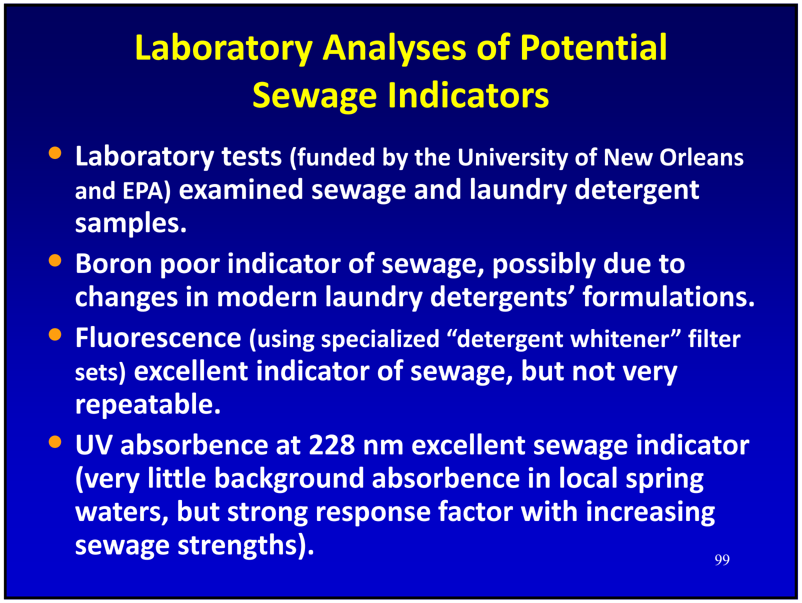
Widespread Field Evaluations of Selected Indicator Parameters

- Nationwide tests examined several of these potential tracers during a project characterizing stormwater that had collected in telecommunication manholes, funded by Telcordia (previously Bellcore), AT&T, and eight regional telephone companies.
- About 700 water samples were evaluated from throughout the US during all seasons.



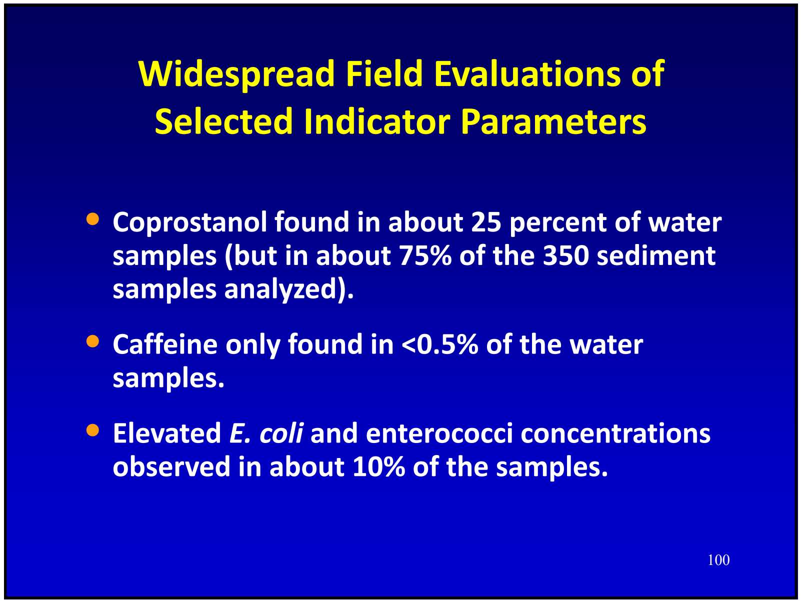
Widespread Field Evaluations of Selected Indicator Parameters

- Numerous conventional constituents, plus major ions and toxicants, were measured, along with candidate tracers to indicate sewage contamination of this water.
- Boron, caffeine, coprostanol, *E. coli*, enterococci, fluorescence (using specific wavelengths for detergents), and a simple test for detergents were evaluated, along with the use of fluoride, ammonia, potassium, and obvious odors and color.



Laboratory Analyses of Potential Sewage Indicators

- Laboratory tests (funded by the University of New Orleans and EPA) examined sewage and laundry detergent samples.
- Boron poor indicator of sewage, possibly due to changes in modern laundry detergents' formulations.
- Fluorescence (using specialized "detergent whitener" filter sets) excellent indicator of sewage, but not very repeatable.
- UV absorbence at 228 nm excellent sewage indicator (very little background absorbence in local spring waters, but strong response factor with increasing sewage strengths).



Widespread Field Evaluations of Selected Indicator Parameters

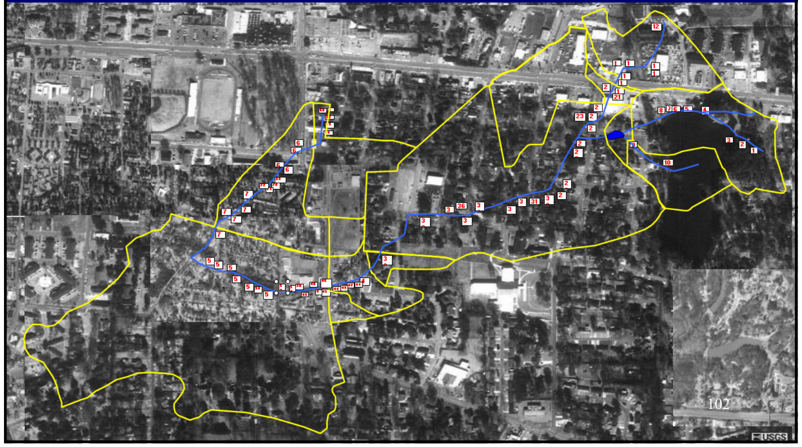
- Coprostanol found in about 25 percent of water samples (but in about 75% of the 350 sediment samples analyzed).
- Caffeine only found in <0.5% of the water samples.
- Elevated *E. coli* and enterococci concentrations observed in about 10% of the samples.

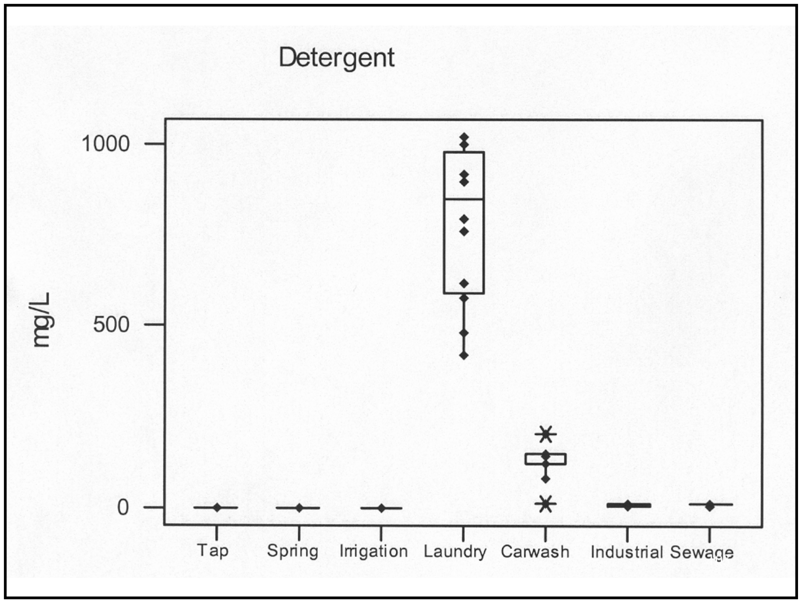
Widespread Field Evaluations of Selected Indicator Parameters

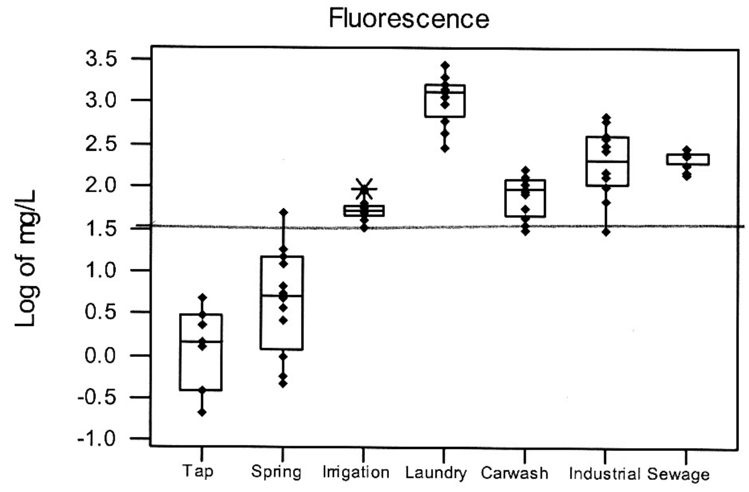
- Strong sewage odors detected in about 10% of the water and sediment samples.
- About ten percent of the samples estimated to be contaminated with sanitary sewage using these methods, similar to what is expected for most stormwater systems.

Storm Drainage System with Outfalls Studied to Verify Methods

A typical storm drainage system in Tuscaloosa, Alabama

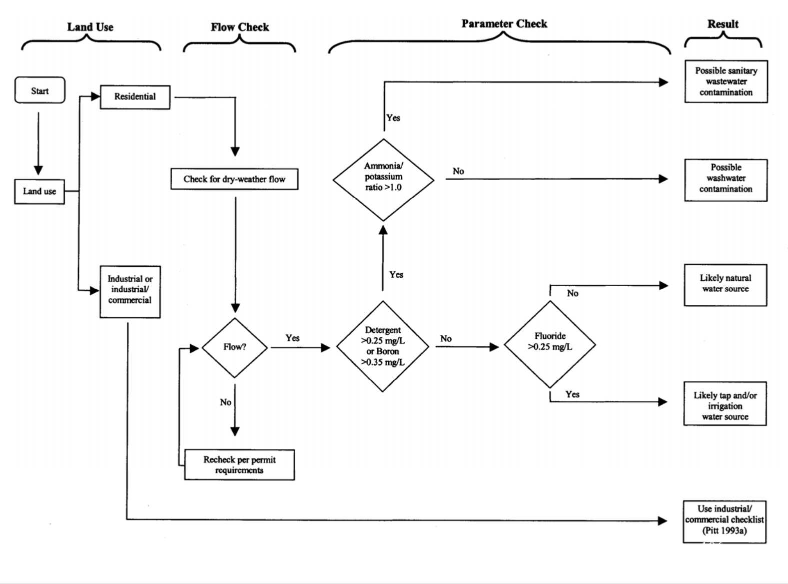






Chemical “Fingerprints” of Major Sources

- Sewage
- Wash water
- Septage
- Shallow groundwater
- Tap water
- Spring water
- Landscape irrigation
- Laundromats
- Car washes
- Industrial process waters



Example Flowsheet Evaluation

	Value	Likely source
Detergents	0.23 mg/L	Sanitary wastewater or washwater
Fluoride	0.35 mg/L	Domestic water source
Ammonia/ Potassium ratio	1.3	Sanitary wastewater source

The major flow component is most likely sanitary wastewater

Chemical Mass Balance Equations

$$(m_1)(x_{11}) + (m_2)(x_{12}) + (m_3)(x_{13}) = C_1$$

$$(m_1)(x_{21}) + (m_2)(x_{22}) + (m_3)(x_{23}) = C_2$$

$$(m_1)(x_{31}) + (m_2)(x_{32}) + (m_3)(x_{33}) = C_3$$

$$\Sigma_n(m_n)\ (x_{pn}) = C_p$$

m_n = the fraction of flow from source type n
x_{pn} = the concentration of tracer p in source type n
C_p = the concentration of tracer p in the outfall flow

Example Background (Library) Data

Infiltrating Groundwater

Tracer	Median Concentration	COV	Distribution
Conductivity	51.4	0.84	N
Fluoride	0.06	0.5	L
Hardness	27.3	0.39	N
Detergent	0	0	
Fluorescence	29.9	1.55	L
Potassium	1.19	0.44	N
Ammonia	0.24	1.26	N
Color	8	1.42	L

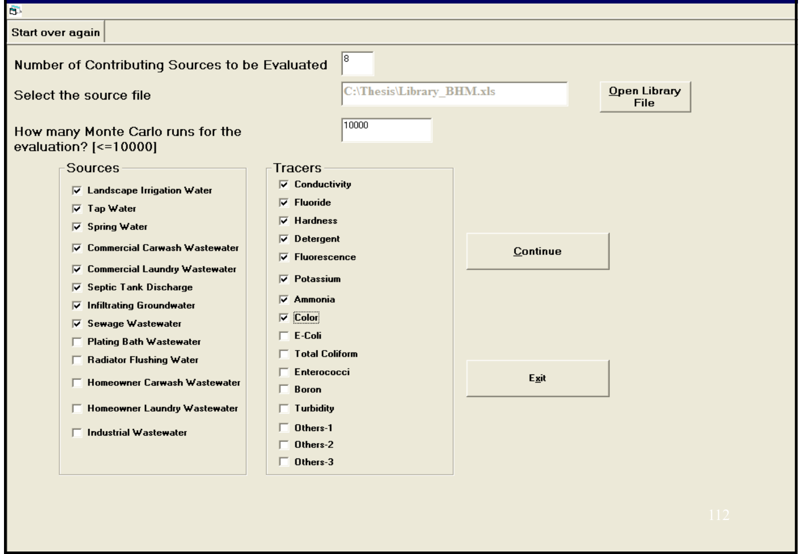
Tuscaloosa, AL, “Library” File Data (conc. and COV)

Mean/COV	Fluoride (mg/L)	Detergents (mg/L MBAS)	Ammonia (mg/L, as N)	Potassium (mg/L)
Tap water	0.95 (0.03)	0 (0)	0 (0)	1 (0)
Spring water	0.024 (1.3)	0 (0)	0.034 (0.82)	3.4 (0.79)
Car wash water	0.02 (1.4)	80 (1.2)	0.55 (0.27)	6 (0.94)
House laundry water	1.1 (0.18)	960 (0.06)	1.0 (0.15)	2 (0)
Sewage	0.68 (0.07)	11 (0.12)	22 (0.71)	12 (0.19)
Industrial wastewater	0.21 (1.7)	6.0 (0.68)	5.3 (0.73)	49 (0.52)

Tuscaloosa, AL, “Library” File Data

Mean/COV	Hardness (mg/L)	Fluorescence (mg/L as Tide)	*E. Coli* (mpn/100 mL)	Enterococci (mpn/100 mL)
Tap water	66 (0.07)	0 (0)	0 (0)	0 (0)
Spring water	34 (0.22)	2.7 (1.6)	2.4 (0.8)	1.0 (1.6)
Car wash water	36 (0.82)	131 (0.01)	1480 (0.07)	1213 (1.4)
House laundry water	16 (0.23)	1117 (0.15)	n/a	n/a
Sewage	50 (0.28)	187 (0.28)	1413 (not (0.65) discrete)	1220 (not (1.1) discrete)
Industrial wastewater	32 (0.15)	278 (0.78)	409 (2.7)	477 (2.3)

Monte Carlo Chemical Mass Balance Model



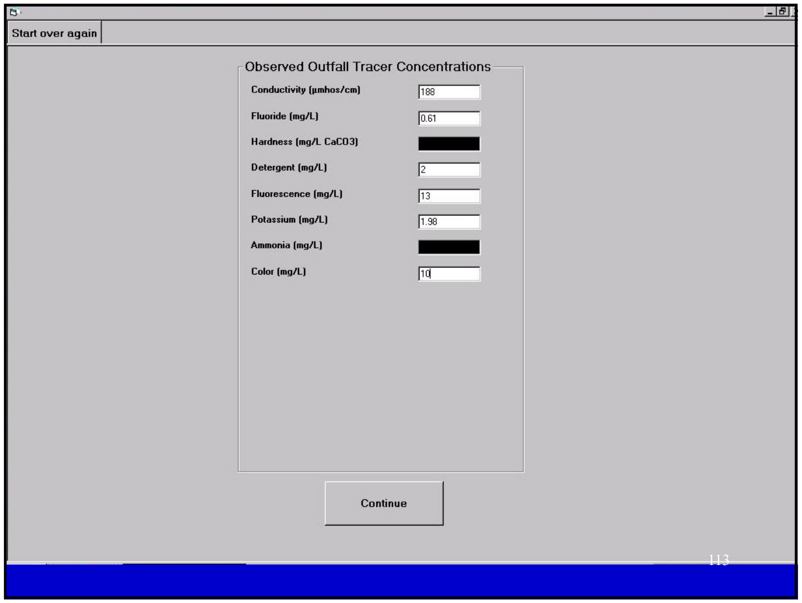
Number of Contributing Sources to be Evaluated: 8

Select the source file: C:\Thesis\Library_BHM.xls

How many Monte Carlo runs for the evaluation? [<=10000]: 10000

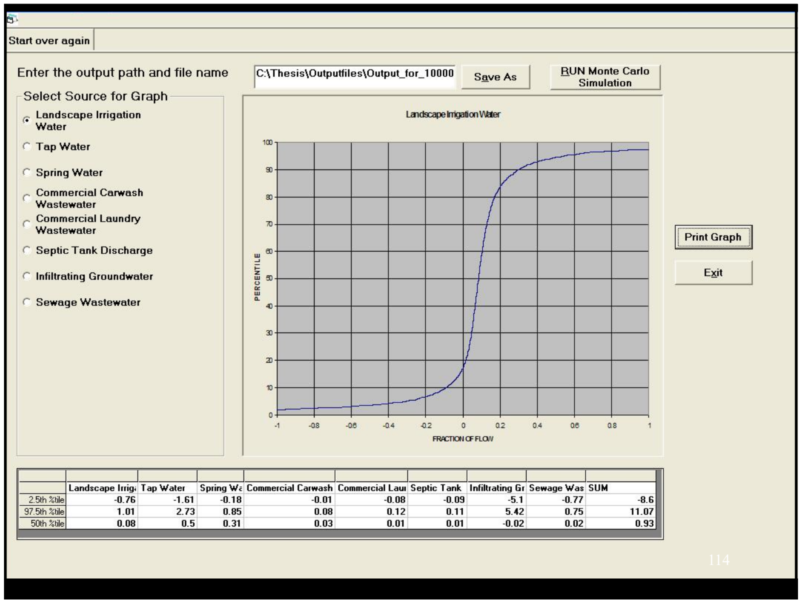
Sources
- ☑ Landscape Irrigation Water
- ☑ Tap Water
- ☑ Spring Water
- ☑ Commercial Carwash Wastewater
- ☑ Commercial Laundry Wastewater
- ☑ Septic Tank Discharge
- ☑ Infiltrating Groundwater
- ☑ Sewage Wastewater
- ☐ Plating Bath Wastewater
- ☐ Radiator Flushing Water
- ☐ Homeowner Carwash Wastewater
- ☐ Homeowner Laundry Wastewater
- ☐ Industrial Wastewater

Tracers
- ☑ Conductivity
- ☑ Fluoride
- ☑ Hardness
- ☑ Detergent
- ☑ Fluorescence
- ☑ Potassium
- ☑ Ammonia
- ☑ Color
- ☐ E-Coli
- ☐ Total Coliform
- ☐ Enterococci
- ☐ Boron
- ☐ Turbidity
- ☐ Others-1
- ☐ Others-2
- ☐ Others-3



Observed Outfall Tracer Concentrations

Conductivity (µmhos/cm)	188
Fluoride (mg/L)	0.61
Hardness (mg/L CaCO3)	
Detergent (mg/L)	2
Fluorescence (mg/L)	13
Potassium (mg/L)	1.98
Ammonia (mg/L)	
Color (mg/L)	10



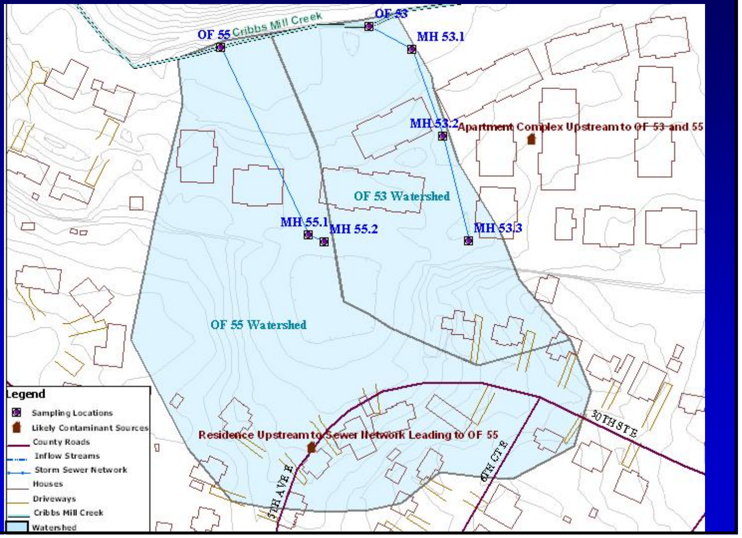
Enter the output path and file name: C:\Thesis\Outputfiles\Output_for_10000

Select Source for Graph

- ● Landscape Irrigation Water
- ○ Tap Water
- ○ Spring Water
- ○ Commercial Carwash Wastewater
- ○ Commercial Laundry Wastewater
- ○ Septic Tank Discharge
- ○ Infiltrating Groundwater
- ○ Sewage Wastewater

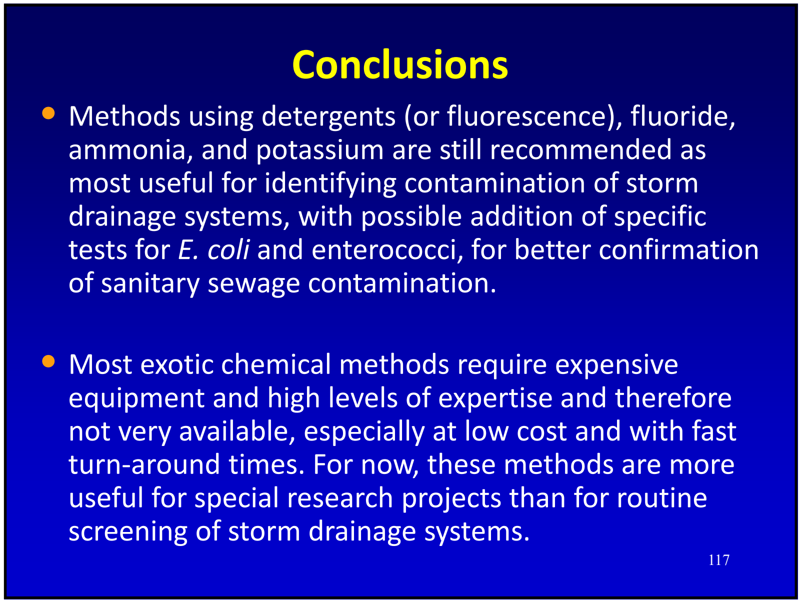
	Landscape Irriga	Tap Water	Spring Wa	Commercial Carwash	Commercial Laui	Septic Tank	Infiltrating Gr	Sewage Was	SUM
2.5th %tile	-0.76	-1.61	-0.18	-0.01	-0.08	-0.09	-5.1	-0.77	-8.6
97.5th %tile	1.01	2.73	0.85	0.08	0.12	0.11	5.42	0.75	11.07
50th %tile	0.08	0.5	0.31	0.03	0.01	0.01	-0.02	0.02	0.93

The use of GIS to identify potential contaminant sources in drainage areas.



Summary Table of Outfalls with Problem Sources

Corresponding outfall number	Flow chart result for all observations related to each outfall (No. of Contaminated sources)	Percentage of Samples with problems
3	4 of 13	31
4	0 of 19	0
27	0 of 9	0
36	2 of 13	15
39	1 of 8	13
45	0 of 13	0
53	2 of 16	13
55	4 of 9	44



Conclusions

- Methods using detergents (or fluorescence), fluoride, ammonia, and potassium are still recommended as most useful for identifying contamination of storm drainage systems, with possible addition of specific tests for *E. coli* and enterococci, for better confirmation of sanitary sewage contamination.

- Most exotic chemical methods require expensive equipment and high levels of expertise and therefore not very available, especially at low cost and with fast turn-around times. For now, these methods are more useful for special research projects than for routine screening of storm drainage systems.