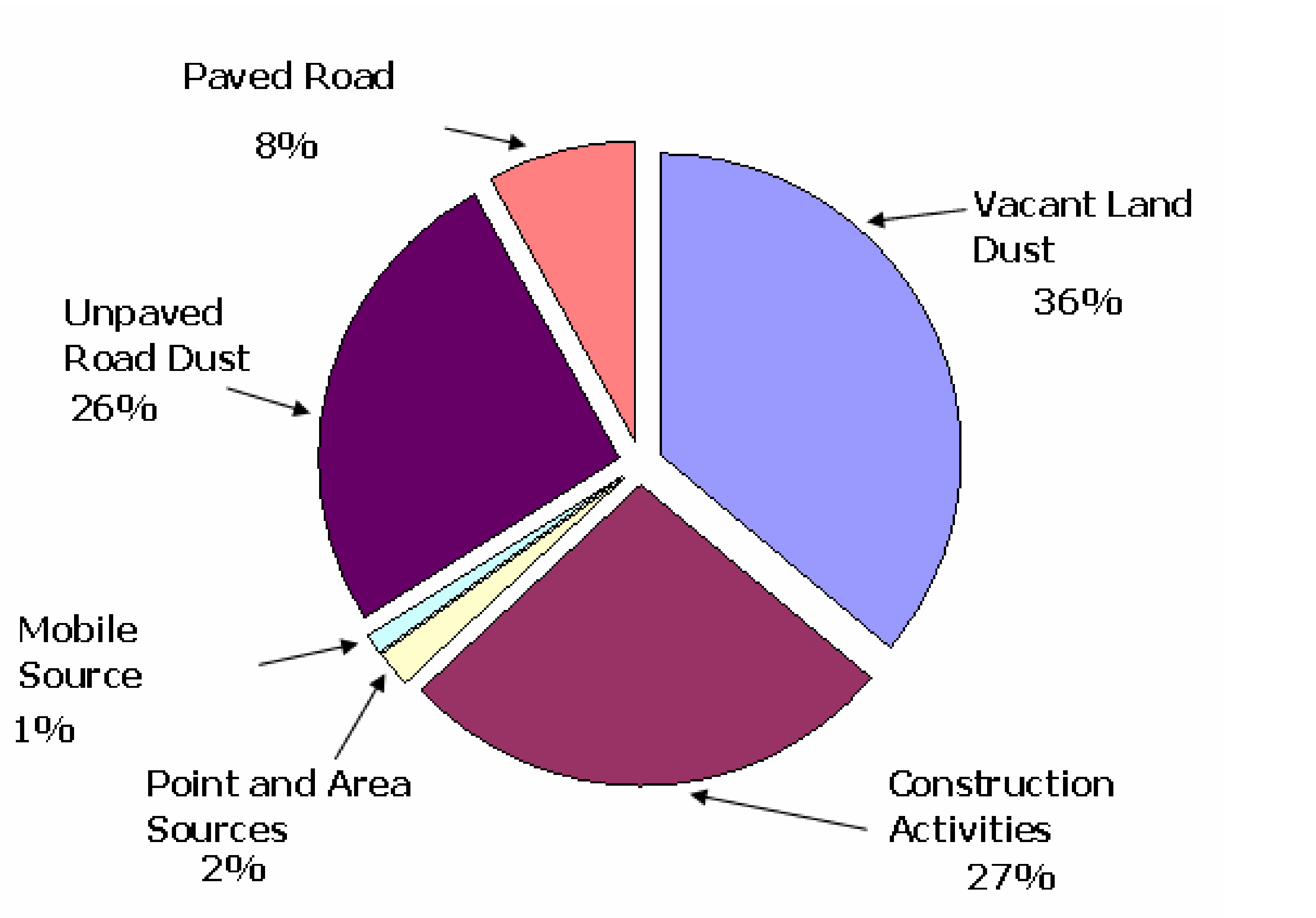
Wind Tunnel measurement of emission factors from crusted and intentionally disturbed urban soils

UNLV - David James, Rosangela Wacaser, Kayli Barber, Jennifer Bentley, Vinod Chakka, Srinivas Pulugurtha

Clark County Dept of Air Quality Management - Russ Merle, Michael Uhl, Rodney Langston

Clark County 2001 PM-10 inventory



Wind blown dust – rationale for additional study

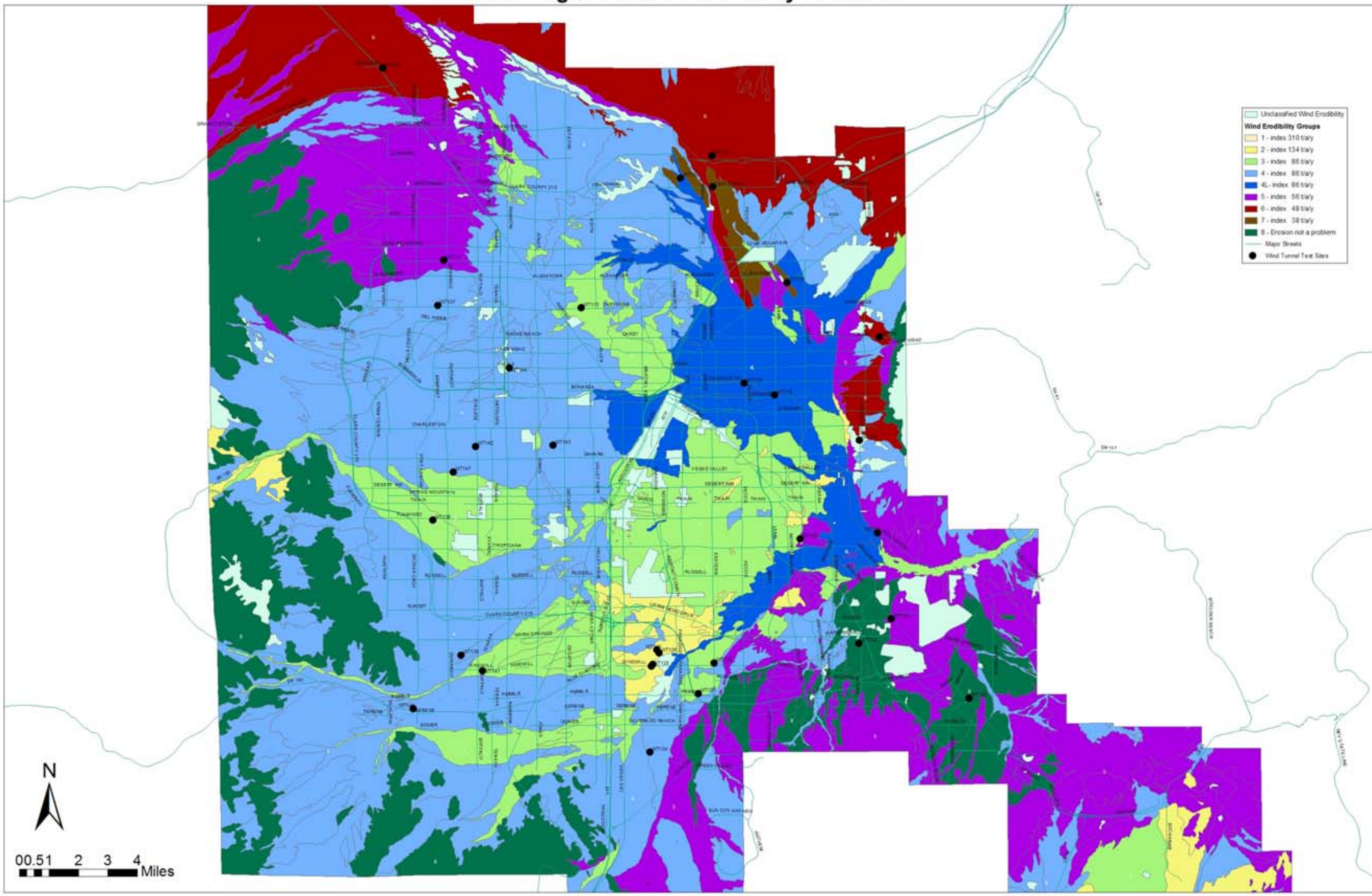
- Many 1995 field sites now overbuilt
  - *Overbuilt sites no longer exposed to wind*
- 1995 data set size too small for unstable surface predictions
  - *78 different sites, 3 runs/site – 268 records (some repeats)*
  - *Most (n=18x) site surfaces were stable*
  - *Unstable (n=63): sparse matrix of windspeeds/soil groups*
  - *Some windspeed/soil group combinations had no data*
- Tunnel field techniques and data reduction methods improved

Scope of 2004 field study

- Field reconnaissance & site characterization
- Selected 32 sites representing 7 of 9 major USGS soil Wind Erodibility classifications
- Test as-found, then destroy crust
- Three runs stable, 3 unstable

NRCS Wind erodibility groups

2004 Las Vegas Wind Tunnel Study Test Sites



Site summary & GIS analysis

WEG	COUNT	TOTAL AREA (ft^2)	TOTAL AREA (square miles)	NUMBER OF SITES	SQUARE MILE PER SITE	SITES PER SQUARE MILE
Unclassified	0	796,869,944	28.58	1	28.58	3.50E-02
2	25	526,255,269	18.88	4	4.72	2.12E-01
3	63	2,474,638,279	88.77	6	14.79	6.76E-02
4	180	7,416,845,250	266.04	8	33.26	3.01E-02
4L	18	1,194,982,715	42.86	3	14.29	7.00E-02
5	162	3,502,786,243	125.65	3	41.88	2.39E-02
6	15	1,817,786,973	65.20	3	21.73	4.60E-02
7	6	98,860,921	3.55	2	1.77	5.64E-01
8	61	2,983,670,293	107.02	2	53.51	1.87E-02

Surface Site characterization methods– to determine *in-situ* stability

- Followed Clark County Construction BMP manual
- 3 Random quadrat casts
  - 5 Ball bearing drops from 1 foot
- 3 more random casts –
  - Field sieve – to estimate TFV
  - Cake pan test – (rocks > 3/8” surface coverage)
- Rock count > 1 cm – 3 100 ft transects

Surface characterization results

- 38 sites studied
  - 6 rejected – construction activity or permission refused
- 32 sites tested with wind tunnel
  - 1 site rated Unstable by BMP methods
  - 31 sites rated Stable by BMP methods
- To develop unstable data
  - Intentionally broke crust with gravel rake

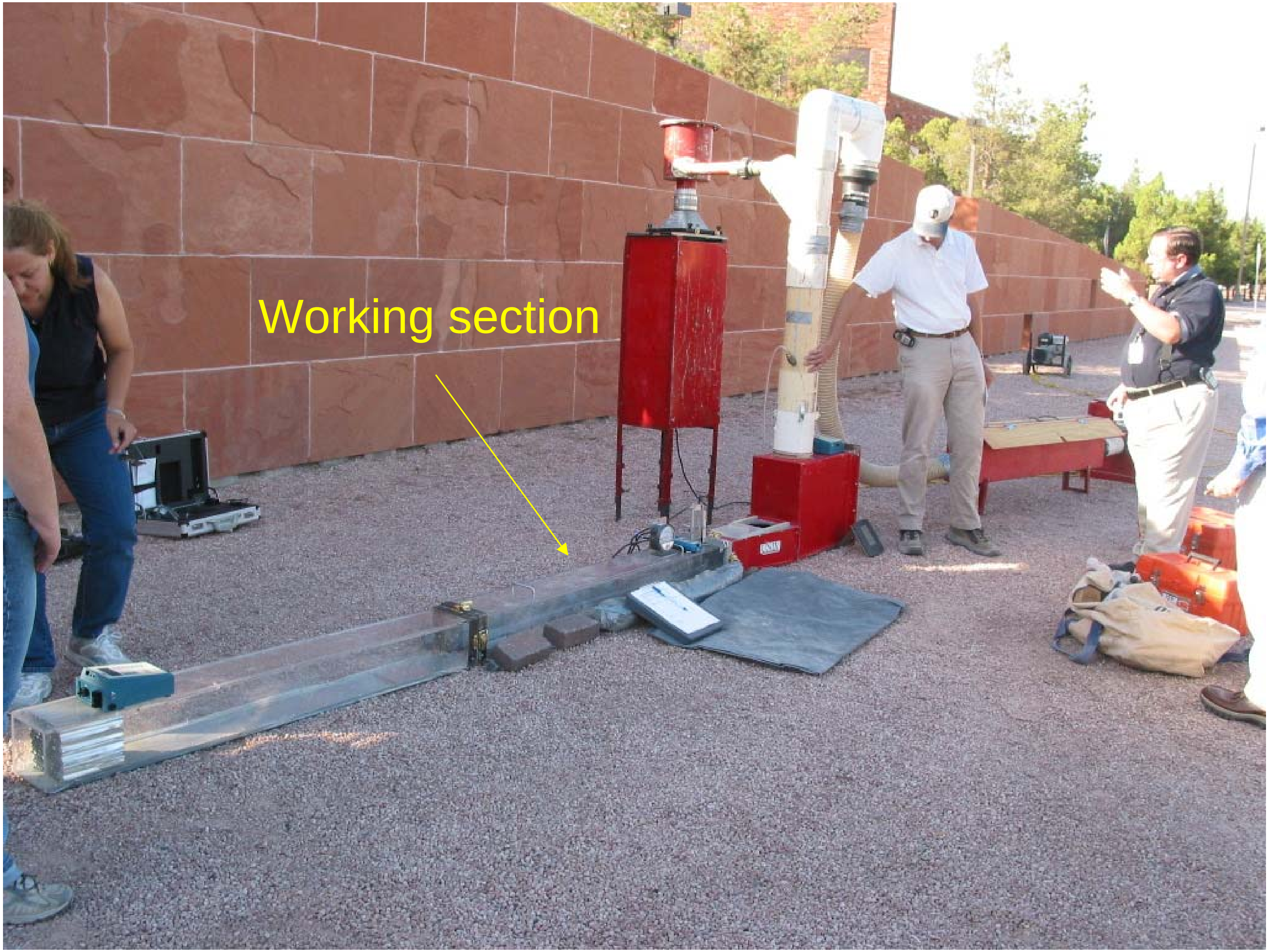
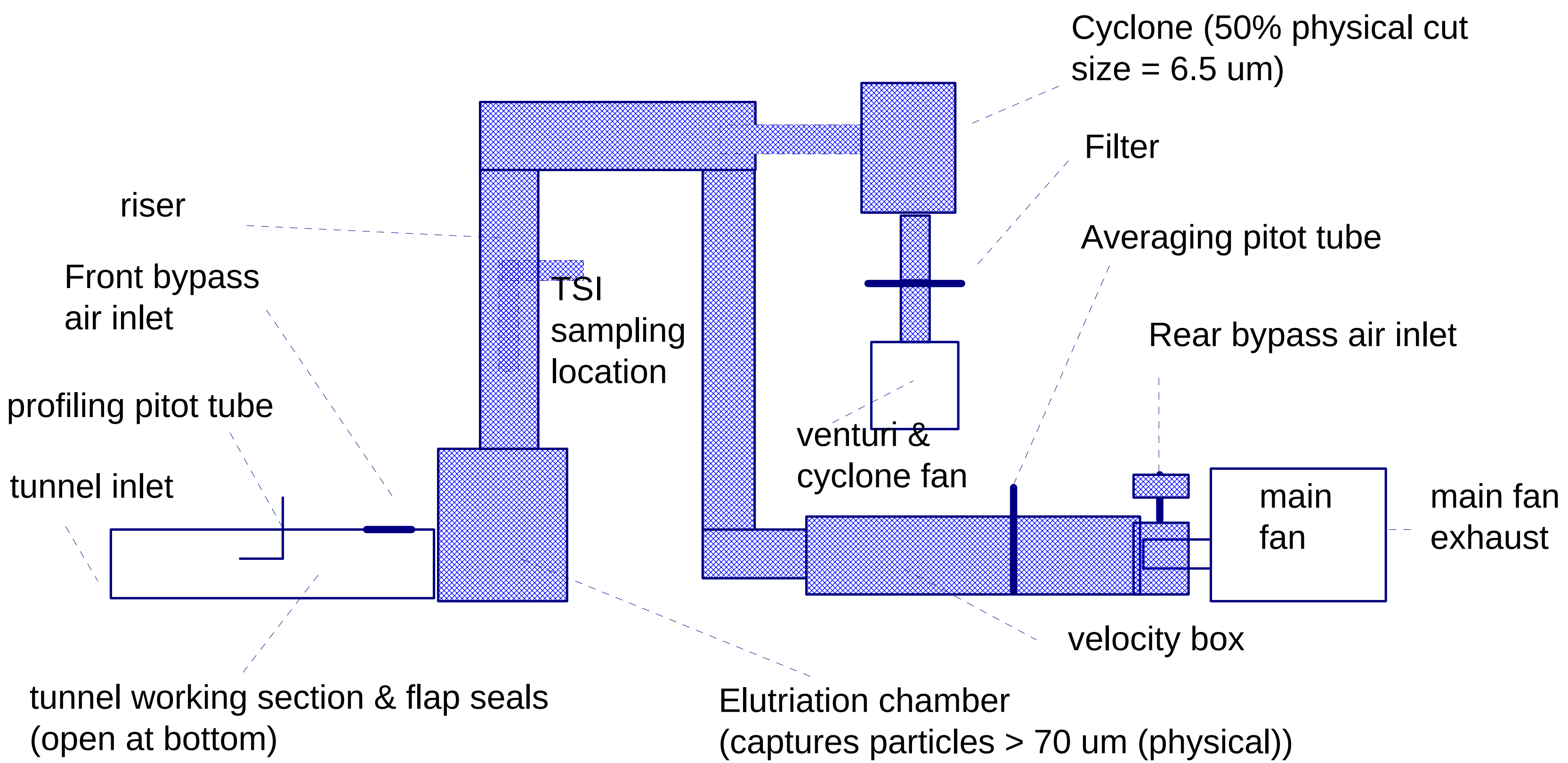
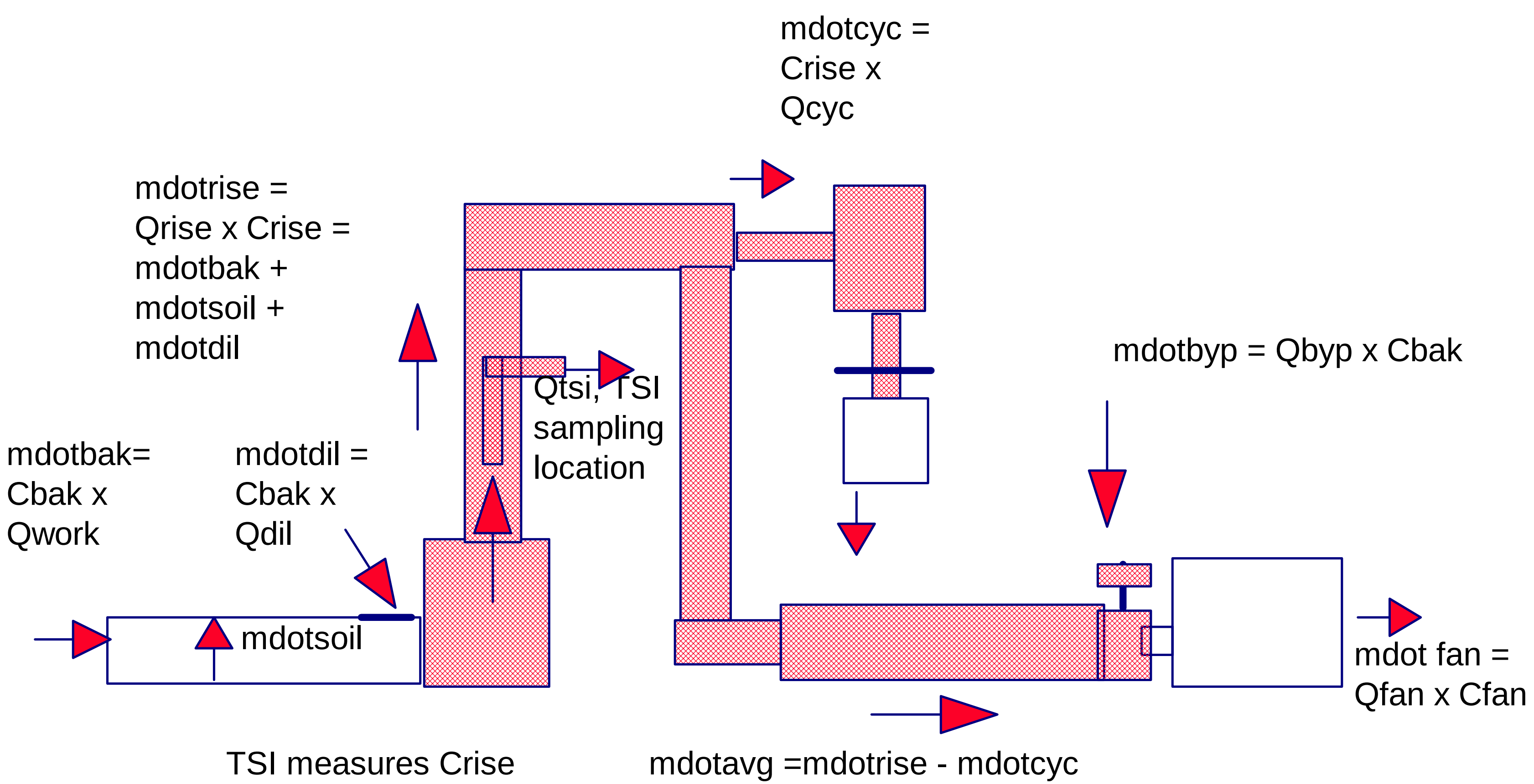

Working section

Figure 1 - Wind Tunnel Component Diagram




Profiling pitot tube and recording transducer
Damper controls working section velocity
UNLV

Figure 2: Wind Tunnel PM-10 Mass Balance
arrows indicate PM-10 mass fluxes



Solve mass balance

- Flux = [(Flow rate) x (Avg Erosion concentration – Avg ambient concentration)] / (Floor area)
- Typical data:
  - Flow rate: 440-500 cfm
  - Floor area: 2.5 ft^2
  - Erosion concentration: 0.050 – 2.00 mg/m^3
  - Ambient concentration: 0.010-0.200 mg/m^3

Wind tunnel operations

- Deploy and seal to surface
- Measure in-tunnel velocity profile & estimate aerodynamic roughness, z_o
- Apply z_o & desired 10 meter wind speeds to determine u* and air velocity at tunnel centerline
- Run tunnel 4 velocity steps, 4 minutes each
- Remove tunnel, destabilize surface, reinstall
- Move tunnel to new location, repeat

Wind stress strategy

- 1995
  - One fixed wind speed each run
  - 3 runs/site, as-found (no intentional destabilization)
  - ~20-30,~30-40,~40-50 mph, 10 minutes each
- 2004
  - 4 wind speed steps, each run
  - 3 run pairs/site (as found, then destabilized)
  - 15-20, 20-30, 30-40, >40 mph, 4 min each

New 2004 field methods

- Background correction:
  - Record ambient PM-10 simultaneously with erosion in wind tunnel
  - was found to be needed, most sites
- Wind gust correction/seal leak detect
  - Record pitot tube pressure drop with recording micromanometer (TSI DPCalc™)
  - Seldom needed to correct for gust or leak

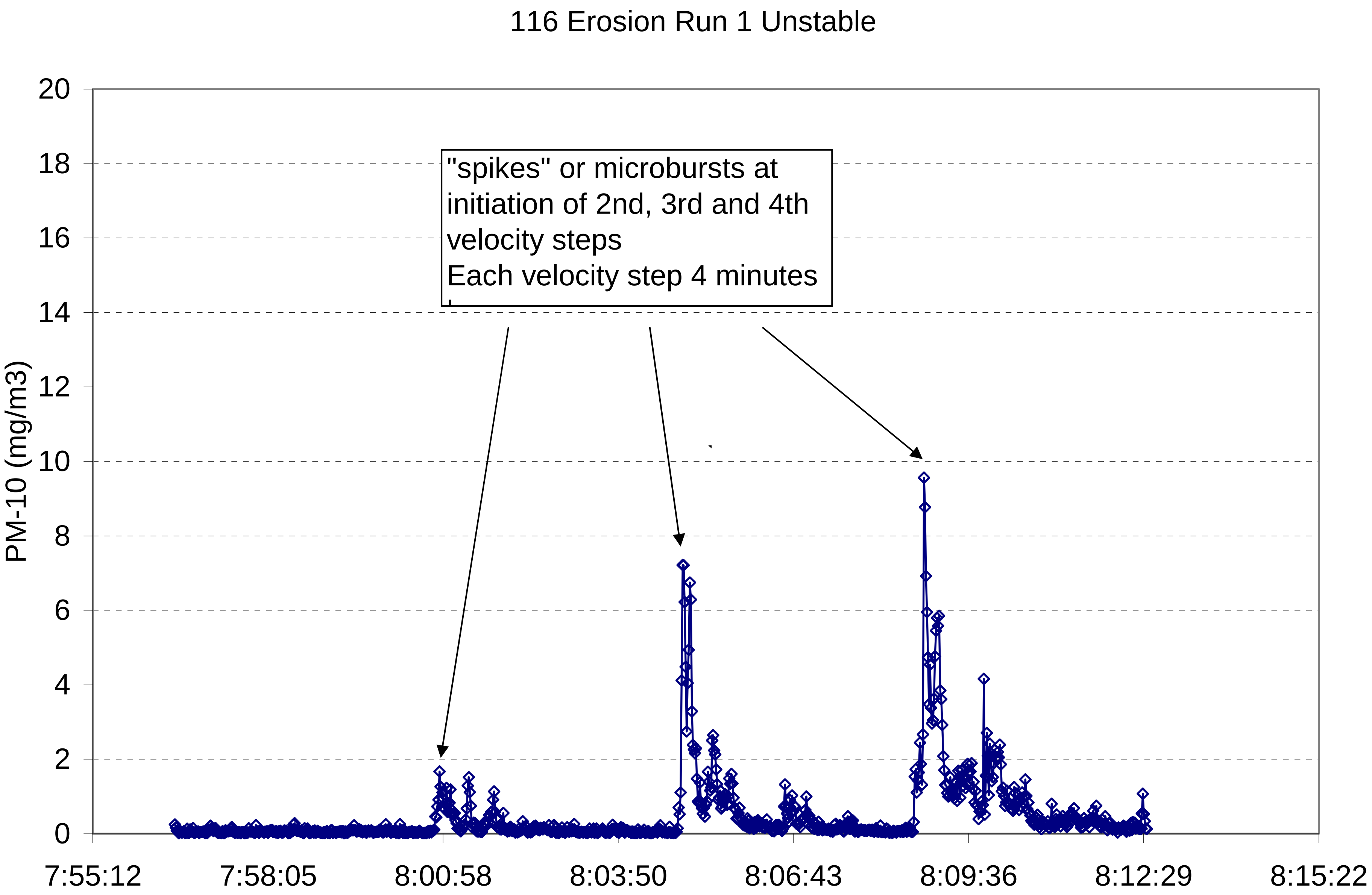
New 2004 field methods (cont)

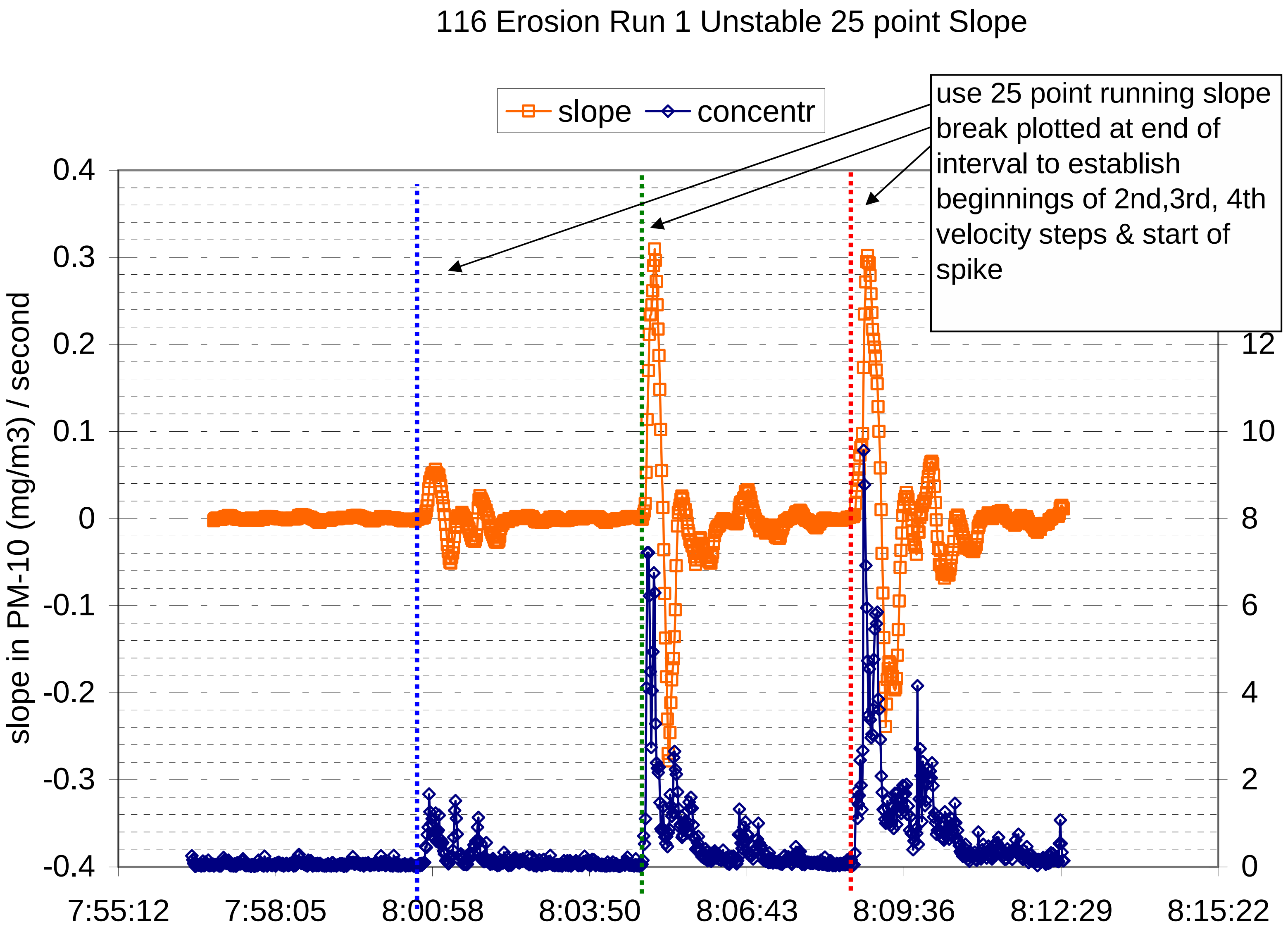
- Surface depletion during profiling
  - Done at minimum velocity – damper wide open
- 1995 – did not correct for surface depletion during profiling
- 2004 – measured ambient and tunnel-eroded PM-10 during profiling

2004 data reduction methods
Microburst or “spike” processing

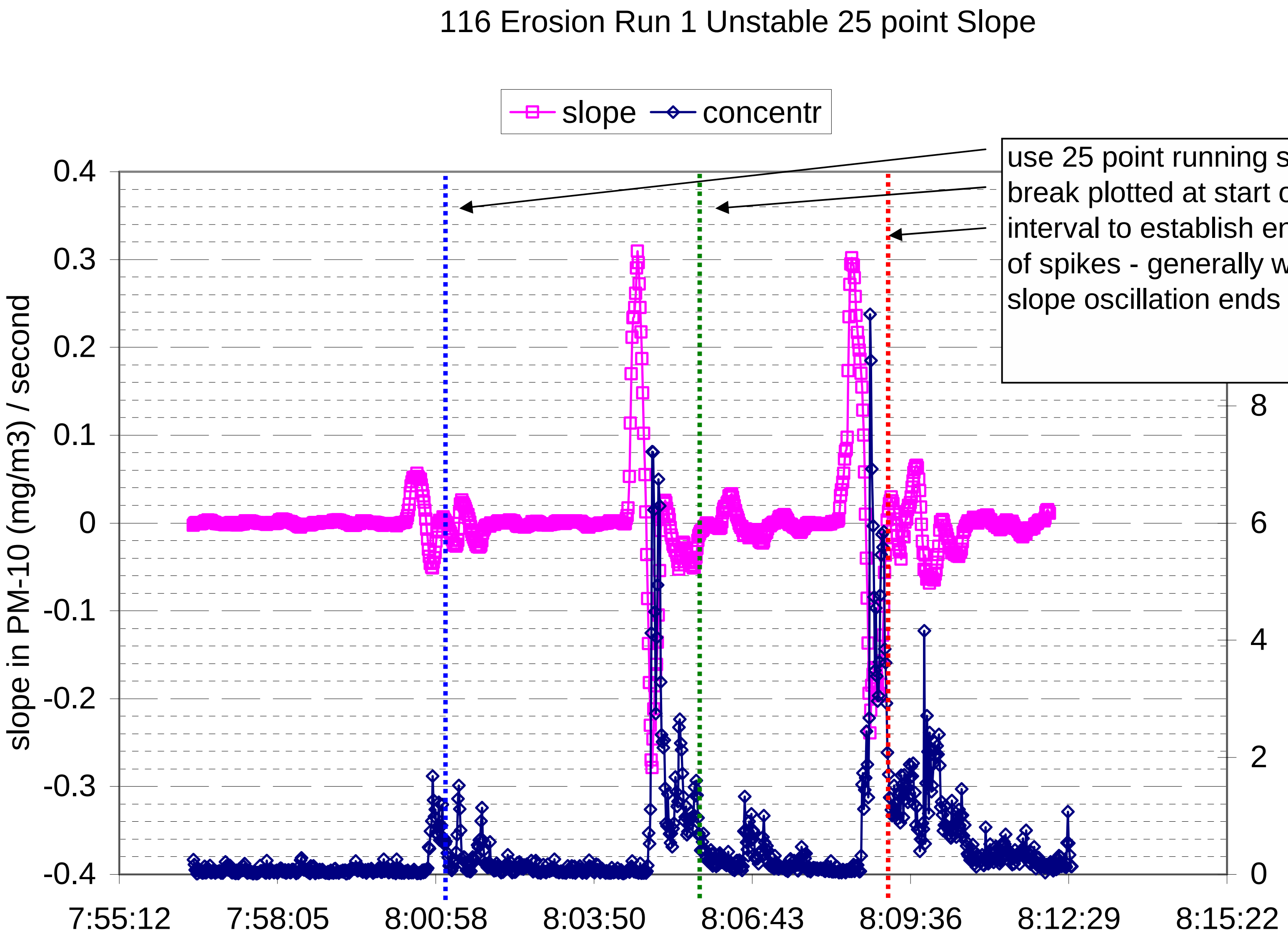
- 1995 – eyeball onset and completion of spike,
  - correct flux by proportion of non-spike area

- 2004 – objective evaluation of spike onset and completion using 25 point running slope
  - Compute average over time corresponding to “non-spike” portion of signal
  - Compute flux using non-spike average


116 Erosion Run 1 Unstable
"spikes" or microbursts at initiation of 2nd, 3rd and 4th velocity steps
Each velocity step 4 minutes
PM-10 (mg/m3)
20
18
16
14
12
10
8
6
4
2
0
7:55:12
7:58:05
8:00:58
8:03:50
8:06:43
8:09:36
8:12:29
8:15:22



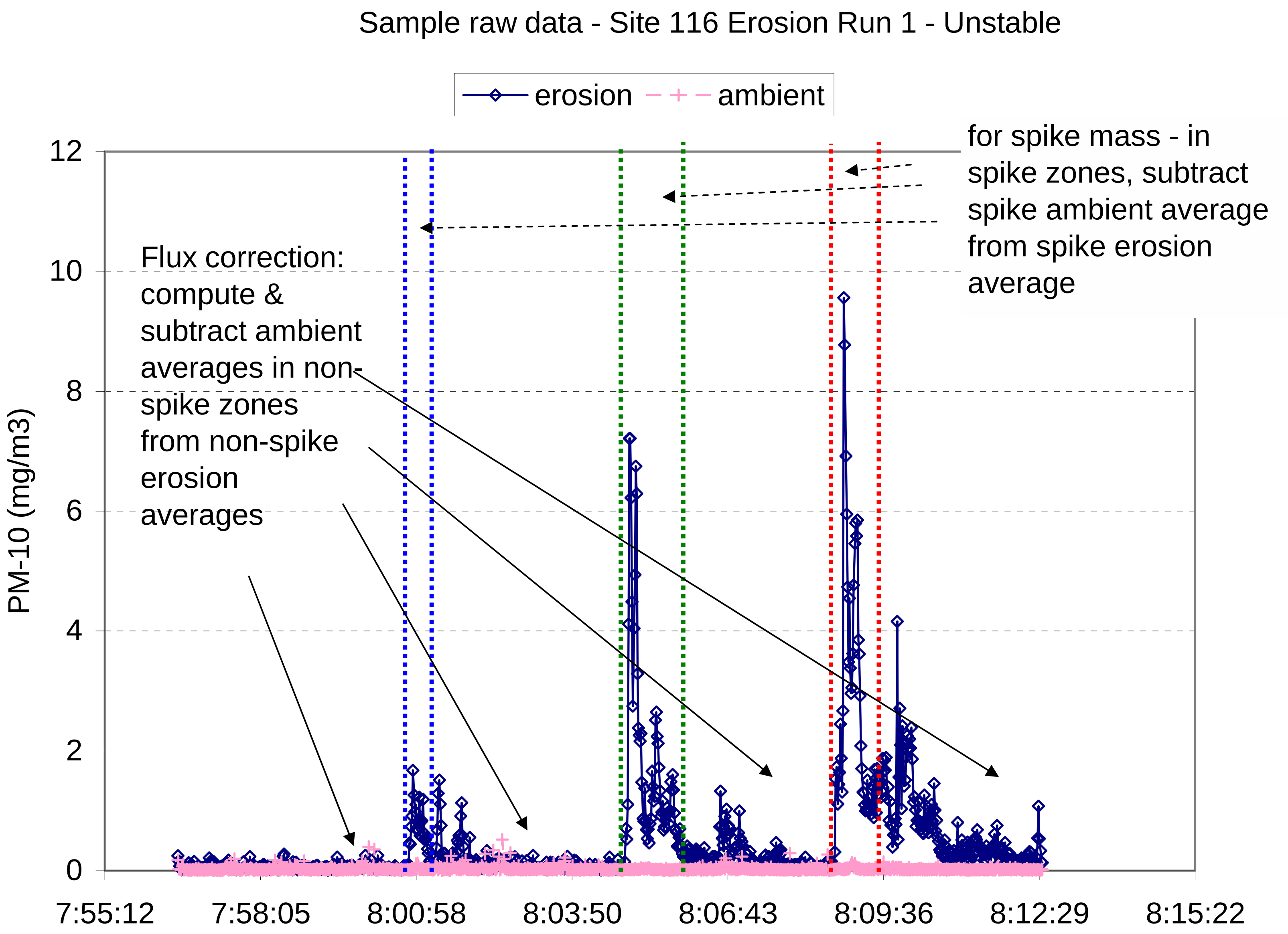
116 Erosion Run 1 Unstable 25 point Slope
slope
concentr
use 25 point running slope break plotted at end of interval to establish beginnings of 2nd,3rd, 4th velocity steps & start of spike
slope in PM-10 (mg/m3) / second
PM-10 (mg/m3)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
12
10
8
6
4
2
0
7:55:12
7:58:05
8:00:58
8:03:50
8:06:43
8:09:36
8:12:29
8:15:22



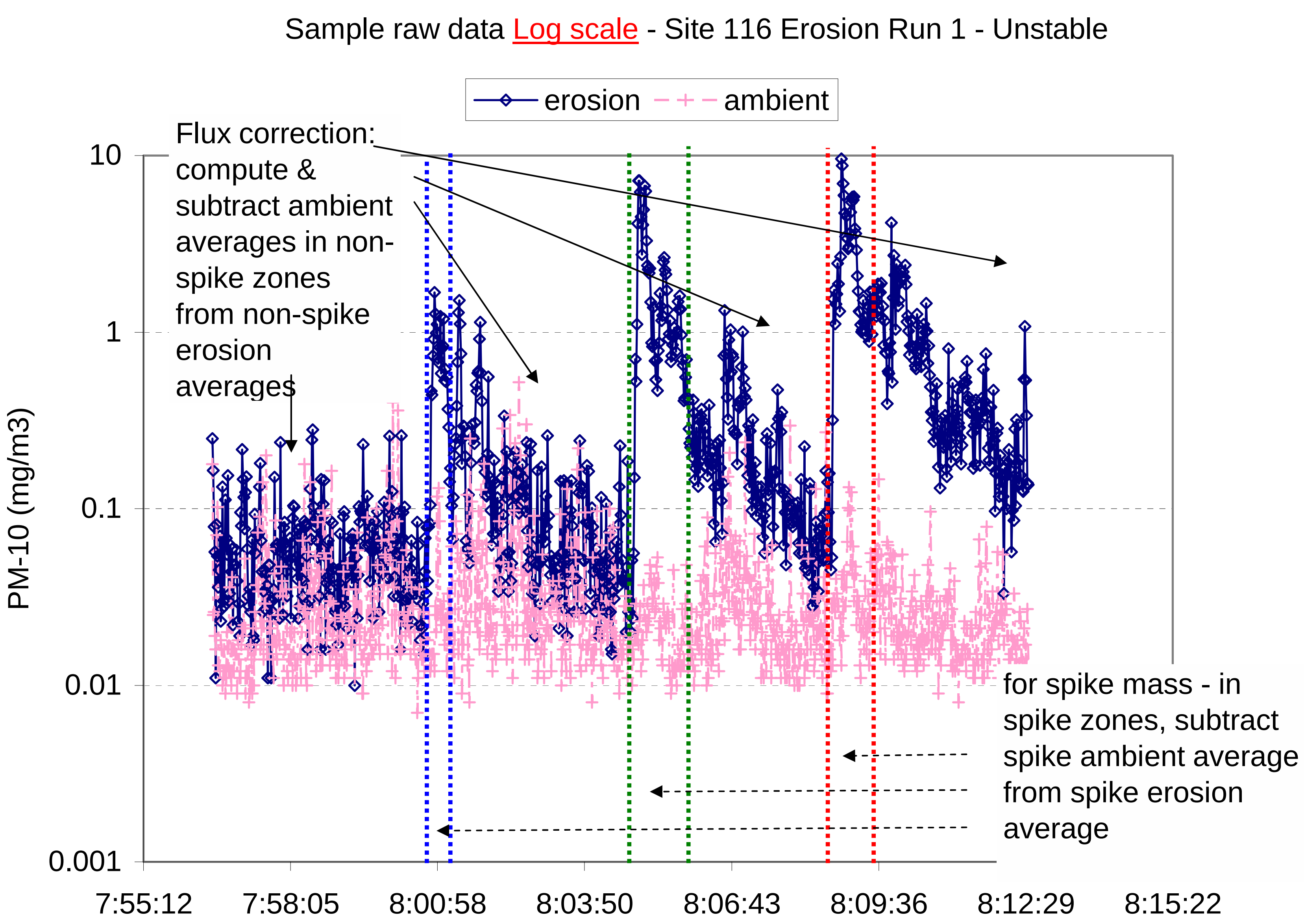
116 Erosion Run 1 Unstable 25 point Slope
slope
concentr
use 25 point running slope break plotted at start of interval to establish ends of spikes - generally where slope oscillation ends
slope in PM-10 (mg/m3) / second
PM-10 (mg/m3)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
8
6
4
2
0
7:55:12
7:58:05
8:00:58
8:03:50
8:06:43
8:09:36
8:12:29
8:15:22

Ambient background correction

- Tunnel ingests air with ambient PM-10
- 1995
  - Use assumed value, ~ 30 μg/m3
- 2004
  - Record on-site ambient 2nd TSI DustTrak®
  - Calculate average for same interval as spike corrected erosion average
  - Subtract to get net erosion



Sample raw data - Site 116 Erosion Run 1 - Unstable
erosion
ambient
for spike mass - in spike zones, subtract spike ambient average from spike erosion average
Flux correction: compute & subtract ambient averages in non-spike zones from non-spike erosion averages
PM-10 (mg/m3)
0
2
4
6
8
10
12
7:55:12
7:58:05
8:00:58
8:03:50
8:06:43
8:09:36
8:12:29
8:15:22


Sample raw data Log scale - Site 116 Erosion Run 1 - Unstable
erosion
ambient
Flux correction:
compute &
subtract ambient
averages in non-
spike zones
from non-spike
erosion
averages
for spike mass - in
spike zones, subtract
spike ambient average
from spike erosion
average
PM-10 (mg/m3)
10
1
0.1
0.01
0.001
7:55:12
7:58:05
8:00:58
8:03:50
8:06:43
8:09:36
8:12:29
8:15:22

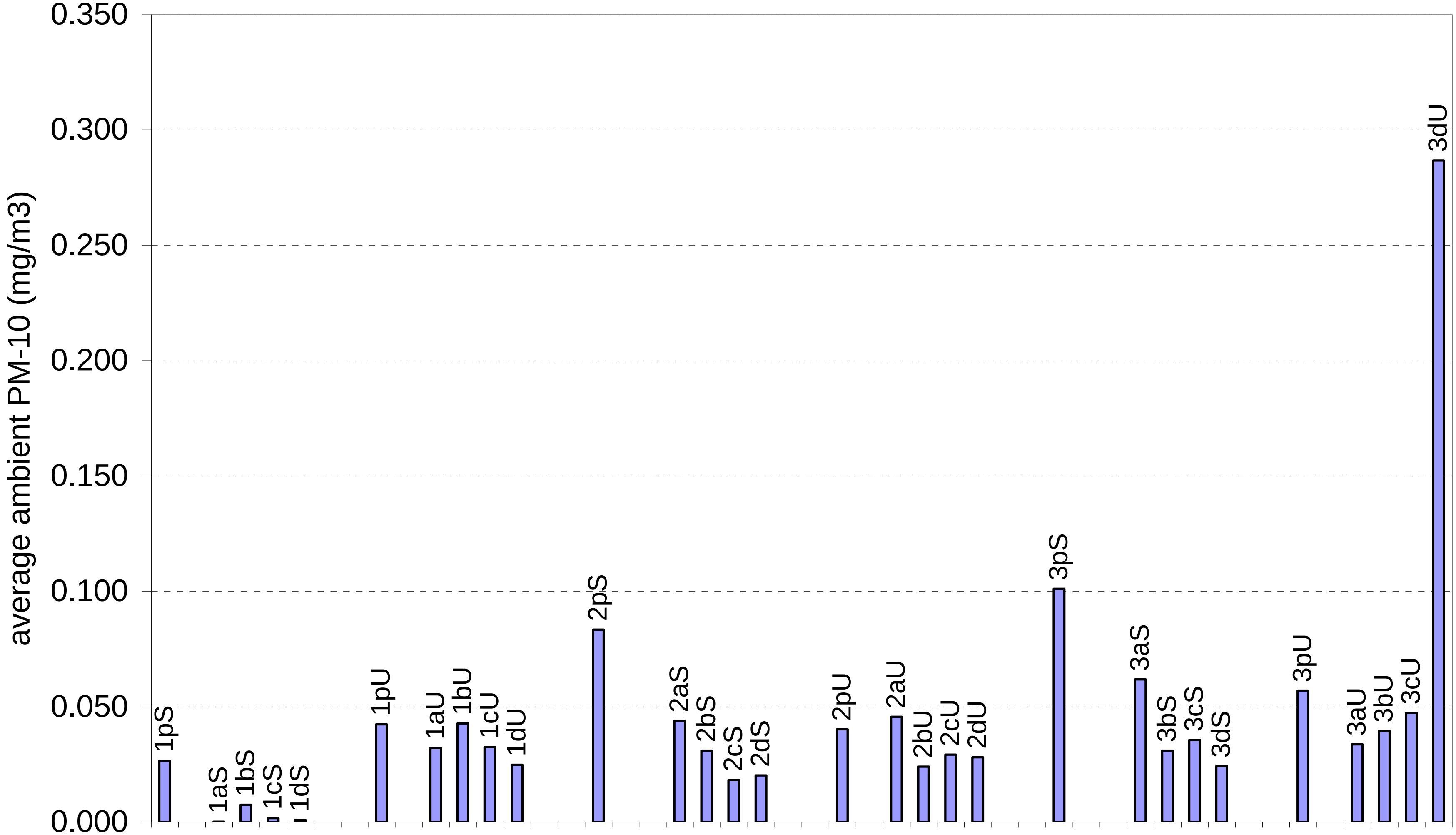
Site 116 1UN Example spike result

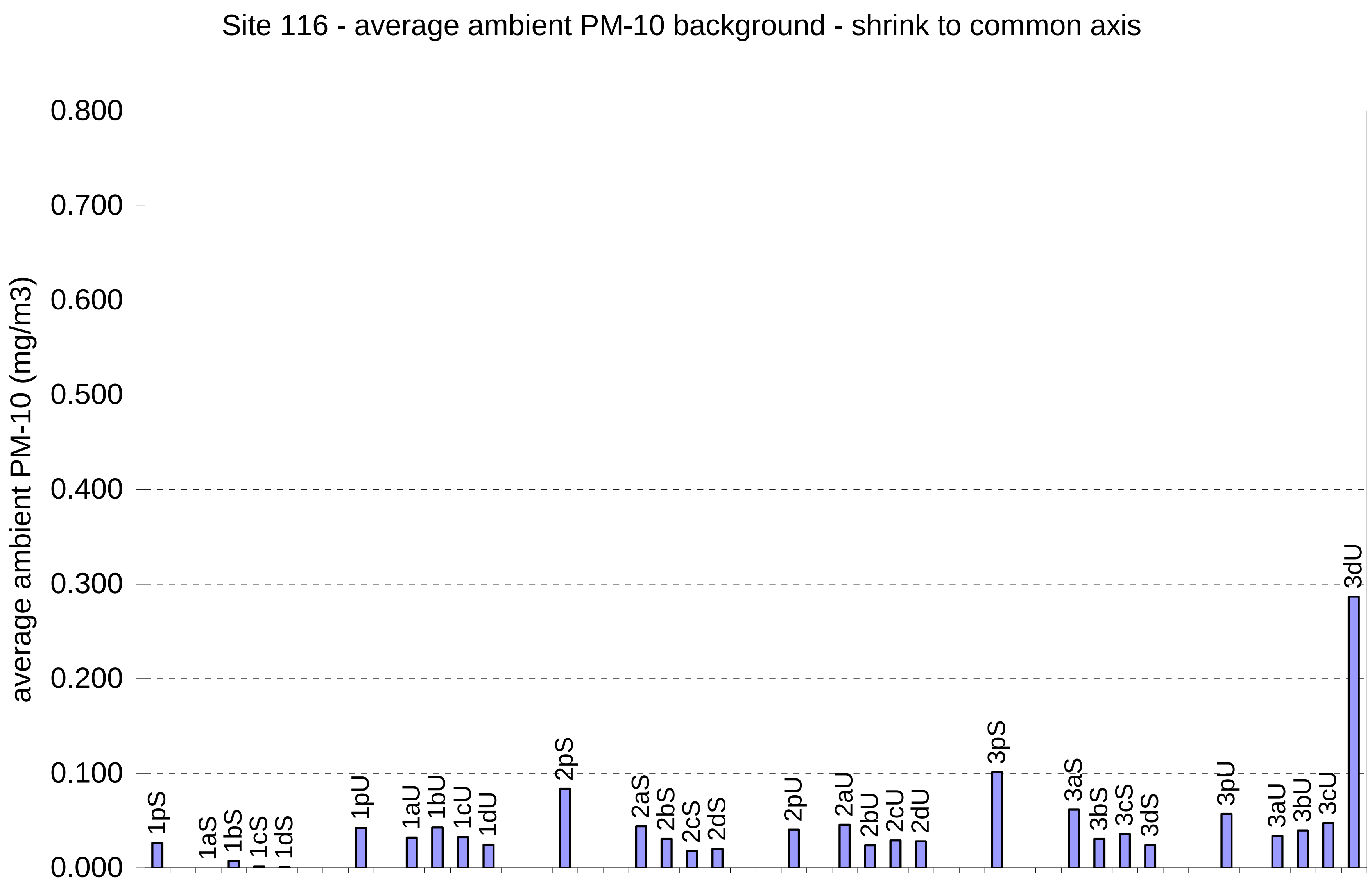
Site116 Erosion R1UN speed range	velocity at 10 meters (mph)	spike duration (seconds)	Erosion or profiling spike mass (mg)	Individual PM 10 ambient net spike mass (mg)	Individual PM 10 net spike mass (mg)	Spike mass (ton/acre)
p	15.5	1	5.1E-05	2.4E-05	2.7E-05	5.2E-10
1	15.6	2	7.1E-04	3.5E-04	3.6E-04	6.9E-09
2	24.4	18	2.2E-02	1.0E-03	2.1E-02	3.9E-07
3	34.4	68	2.0E-01	2.6E-03	2.0E-01	3.8E-06
4	42.6	32	1.9E-01	2.3E-03	1.9E-01	3.6E-06

Site 116 1UN example flux result next slide, plots of yellow columns

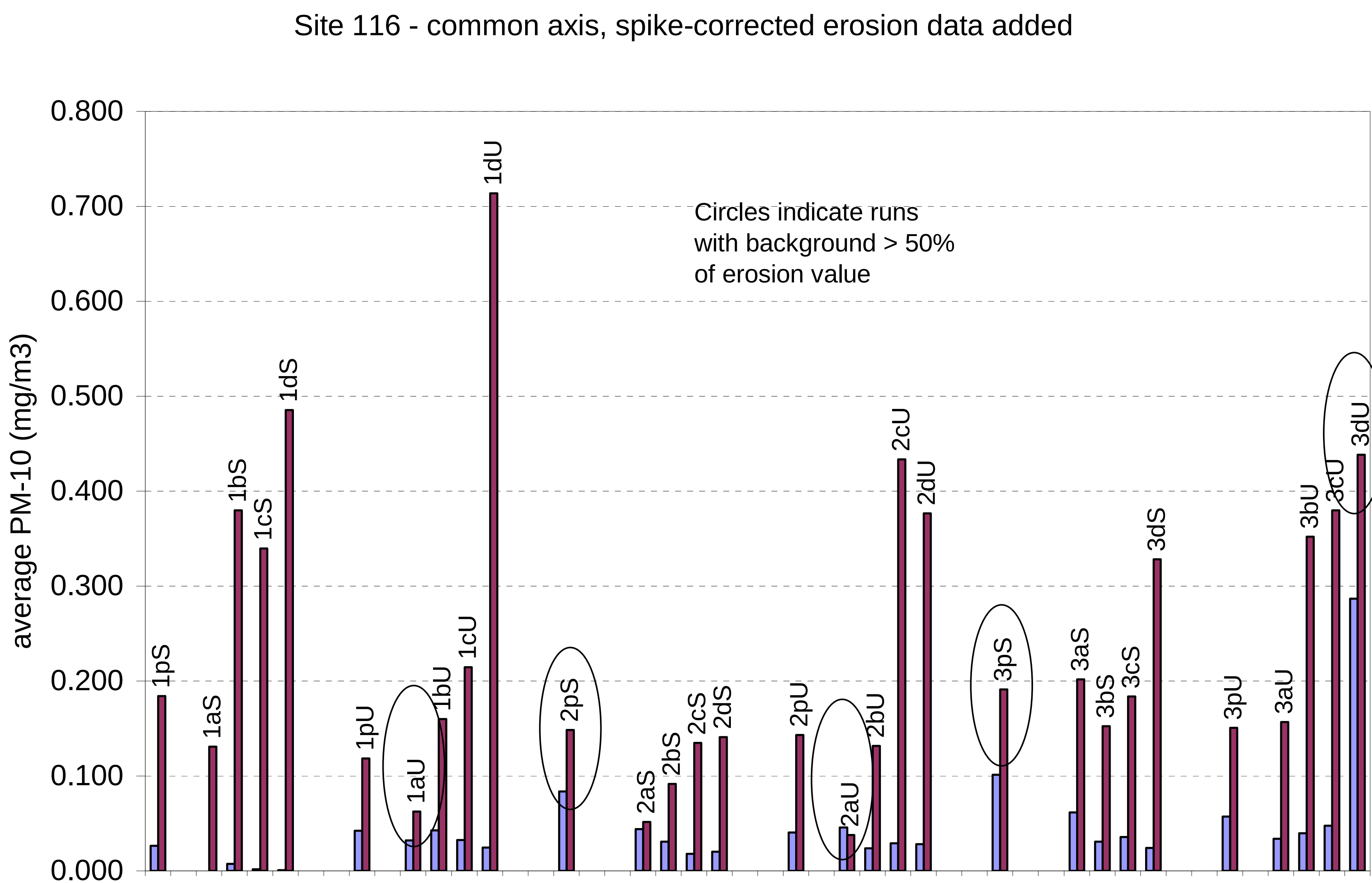
Site116 Erosion R1UN speed range	uncorrected average concentr (mg/m3)	nonspike duration (sec)	corrected (non-spike) average concen-tration (mg/m3)	Avg Tsi Ambient Conc. (mg/m3)	Net concen-tration, mg/m3	Individual Flux (ton/acre/hr)	Cumulative Flux (ton/acre/hr)
p	0.118	0	0.118	0.042	0.076	1.3E-03	1.3E-03
1	0.064	252	0.062	0.032	0.030	5.0E-04	1.8E-03
2	0.201	222	0.160	0.043	0.117	2.0E-03	3.7E-03
3	0.654	168	0.214	0.033	0.182	3.0E-03	6.8E-03
4	1.106	201	0.714	0.025	0.689	1.2E-02	1.9E-02

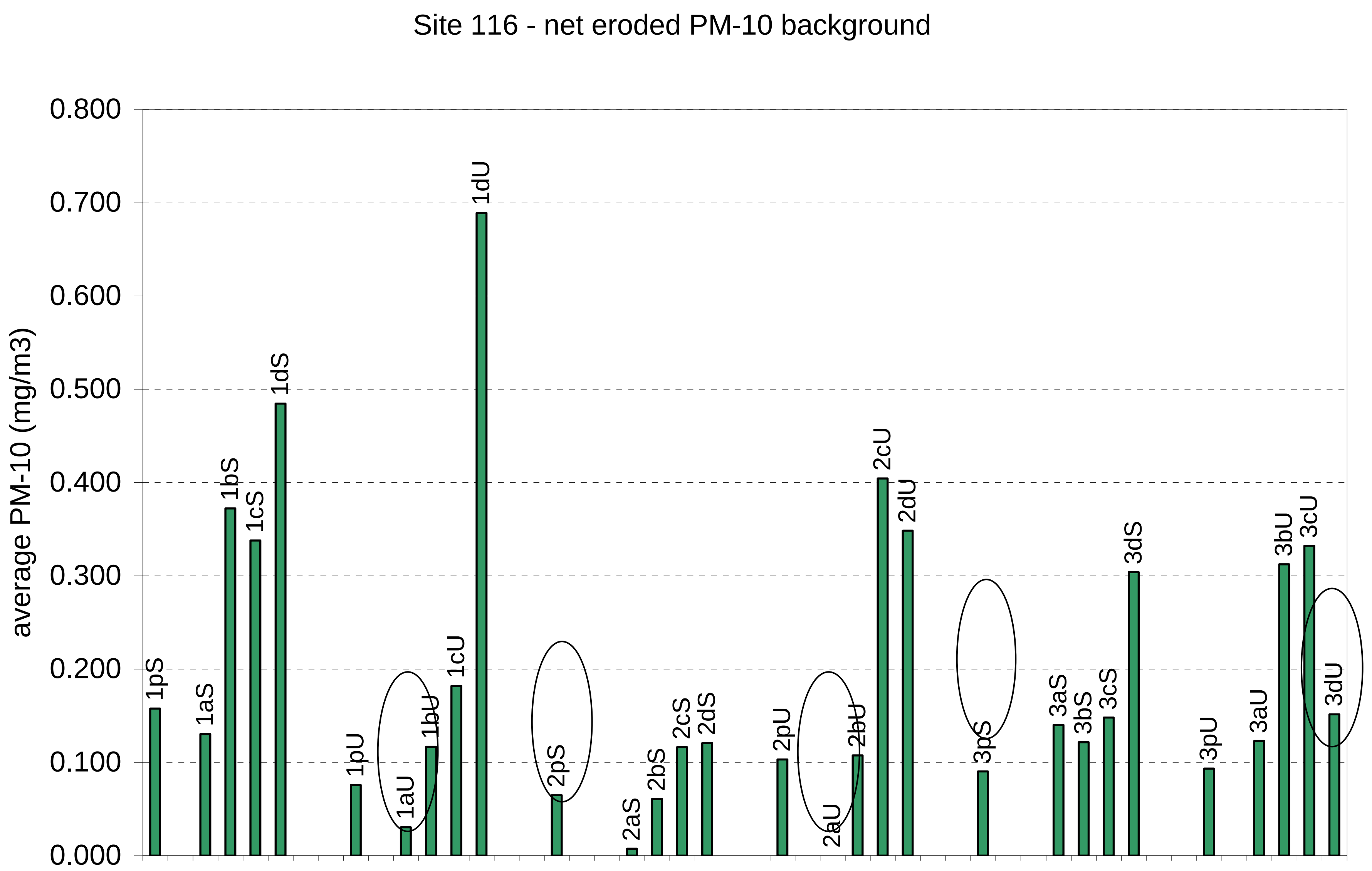
Site 116 - average ambient PM-10 background



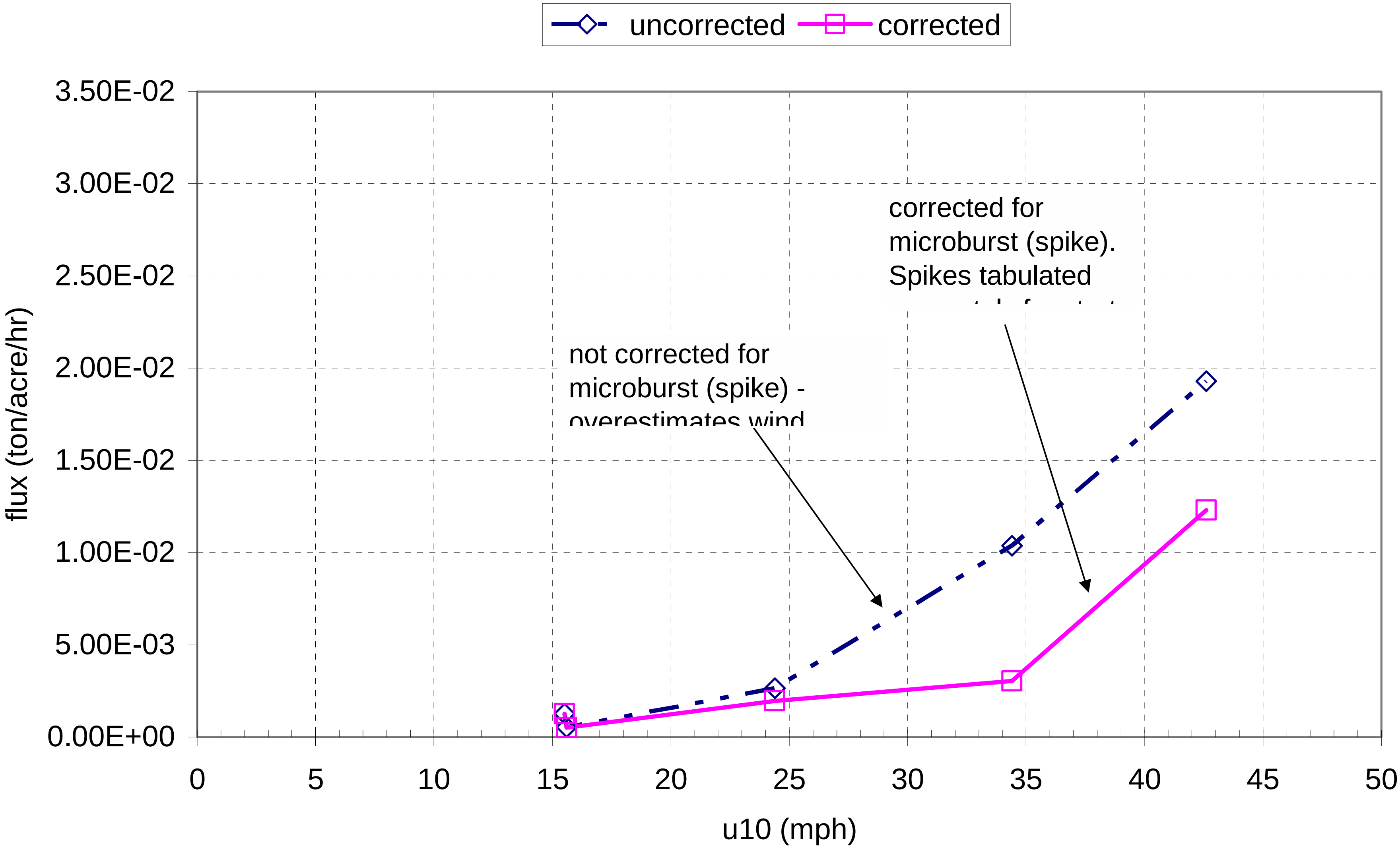


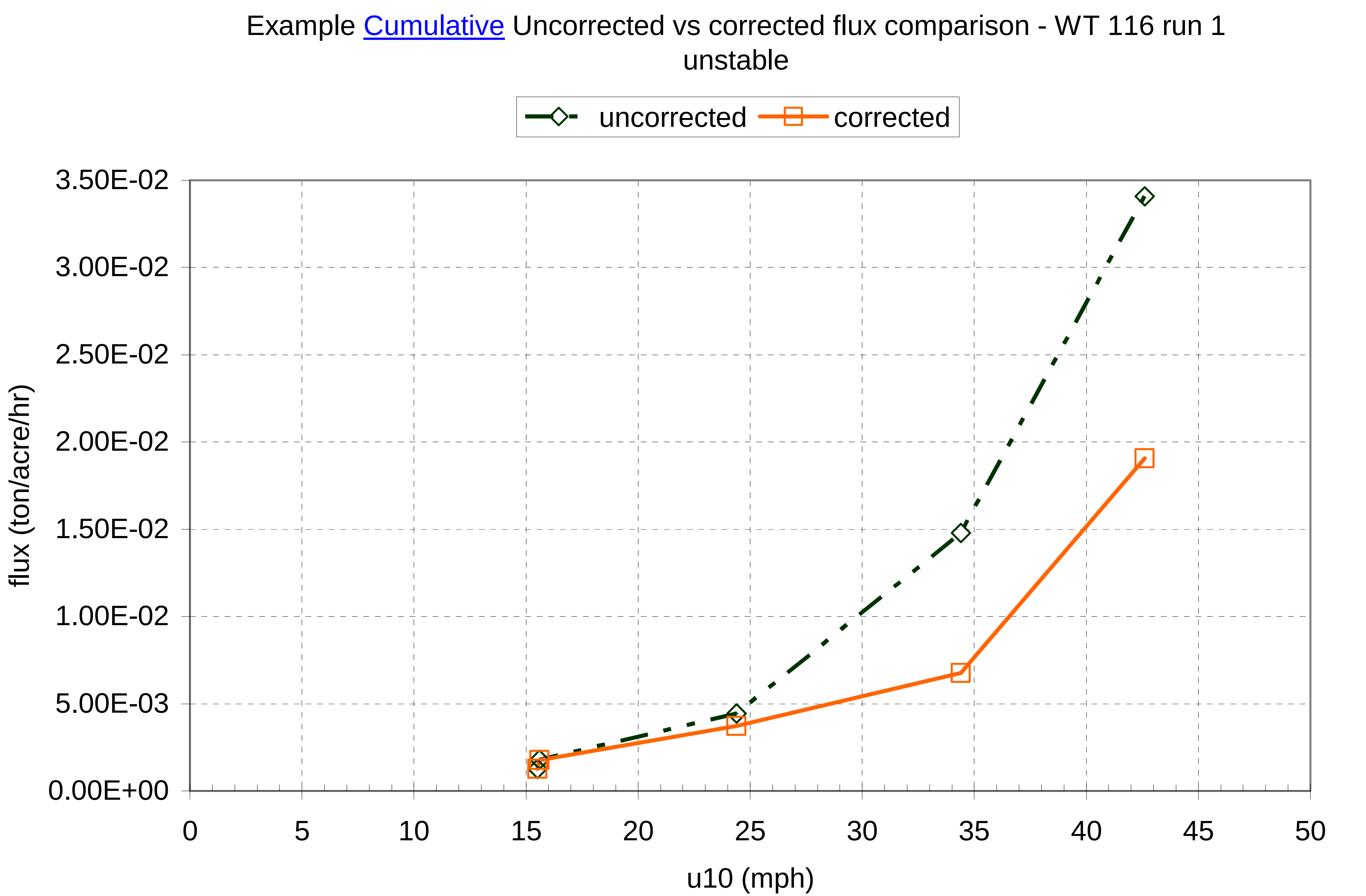
Site 116 - average ambient PM-10 background - shrink to common axis
average ambient PM-10 (mg/m3)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1pS
1aS
1bS
1cS
1dS
1pU
1aU
1bU
1cU
1dU
2pS
2aS
2bS
2cS
2dS
2pU
2aU
2bU
2cU
2dU
3pS
3aS
3bS
3cS
3dS
3pU
3aU
3bU
3cU
3dU

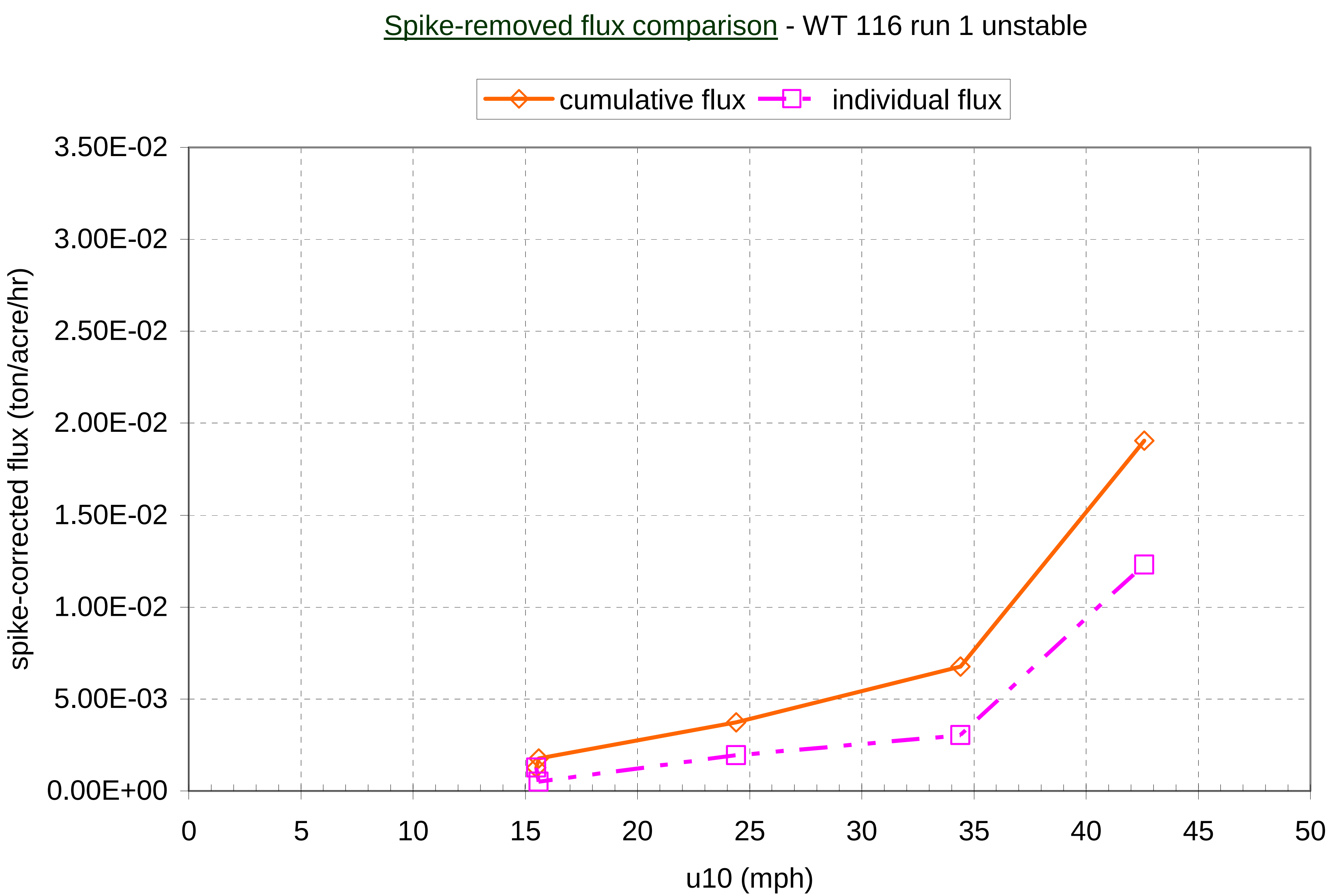

Site 116 - common axis, spike-corrected erosion data added
average PM-10 (mg/m3)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Circles indicate runs with background > 50% of erosion value
1pS
1aS
1bS
1cS
1dS
1pU
1aU
1bU
1cU
1dU
2pS
2aS
2bS
2cS
2dS
2pU
2aU
2bU
2cU
2dU
3pS
3aS
3bS
3cS
3dS
3pU
3aU
3bU
3cU
3dU


Site 116 - net eroded PM-10 background
average PM-10 (mg/m3)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1pS
1aS
1bS
1cS
1dS
1pU
1aU
1bU
1cU
1dU
2pS
2aS
2bS
2cS
2dS
2pU
2aU
2bU
2cU
2dU
3pS
3aS
3bS
3cS
3dS
3pU
3aU
3bU
3cU
3dU

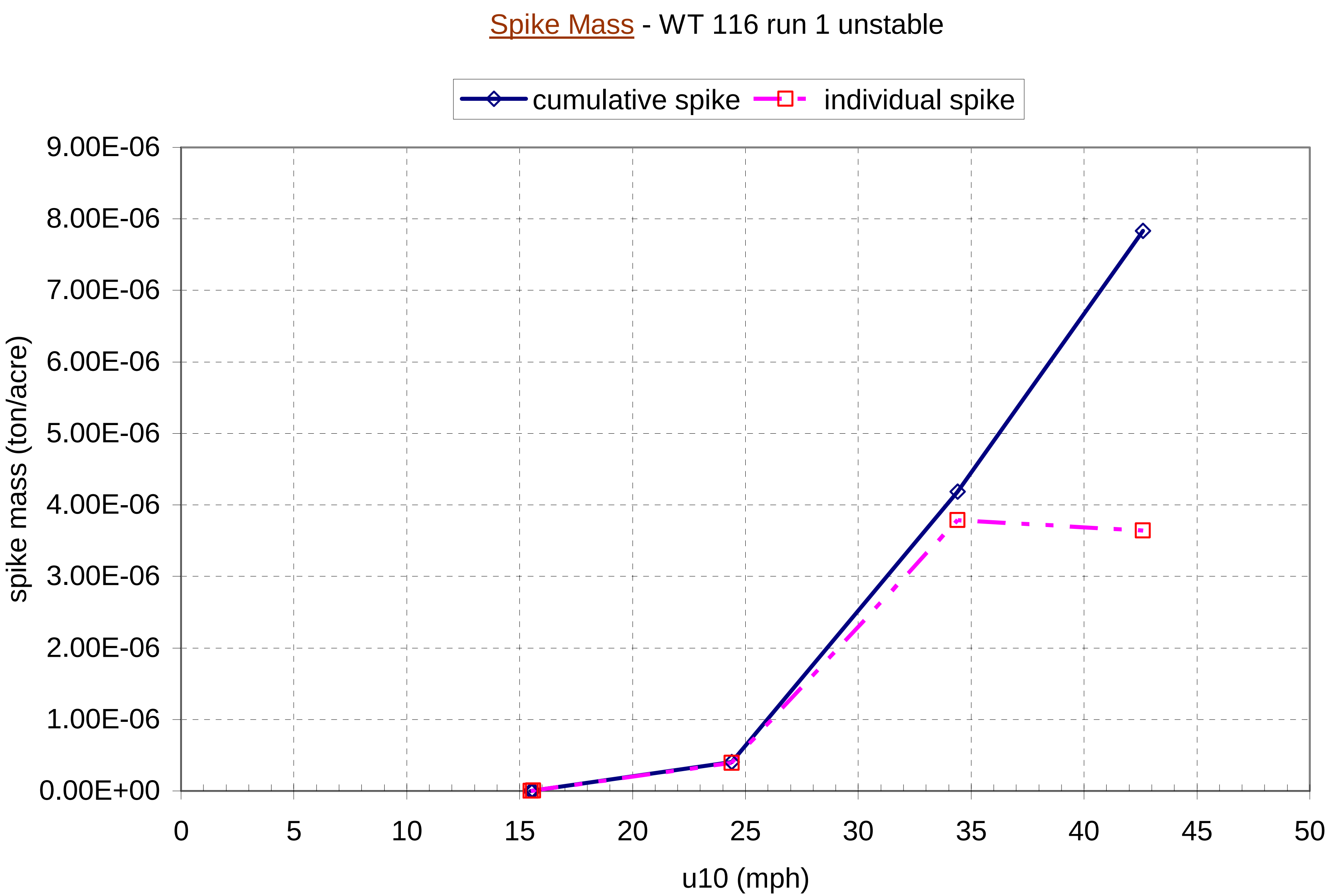
Example Individual Uncorrected vs corrected flux comparison - WT 116 run 1 unstable




Example Cumulative Uncorrected vs corrected flux comparison - WT 116 run 1 unstable
uncorrected
corrected
flux (ton/acre/hr)
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
0
5
10
15
20
25
30
35
40
45
50
u10 (mph)



Spike-removed flux comparison - WT 116 run 1 unstable
cumulative flux
individual flux
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
spike-corrected flux (ton/acre/hr)
0
5
10
15
20
25
30
35
40
45
50
u10 (mph)


Spike Mass - WT 116 run 1 unstable
cumulative spike
individual spike
spike mass (ton/acre)
9.00E-06
8.00E-06
7.00E-06
6.00E-06
5.00E-06
4.00E-06
3.00E-06
2.00E-06
1.00E-06
0.00E+00
0
5
10
15
20
25
30
35
40
45
50
u10 (mph)

Consequences of data reduction approach

- Corrections using in-situ ambient data reduced both spike and flux values

- Spike separation corrects for influence of spike on hourly fluxes

Preparing overall results

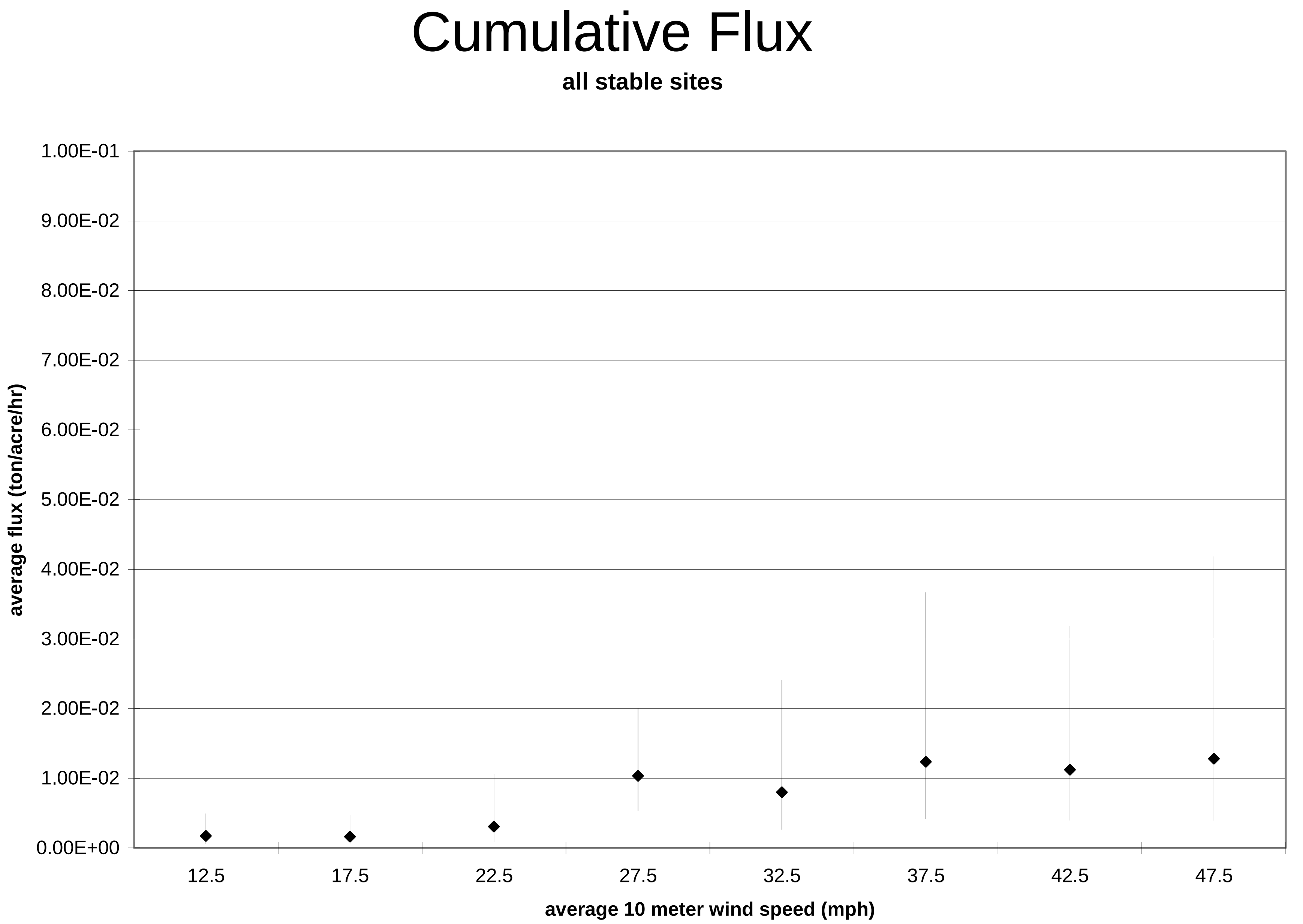
- Corrected Individual run data (948 records) compiled into Access® database
- Queries developed by CC DAQEM (M Uhl) to efficiently develop tables of emissions factors for each wind erodibility group in 5 mph wind bands

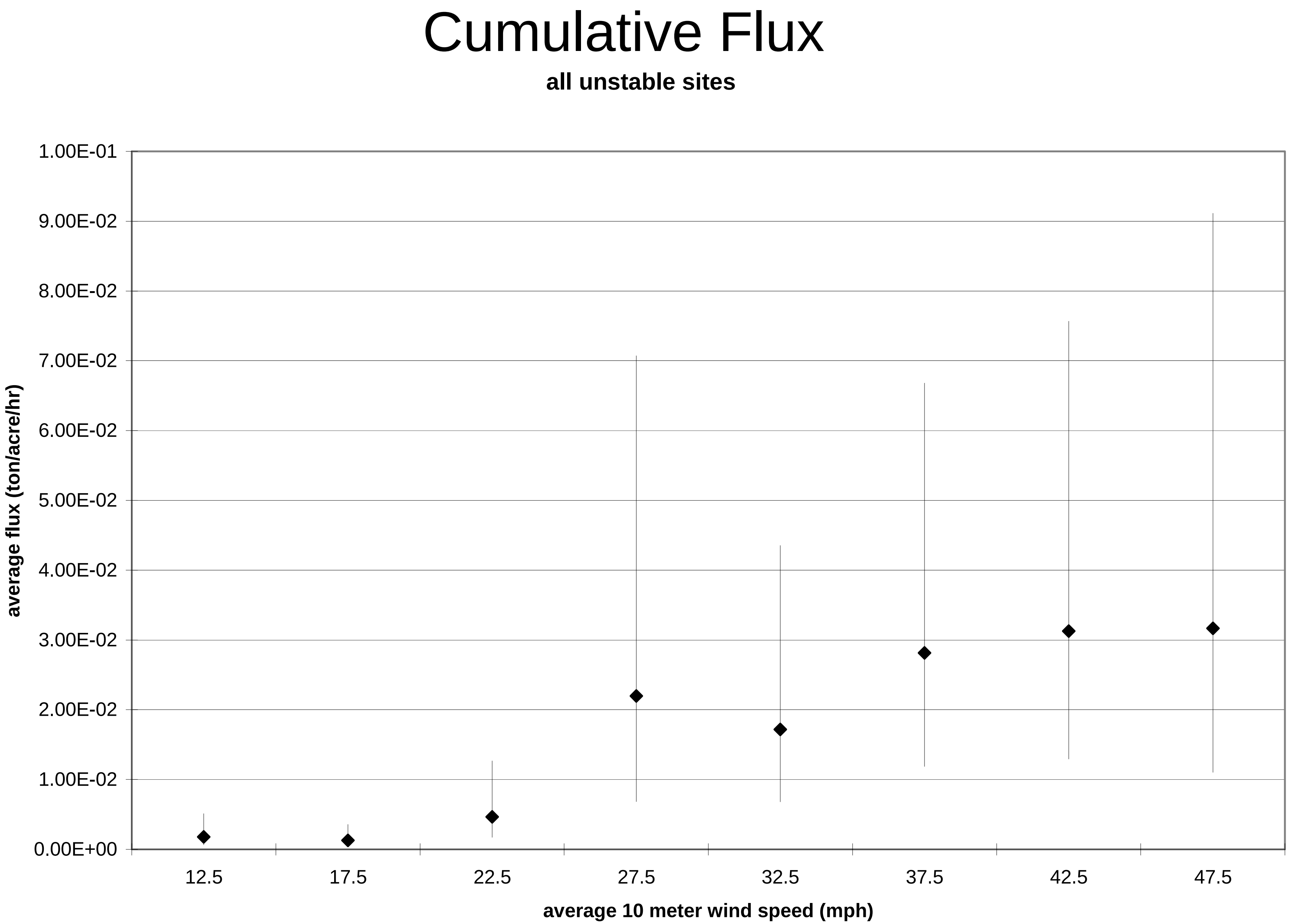
All Stable sites, n = 454

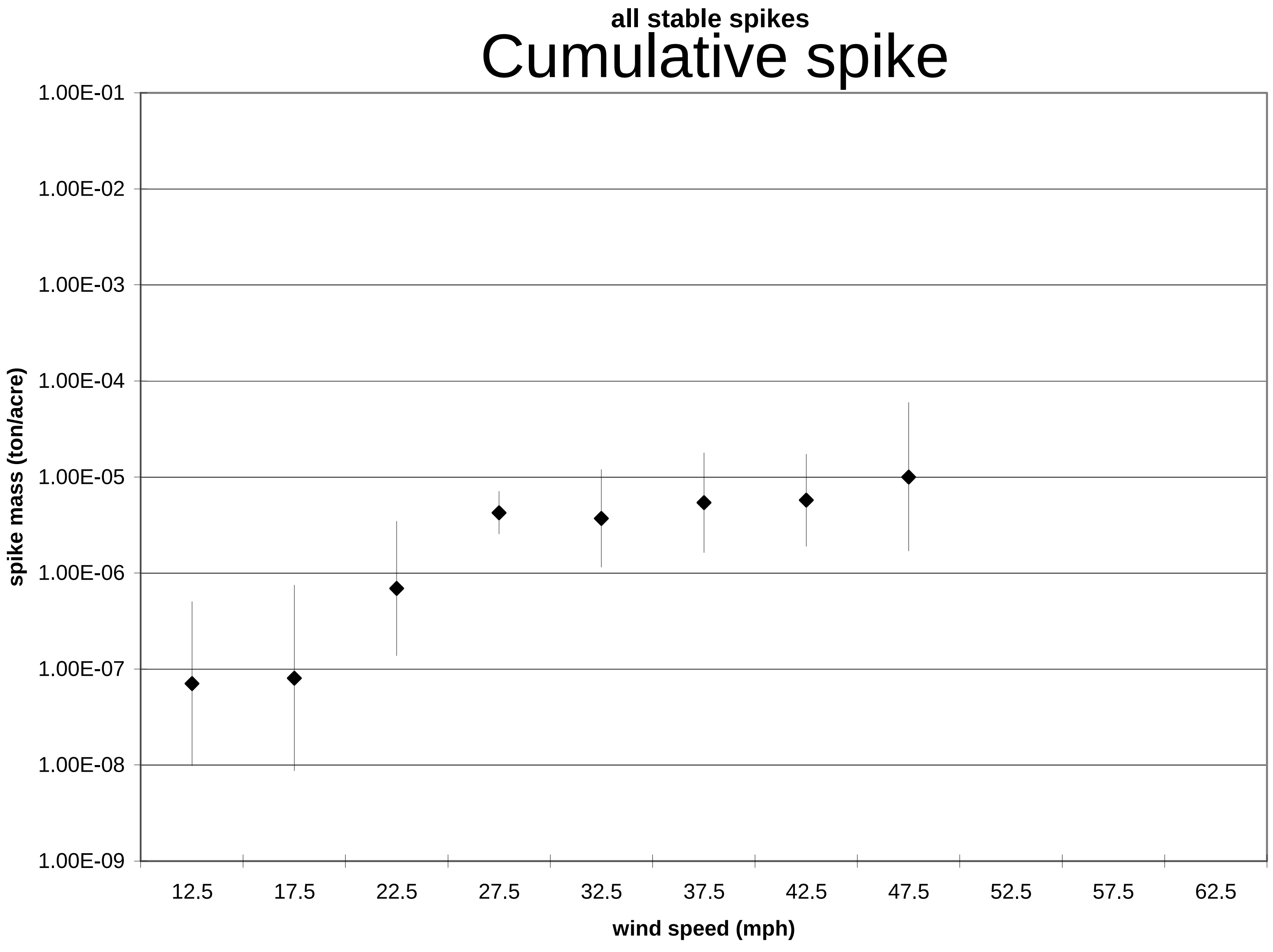
ALL WEG Stable				
wind band (mph)	**geo mean - 1 std.dev flux, ton/acre/hr**	**geo mean flux ton/acre/hr**	**geo mean + 1 std.dev flux, ton/acre/hr**	**sample size, n=**
10-15	6.09E-04	1.73E-03	4.92E-03	77
15-20	5.37E-04	1.60E-03	4.78E-03	91
20-25	8.88E-04	3.07E-03	1.06E-02	97
25-30	5.35E-03	1.04E-02	2.01E-02	11
30-35	2.64E-03	7.97E-03	2.41E-02	102
35-40	4.16E-03	1.24E-02	3.67E-02	33
40-45	3.95E-03	1.12E-02	3.18E-02	41
45-50	3.91E-03	1.28E-02	4.18E-02	2

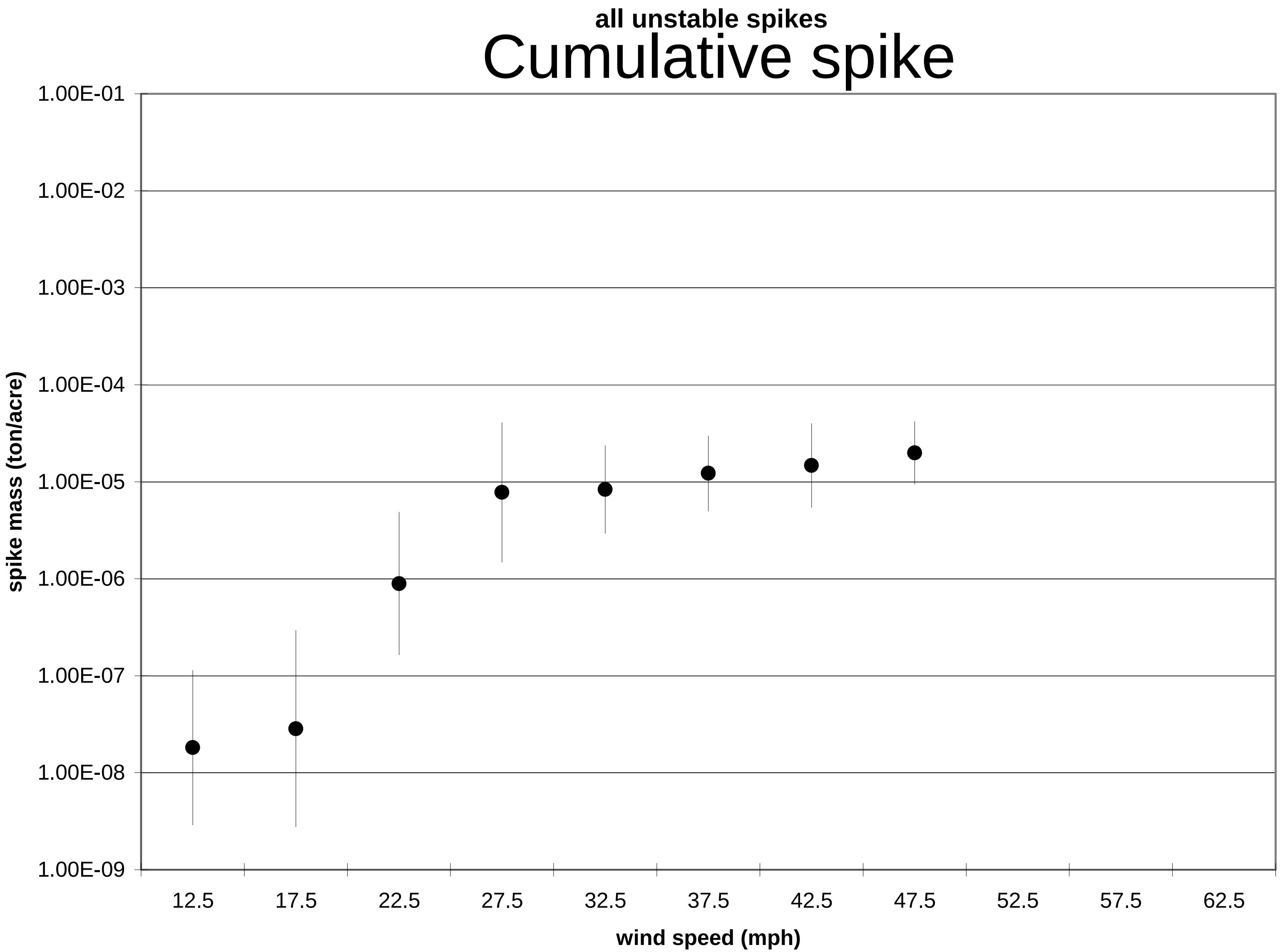
All unstable sites, n = 457
unstable flux = (2 or 3) * stable

ALL WEG UNstable				
wind band (mph)	**geo mean - 1 std.dev flux, ton/acre/hr**	**geo mean flux ton/acre/hr**	**geo mean + 1 std.dev flux, ton/acre/hr**	**sample size, n=**
10-15	6.29E-04	1.80E-03	5.13E-03	63
15-20	4.66E-04	1.29E-03	3.56E-03	102
20-25	1.71E-03	4.66E-03	1.27E-02	103
25-30	6.83E-03	2.20E-02	7.07E-02	12
30-35	6.79E-03	1.72E-02	4.35E-02	96
35-40	1.19E-02	2.81E-02	6.68E-02	30
40-45	1.29E-02	3.13E-02	7.57E-02	46
45-50	1.10E-02	3.17E-02	9.11E-02	5


Cumulative Flux
all stable sites
average flux (ton/acre/hr)
1.00E-01
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
average 10 meter wind speed (mph)


Cumulative Flux
all unstable sites
1.00E-01
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
average flux (ton/acre/hr)
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
average 10 meter wind speed (mph)


all stable spikes
Cumulative spike
spike mass (ton/acre)
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
wind speed (mph)


all unstable spikes
Cumulative spike
spike mass (ton/acre)
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
wind speed (mph)

Flux comparison, ‘04 vs ‘95

- Stable fluxes
  - *Higher* by factor of 2-4 for 2004 study (n=454) compared to 1995 (n=169)
- Unstable fluxes
  - *Lower* in 15-20, 20-25 mph wind speed bands
  - *Higher* in 25-30 mph bands and above
  - 1995 (n=68) 2004 (n=457)

Spike comparison, ’04 vs ‘95

- Stable spikes
  - *Lower* by 2-4 *orders of magnitude* for 2004 study (n=462) compared to 1995 (n=163)
- Unstable spikes
  - *Lower* by 2-4 *orders of magnitude* for 2004 study (n=460) compared to 1995 (n=56)

Why higher fluxes and lower spikes?

- 2004 field procedures
  - Generate real-time ambient data used for correction for profile & erosion flux and spikes
  - account for erosion during profiling
  - Generate “fresh” unstable surfaces, larger reservoir, less crust

- 2004 spike removal procedure
  - Generally removes less of the spike “signal” than 1995 procedure
  - More of signal remains for flux calculation
  - Less of signal present for spike calculation
  - Calculates spike mass by different method

Study or data source	Fugitive dust	Total Suspended Particulates (30-50 μm)	PM-10	Comment
Gillette and Passi 1988		*3.0 x 10^{-5}g/m²/s* 4.8 x 10^{-4} t/ac/hr		
Nickling & Gillies 1989 disturbed		*9.8 x 10^{-4} g/m²/s* 1.6 x 10^{-2} t/ac/hr	*	95% < 10 μm
Nickling & Gillies 1989 undisturbed		*1.8 x 10^{-4} g/m²/s* 2.9 x 10^{-3} t/ac/hr		95% < 10 μm
Shao et al 1993		*1.1 x 10^{-6} g/m²/s* 1.8 x 10^{-5} t/ac/hr		
AP-42 1994	*1.1 x 10^{-7} g/m²/s* 1.8 x 10^{-6} t/ac/hr			
UNLV, 1995 Unstable			*3.5 x 10^{-4} g/m²/s* 5.6 x 10^{-3} t/ac/hr	
UNLV 1995 Stable			*1.5 x 10^{-4} g/m²/s* 2.4 x 10^{-3} t/ac/hr	
Stetler & Saxton 1996 (field measurements)	*1.0 x 10^{-4} g/m²/s* 1.6 x 10^{-3} t/ac/hr			
UNLV 2004, Unstable			*9.1 x 10^{-4} g/m²/s* 1.5 x 10^{-2} t/ac/hr	
UNLV 2004, Stable			*4.4 x 10^{-4} g/m²/s* 7.1 x 10^{-3} t/ac/hr	

Conclusions

- Larger data set from fewer sites
- Fluxes generally 2-4 higher
- Unstable fluxes are “worst” case – freshly destabilized surfaces
- Spikes generally lower
- Results on high end of reported values in literature
- Results not corrected for sheltering effects of nearby vegetation, structures or other objects

Acknowledgments

- Clark County Department of Air Quality Management
- Regional Transportation Commission
- Desert Research Institute
- The field team! – Rosangela Wacaser, Kayli Barber, Jennifer Bentley, Vinod Chakka

References – literature cited in

- Chow, J.C. and J. Watson (1997), Fugitive Dust and Other Source Contributions to PM10 in Nevada's Las Vegas Valley, V II - Final Report, DRI #4039.2F1, DRI Reno NV
  - Gillette, D.A. and R. Passi (1988), Modeling Dust Emission caused by wind erosion, *J. Geophys Res* **93**(D11),14233-14242
  - Nickling, W.G and J.A. Gillies (1989), Emission of fine-grained particulates from Desert Soils. In *Paleoclimatology and Paleometeorology:Modern and Past Patterns of Global Atmospheric Transport*, M. Leinen and M.Sarnthein, eds. Kluwer Academic Publishers, pp. 133-165
  - Shao, Y. MR. Raupach, ad P.A. Findlater (1993), Effect of Saltation Bombardment on the Entrainment of Dust by the Wind, *J. Geophys Res.* **98**(D7),12719-12726
  - Stetler, L. and K. Saxton (1996) Earth Surface Process and Landforms, v.21, 673-685
  - US EPA (1994) Compilation of Air Pollution Emission Factors (AP-42) 5th ed. US EPA, Research Triangle Park, NC