Hydrological, Geophysical, and Geochemical Investigations in Support of Watershed Restoration, Schuylkill River

- ✓ Stream water quantity: Losses of surface water to underground mines can eliminate or reduce streamflow.
- ✓ Stream water quality: Elevated sulfate and metals in CMD degrade water quality and aquatic ecosystems.

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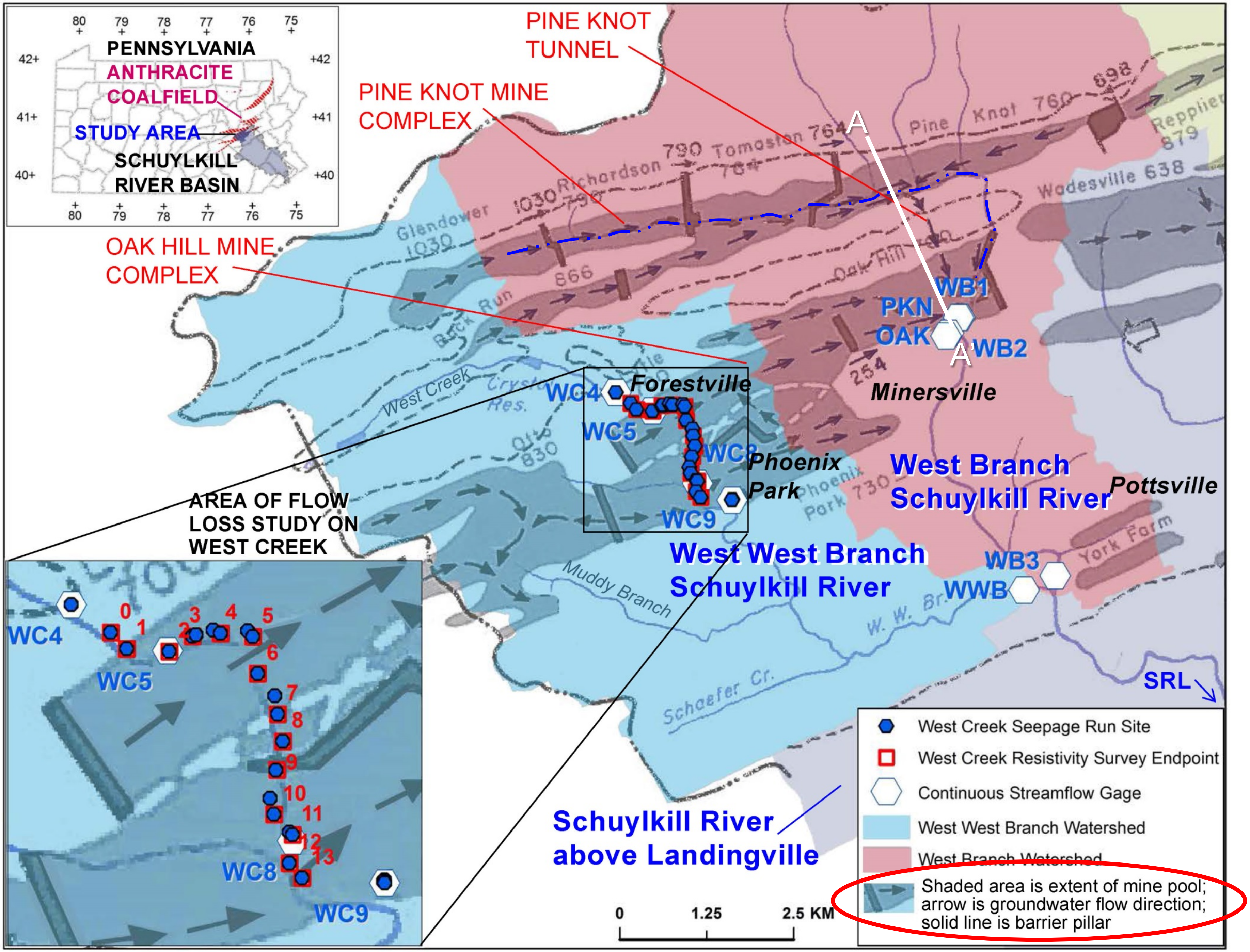
Presented April 10, 2017
National Meeting of American Society of Mining and Reclamation, Morgantown, WV

Goals / Objectives

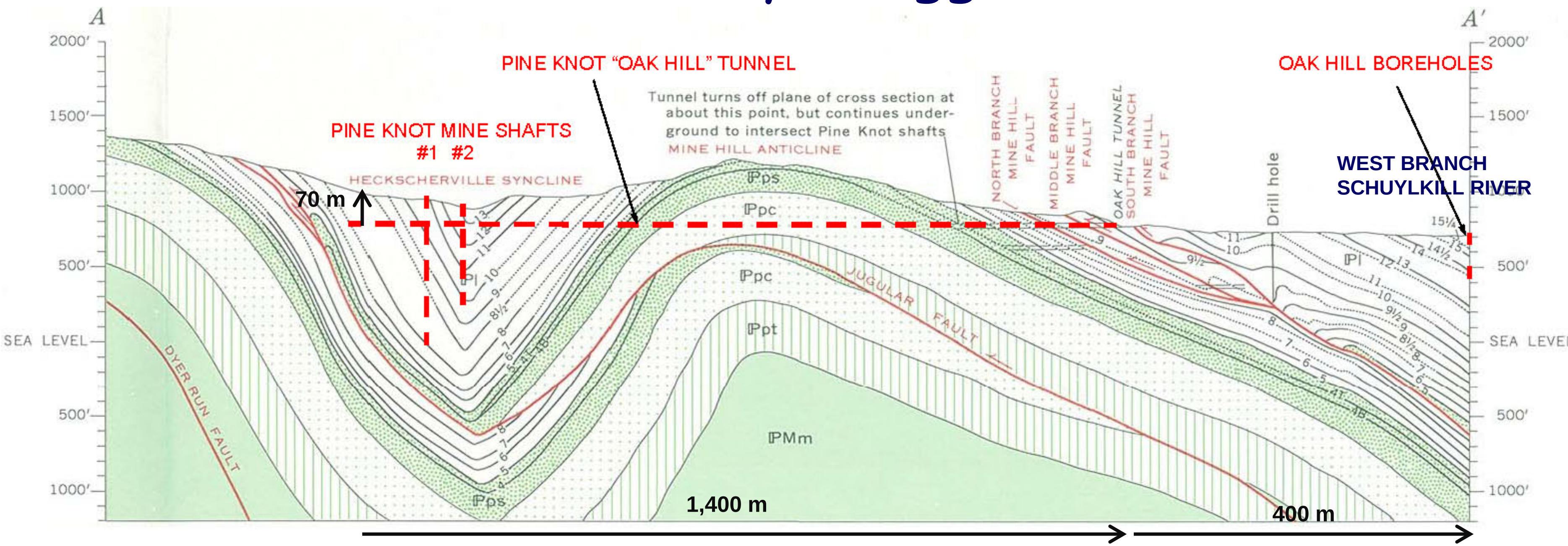
- Elimination of streamflow losses to underground mines can:
  - ✓ Reduce the volume and loading of contaminated mine drainage.
  - ✓ Restore aquatic habitat and provide ecological benefits.
- Hydrological measurements over a range of flow conditions combined with surface geophysical surveys and hyporheic temperature profiles can:
  - ✓ Indicate the locations, duration, and magnitude of streamflow losses to underground mines (and gains).
  - ✓ Indicate priority segments for stream restoration that exhibit high conductivity beneath the streambed *and* downward fluxes (losses).


PENNSYLVANIA
ANTHRACITE
COALFIELD
STUDY AREA
SCHUYLKILL
RIVER BASIN
PINE KNOT
TUNNEL
PINE KNOT MINE
COMPLEX
OAK HILL MINE
COMPLEX
Glendower 1030
Richardson 790
Tomoston 764
Pine Knot 760
898
Reppiler 879
Wadesville 638
Oak Hill
866
Buck Run
West Creek
Otto 830
WB1
PKN
OAK
WB2
A
A'
254
Forestville
Minersville
WC4
WC5
WC8
WC9
Phoenix Park
Phoenix Park 730
West Branch
Schuylkill River
Pottsville
AREA OF FLOW
LOSS STUDY ON
WEST CREEK
West West Branch
Schuylkill River
Muddy Branch
W. W. Br.
WB3
WWB
York Farm
Schaefer Cr.
SRL
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Schuylkill River
above Landingville
0 1.25 2.5 KM
West Creek Seepage Run Site
West Creek Resistivity Survey Endpoint
Continuous Streamflow Gage
West West Branch Watershed
West Branch Watershed
Shaded area is extent of mine pool;
arrow is groundwater flow direction;
solid line is barrier pillar

Cross Section Through Mine Hill (not vertically exaggerated)

North

South



Synclinal basins containing coal deposits (numbered) and underground mines (now abandoned) underlie parallel valleys.

Groundwater floods the Pine Knot Mine (mine pool) to the Pine Knot Tunnel level and then flows 1,400 m by gravity to the tunnel outlet on south side of Mine Hill.

The Oak Hill Mine pool level is maintained by artesian discharge from the Oak Hill Boreholes within the flood plain of the West Branch Schuylkill River.

NOTE: Coal-Mine Drainage (CMD) at Pine Knot Tunnel and Oak Hill Boreholes originates, in part, as streamflow that leaks into underground mines that extend beneath the West Creek/West West Branch watershed

Hydrograph Separation Analysis 2014-15

Table 1. Hydrograph-separation analysis and components of the annual hydrologic budget[a] for continuous streamflow-gaging stations in the West Creek and associated watersheds of upper Schuylkill River basin, Schuylkill County, Pa., July 1, 2014 - June 30, 2015.

Map ID	Gage Location	Drainage area (km^2)	Mean streamflow [b] (L/s)	Mean streamflow [b] Yield (cm/yr)	Streamflow index [c] (%)	Mean baseflow [d] (L/s)	Mean baseflow [d] (cm/yr)	Base-flow index (%)	Mean runoff [e] (L/s)	Mean runoff [e] (cm/yr)	Runoff index (%)
West West Branch Schuylkill River											
WC4	West Cr ab Forestville	13.3	69	16.4	16.1	48	11.4	69.5	21	5.0	30.5
WC5	West Cr at Forestville	13.7	63	14.5	14.2	34	7.8	53.8	29	6.7	46.2
WC8	West Cr at Main St Phoenix Pk	18.9	82	13.7	13.4	46	7.7	56.2	36	6.0	43.8
WC9	West Cr at Ramtown Rd Phoenix Pk	22.3	84	11.9	11.7	50	7.1	59.7	34	4.8	40.3
WWB	West Cr West Branch Schuylkill R	48.5	752	48.9	47.9	639	41.6	85.1	113	7.3	14.9
West Branch Schuylkill River											
WB1	WB Schuylkill River ab Pine Knot	49.8	365	23.1	22.6	281	17.8	77.1	84	5.3	22.9
PKN	Pine Knot Disch 500 m bl Tunnel	*49.1*	484	31.1	30.5	472	30.3	97.4	12	0.8	2.6
PKNWB	PKN + WB1	49.8	849	53.8	52.7	768	48.7	90.5	81	5.1	9.5
OAK	Oak Hill Disch 200 m bl	*21.9*	216	31.1	30.5	212	30.5	98.1	4	0.6	1.9
WB3	WB Schuylkill River ab WWB	61.7	1368	70.0	68.6	1218	62.3	89.0	150	7.7	11.0
Schuylkill River											
SRL	Schuylkill River at Landingville	340.5	6103	56.6	55.4	4933	45.7	80.7	1170	10.9	19.3

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a. Hydrograph separation was conducted using the "PART" computer program (Rutledge, 1998) to divide annual streamflow into base flow and runoff contributions on the basis of daily average flow values during July 1, 2014 through June 30, 2015.

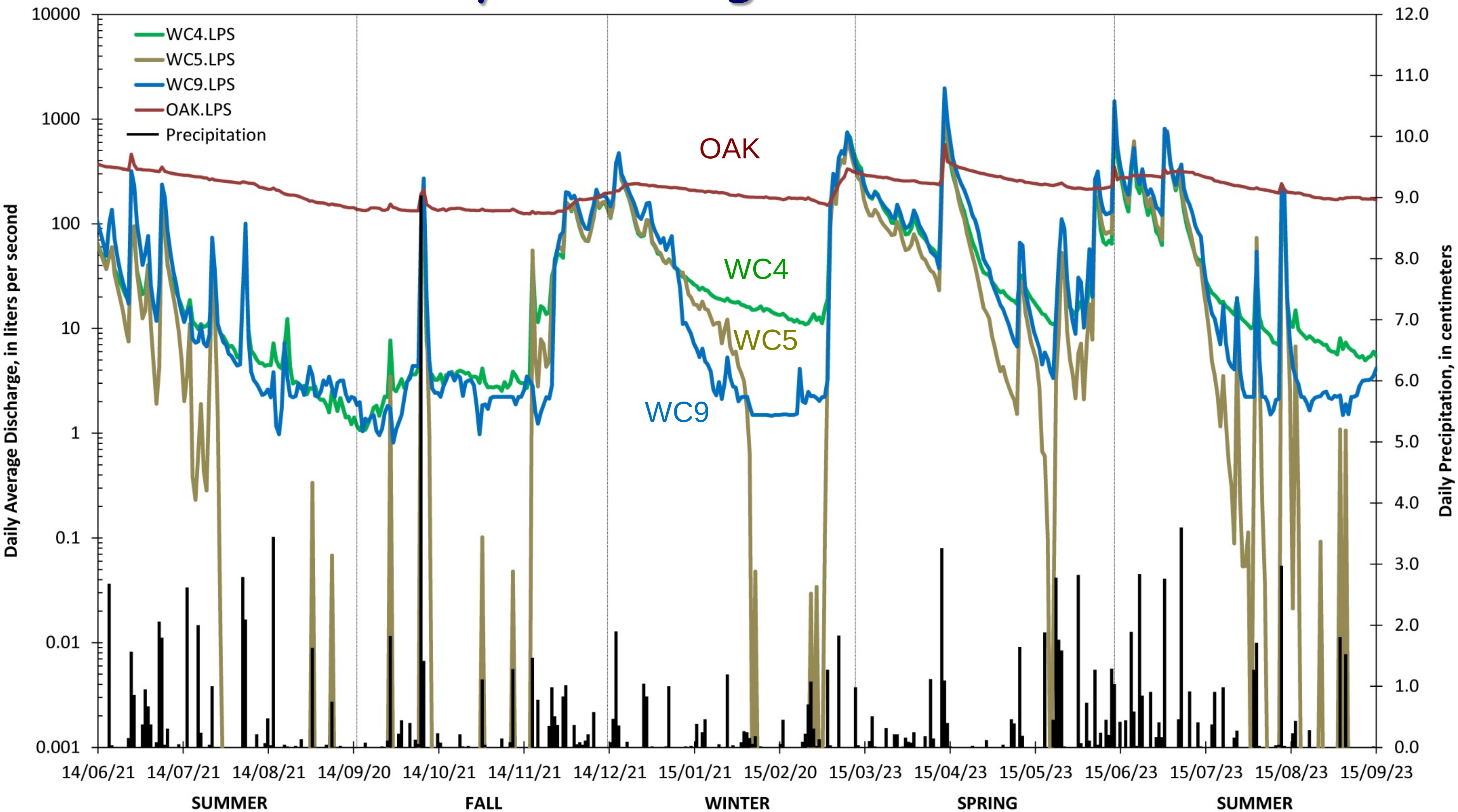
b. Streamflow (yield) expressed as centimeters per year by dividing streamflow in liters per second by the drainage area in square kilometers and then multiplying by the factor 3.156.

c. Streamflow index was computed as the ratio, expressed as percent, of total annual streamflow yield to average total annual rainfall of 102.1 cm/yr based on daily rainfall at local USGS streamflow gaging stations (01469500, 01470500, 01468500) and weather station

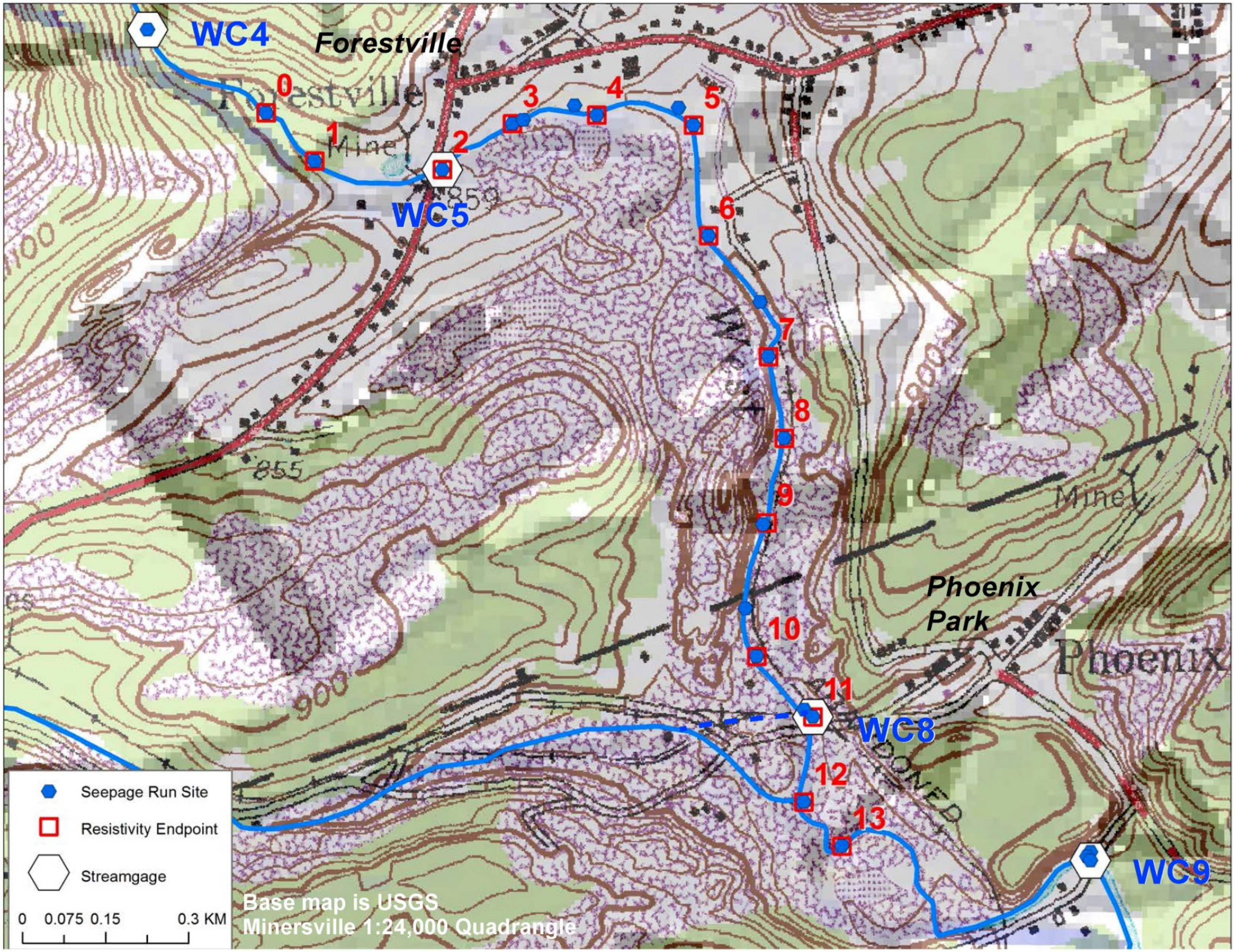
d. Base flow is expressed as liters per second, centimeters per year, and percent of total annual streamflow (base-flow index).

e. Runoff, computed by subtracting the base flow from total streamflow, is expressed as liters per second, centimeters per year, and percent of total annual streamflow (runoff index).

West Creek & Oak Hill Boreholes Daily Discharge 2014-2015

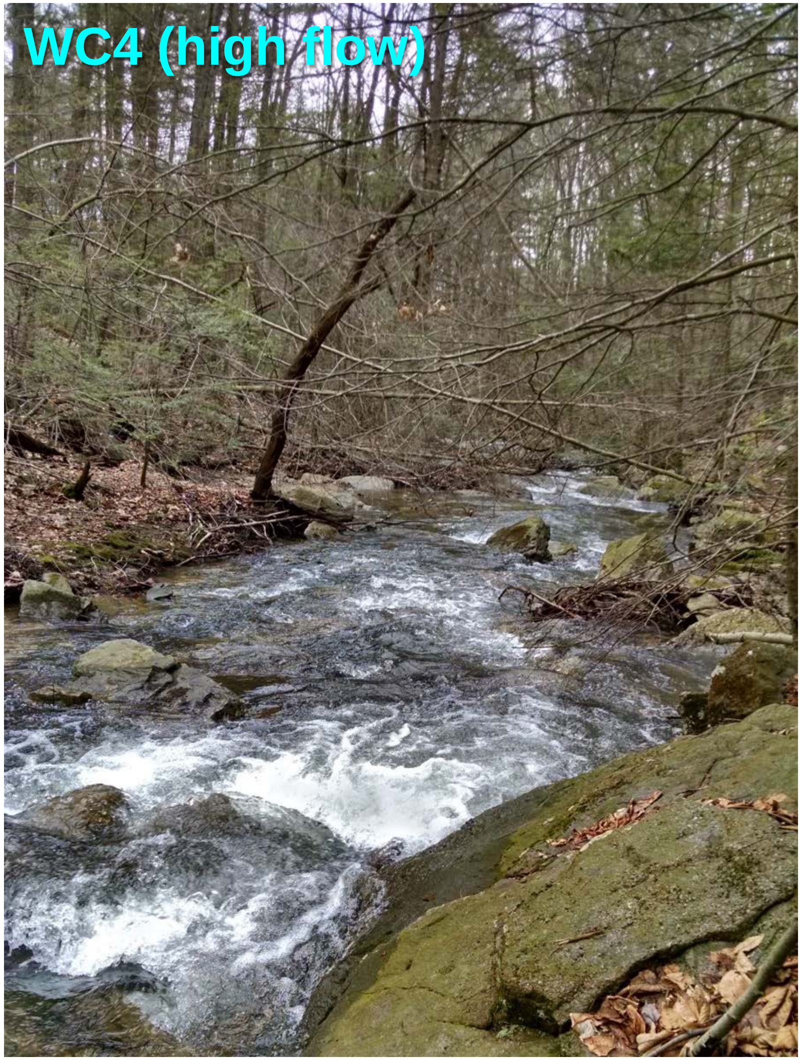


West Creek Flow Loss Study Area
Oak Hill Mine Pool & Stream Monitoring Points



West Creek –
Upstream of Oak Hill Mine Complex

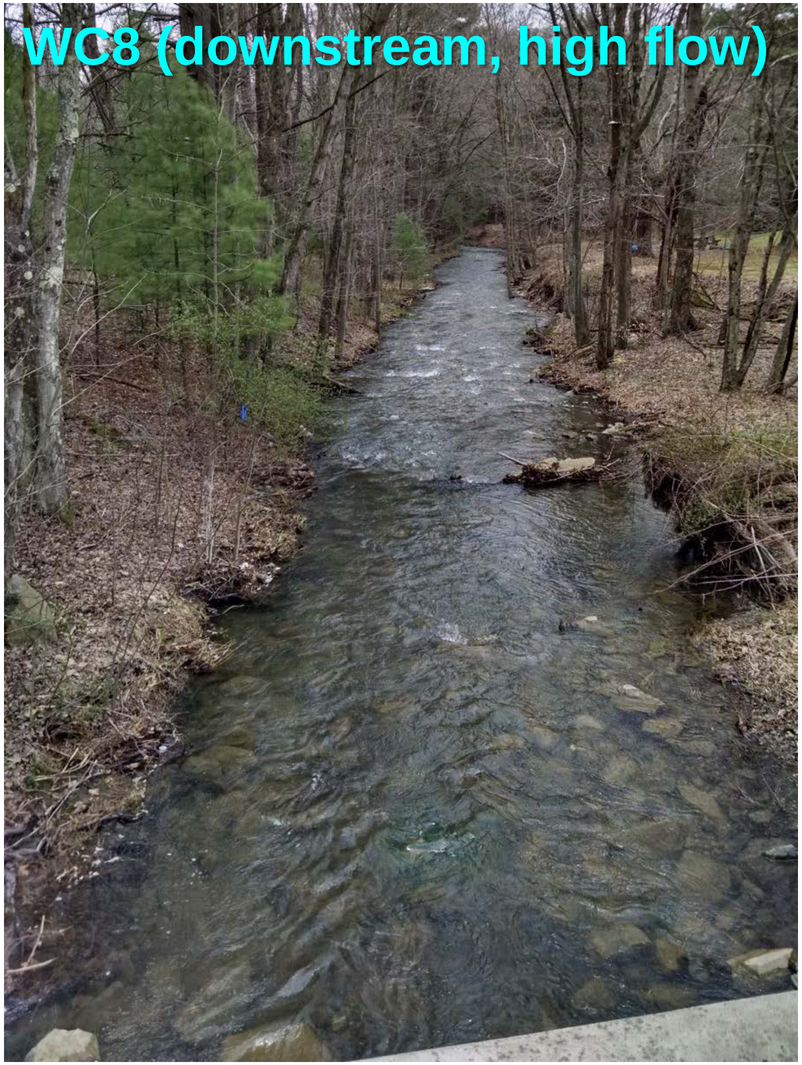
West Creek above Forestville, perennial



West Creek above Forestville, perennial

West Creek –
Downstream of Oak Hill Mine Complex

West Creek below Forestville, intermittent



West Creek below Forestville, intermittent

West Creek Flow Loss Study Methods

Streamflow using Current Meter;
Repeated at same cross sections along 2.1-km reach over varied hydrologic conditions

Electrical Resistivity: 2012, upstream locations, varied conditions; 2014, 2.1-km reach

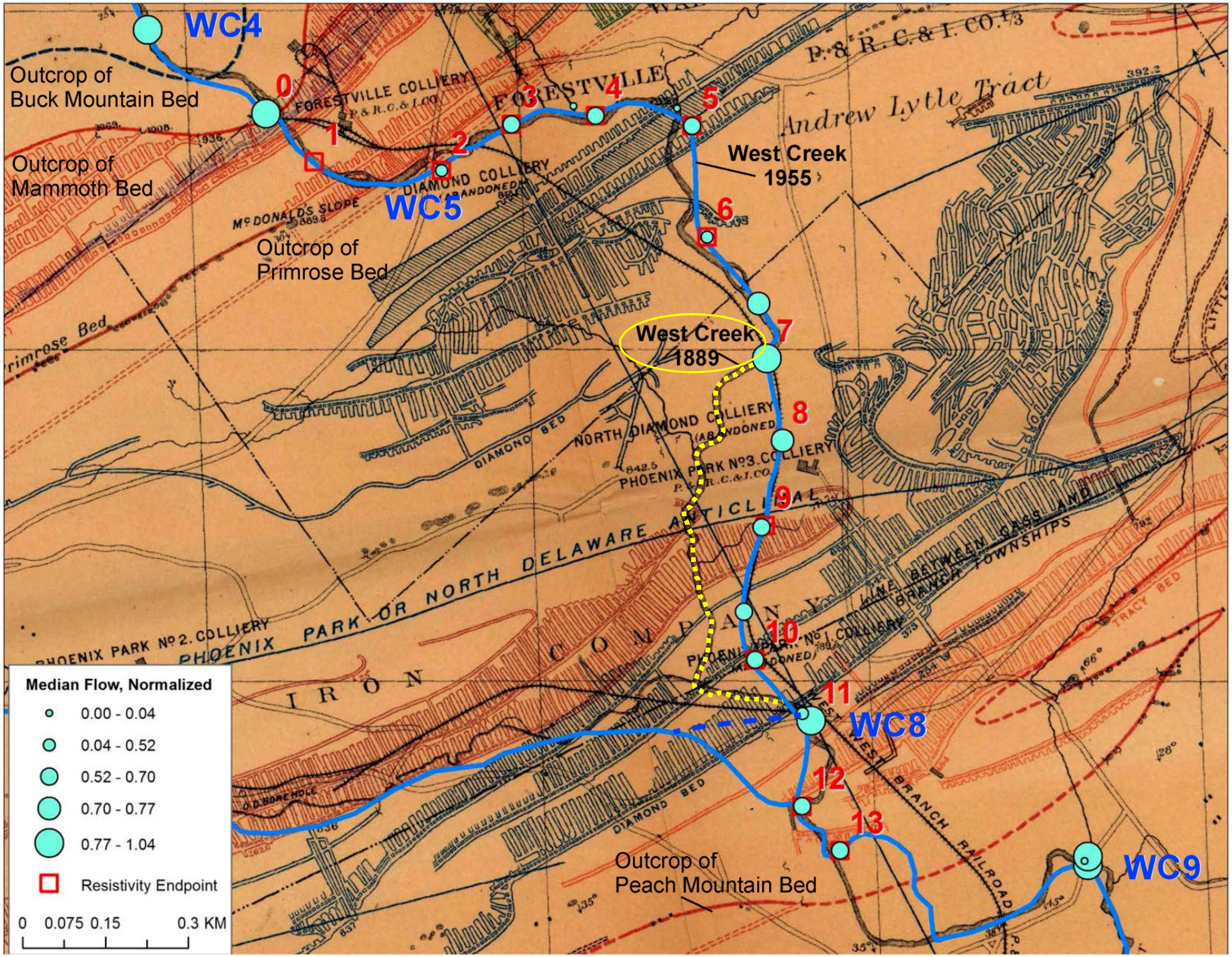
Electromagnetic Conductivity (EM-31): 2015, 2.1-km reach

Periodic Water Quality at Gages and other sites

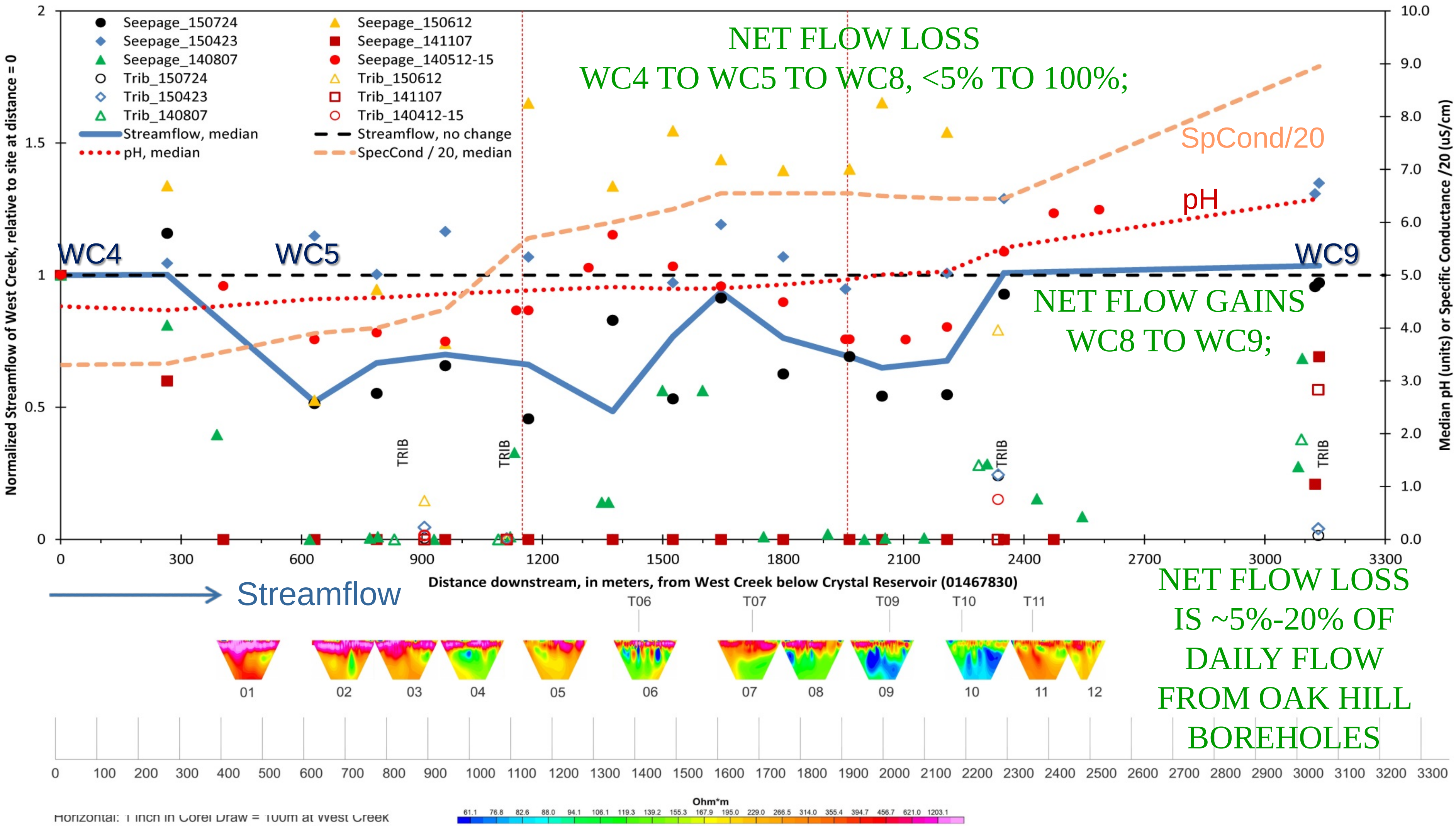
Continuous Stream Stage/Discharge at Gages (WC4, WC5, WC8, WC9)

Continuous Streambed Temperature Probes/Profiles

West Creek Flow Loss Study Results
1889 Mine Map & Normalized Streamflow

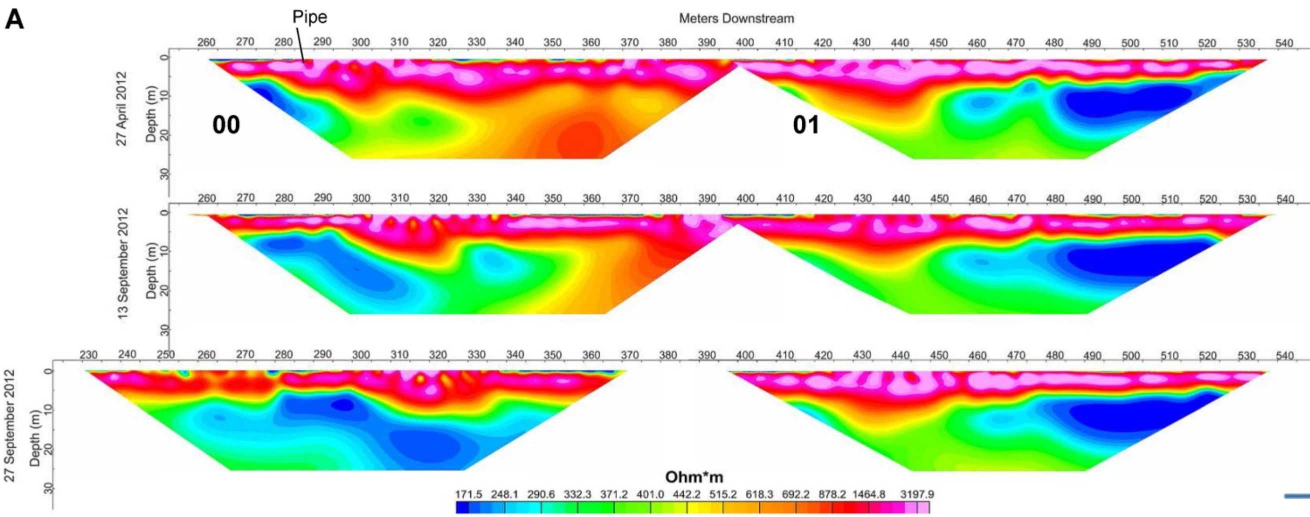


West Creek Longitudinal Seepage Surveys 2012-2015 (normalized to upstream flow at WC4)



NET FLOW LOSS IS ~5%-20% OF DAILY FLOW FROM OAK HILL BOREHOLES

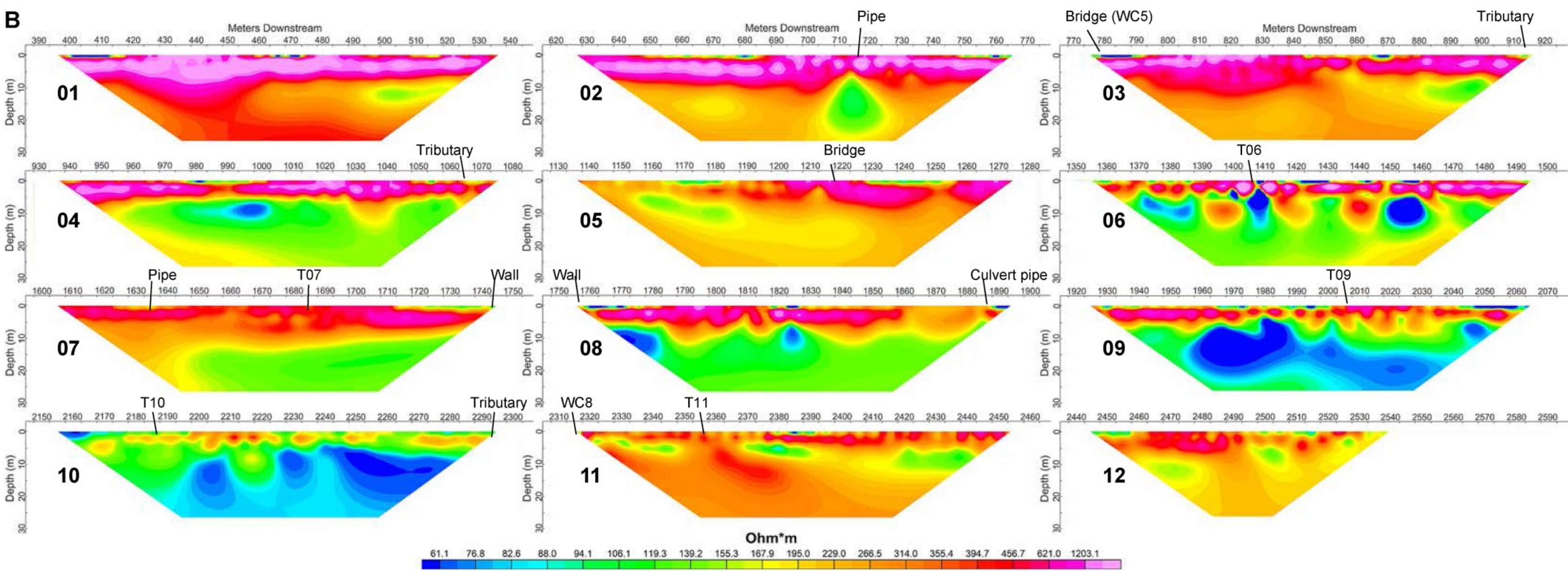
West Creek – Resistivity Surveys 2012 & 2014
(Dr. Laura Sherrod and students at Kutztown U.)



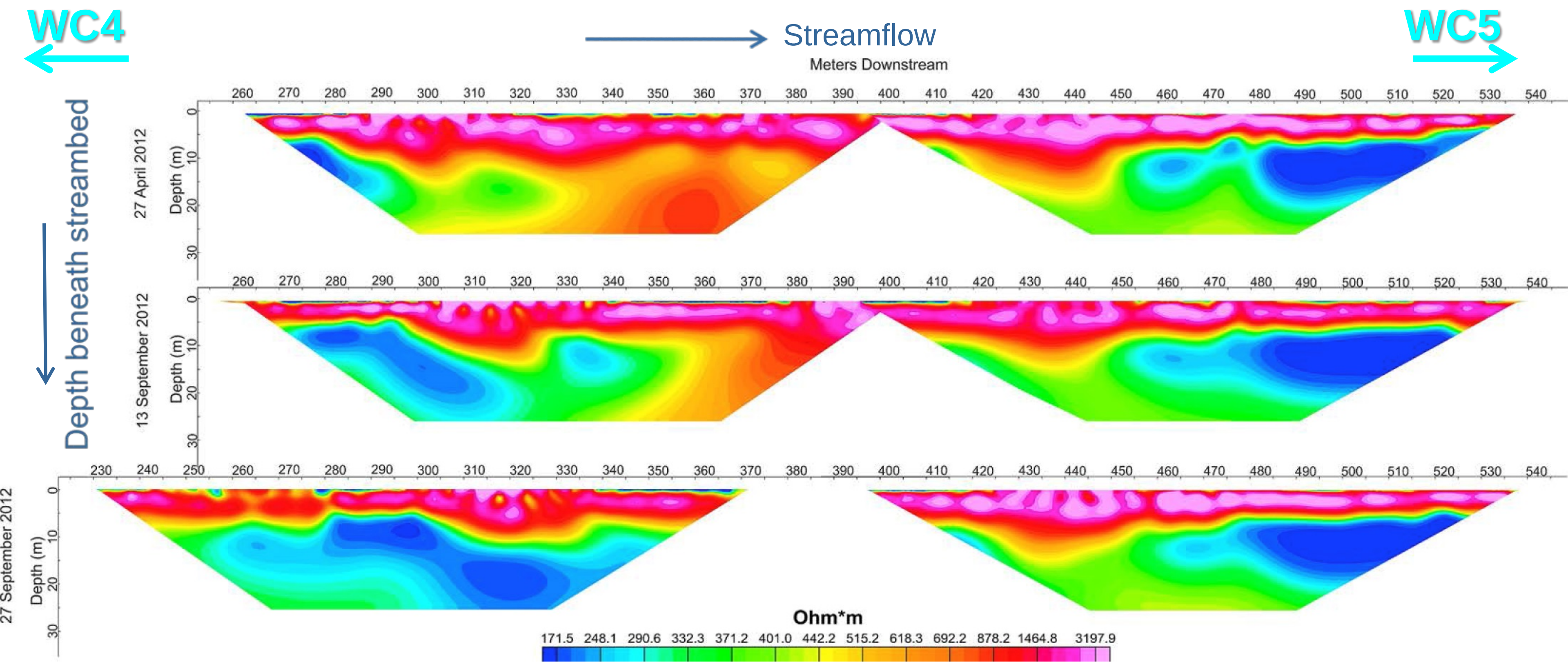
(A) Preliminary surveys along 300-m upper reach in 2012;

(B) 2.2-km survey from upper through lower reaches in May 2014 used MPT DAS-1 Electrical Impedance Tomography System with dipole-dipole array and 5-m electrode spacing.

Streamflow



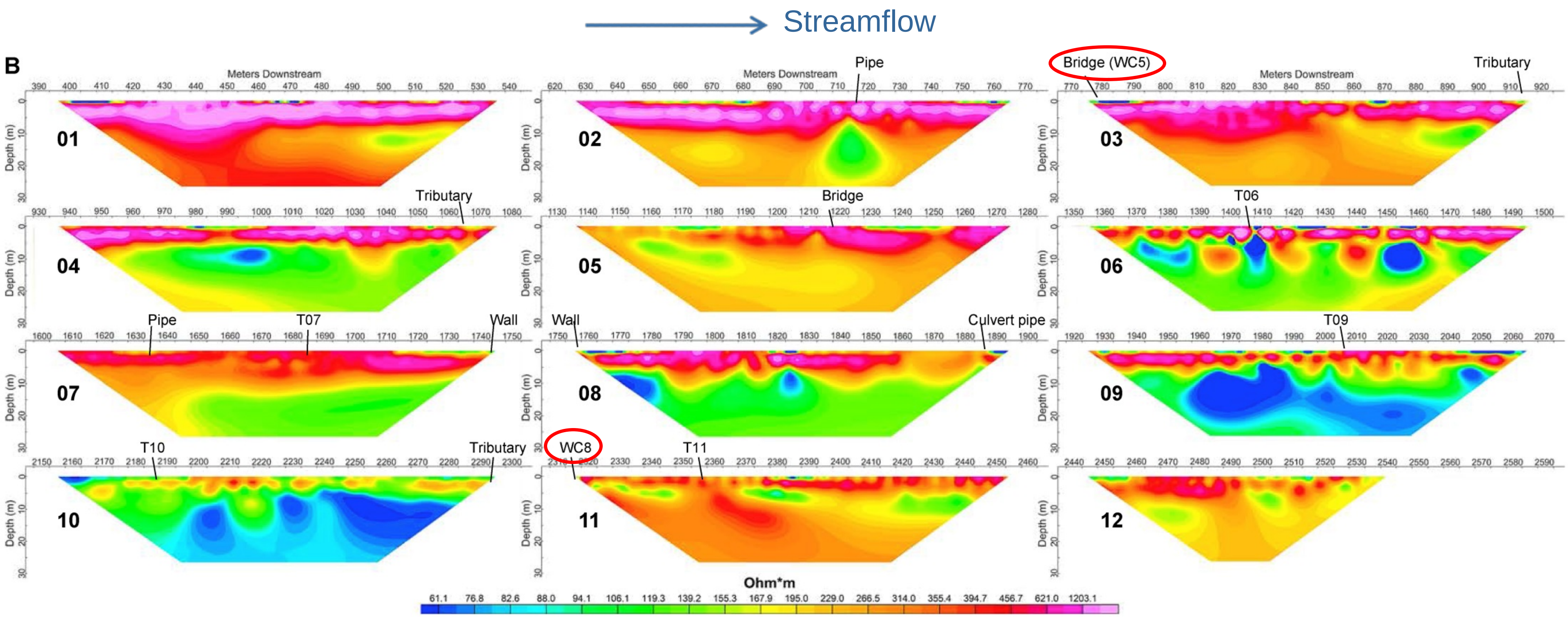
West Creek – Resistivity Survey Profiles 2012



Preliminary surveys along upper reach of West Creek during low-flow conditions on April 27 (top), intermediate-flow conditions on September 13 (middle), and high-flow conditions on September 27 (bottom). All document a high-resistivity upper zone of greater than 1000 ohm-meters (Ω·m) (pink to red) from the streambed surface to a depth of 5 to 10 m. At depths from about 5 m to greater than 30 m, an intermediate resistivity zone of between 1000 Ω·m and 300 Ω·m (orange to green) is present, which is interrupted locally by an anomalously low resistivity, or high conductivity (blue), zone of less than 300 Ω·m.

NOTE: Zones of low resistivity (blue) correspond to the historically mapped coal outcrop locations.

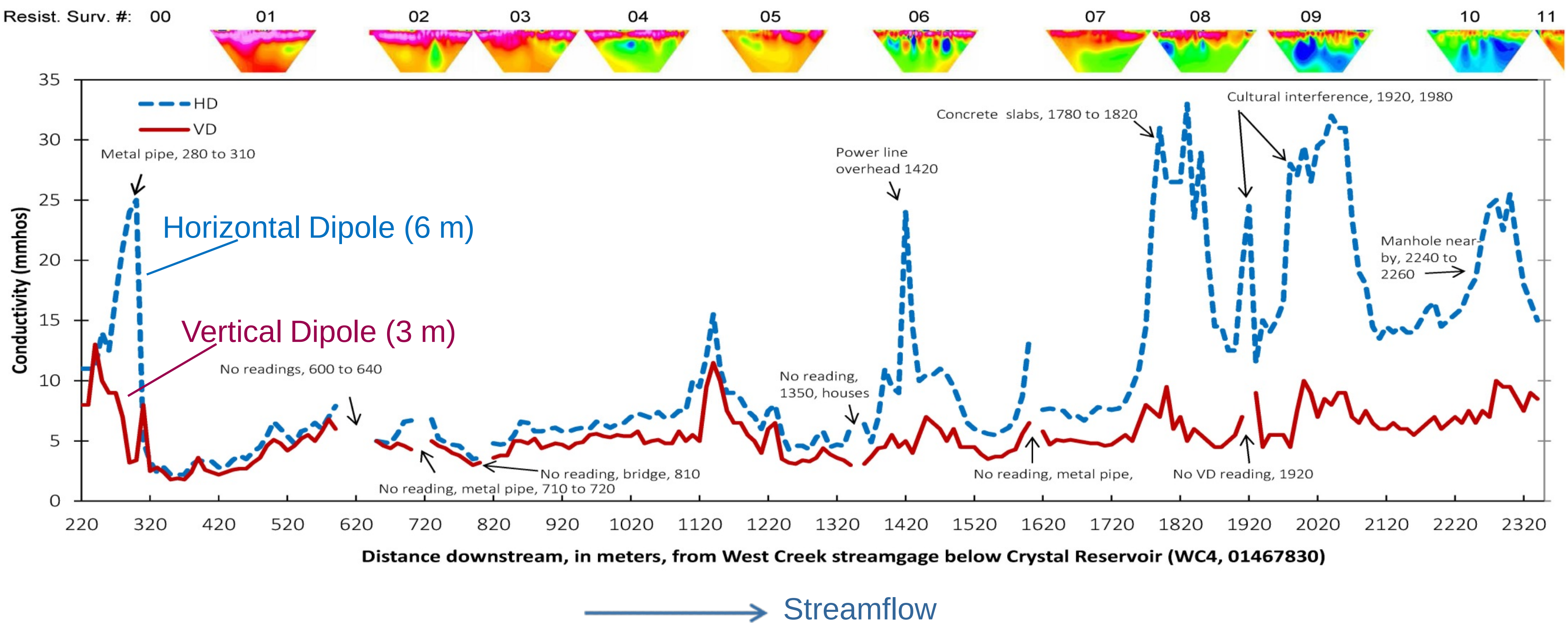
West Creek – Resistivity Survey Profiles 2014



The 2014 surveys overlapped and extended downstream from the 2012 surveys (previous slide) and also indicated a longitudinally extensive 5-to-10 m thick high-resistivity layer near the surface and decreasing resistivity with depth beneath the streambed. The high-resistivity layer at the surface was disrupted locally, primarily within surveys 6, 8, 9, and 10, where low-resistivity anomalies also extended to depths of 10 to 30 m. These low-resistivity anomalies are interpreted to indicate relatively conductive water-saturated zones that could be locations of streamflow loss (surveys 8 to 11), or could be locations of groundwater discharge (survey 6).

NOTE: Zones of low resistivity (surveys 8 to 11) correspond to the mapped location of anticline (shallower mining) and the historically re-routed stream.

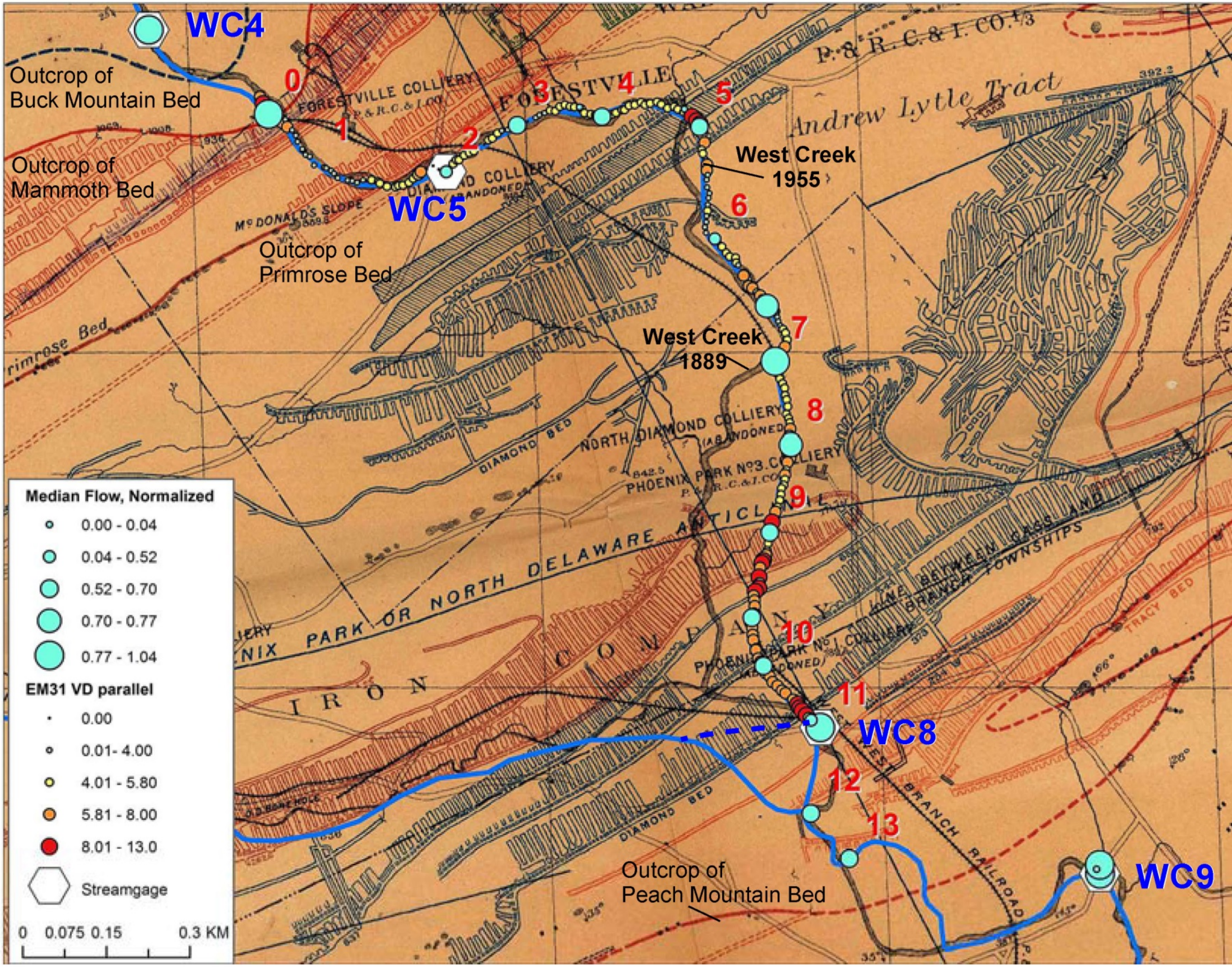
West Creek – EM31 Longitudinal Survey 2015



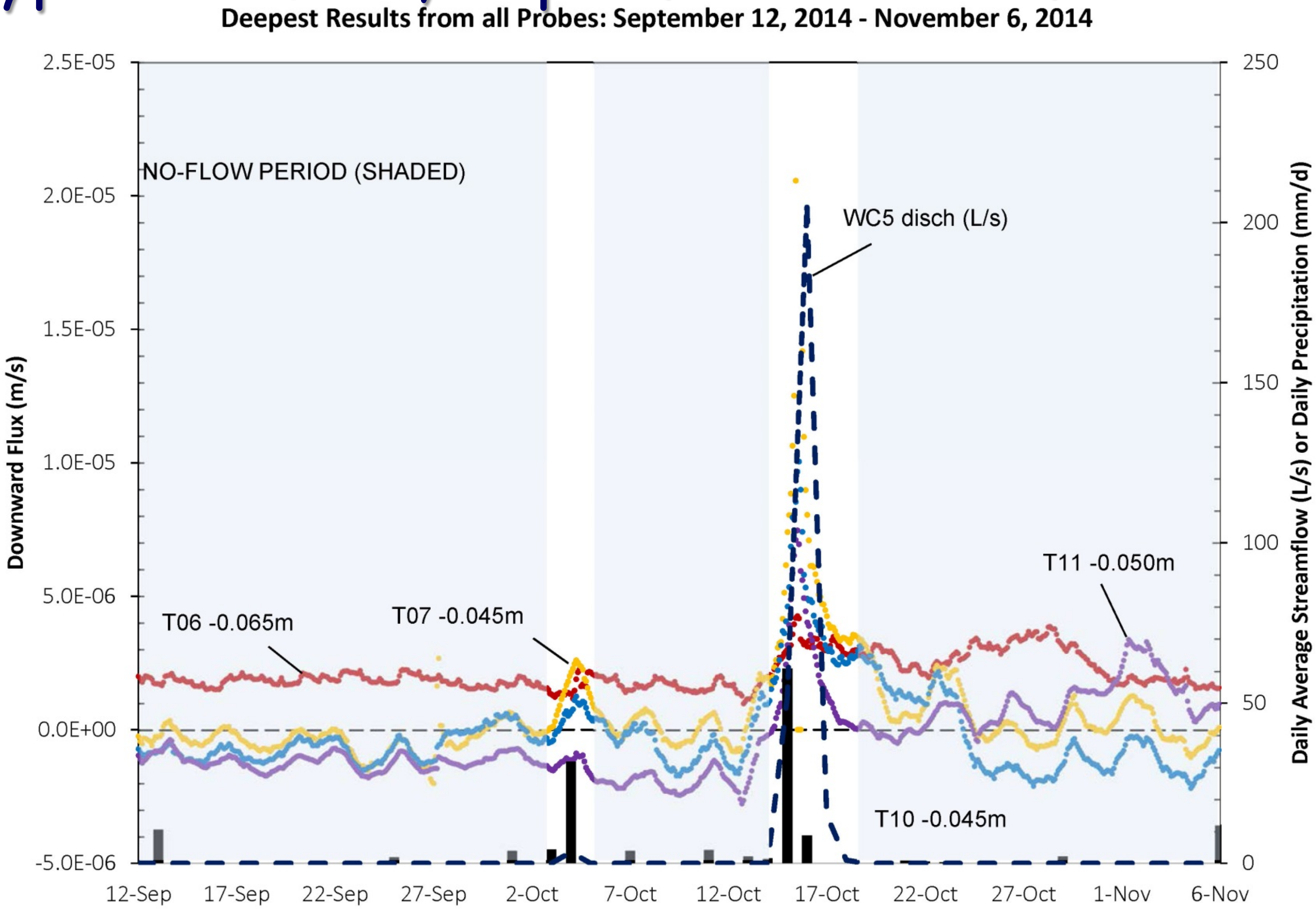
Surface electromagnetic (EM-31) survey data were collected in December 2015 during moderate flow conditions along most of the same segment of West Creek as the 2014 resistivity surveys (between resistivity endpoints 0 to 11). The EM-31 survey results were consistent with resistivity survey results.

NOTE: In the upper 250-320 m zone, the HD conductivity peaks (at 6 m) were offset downstream from the VD peaks (at 3 m). This offset is consistent with the low-resistivity anomaly that angles approximately 30^0 downward from the surface following the same orientation as the mapped coalbed in this location.

West Creek – EM31 Longitudinal Survey 2015

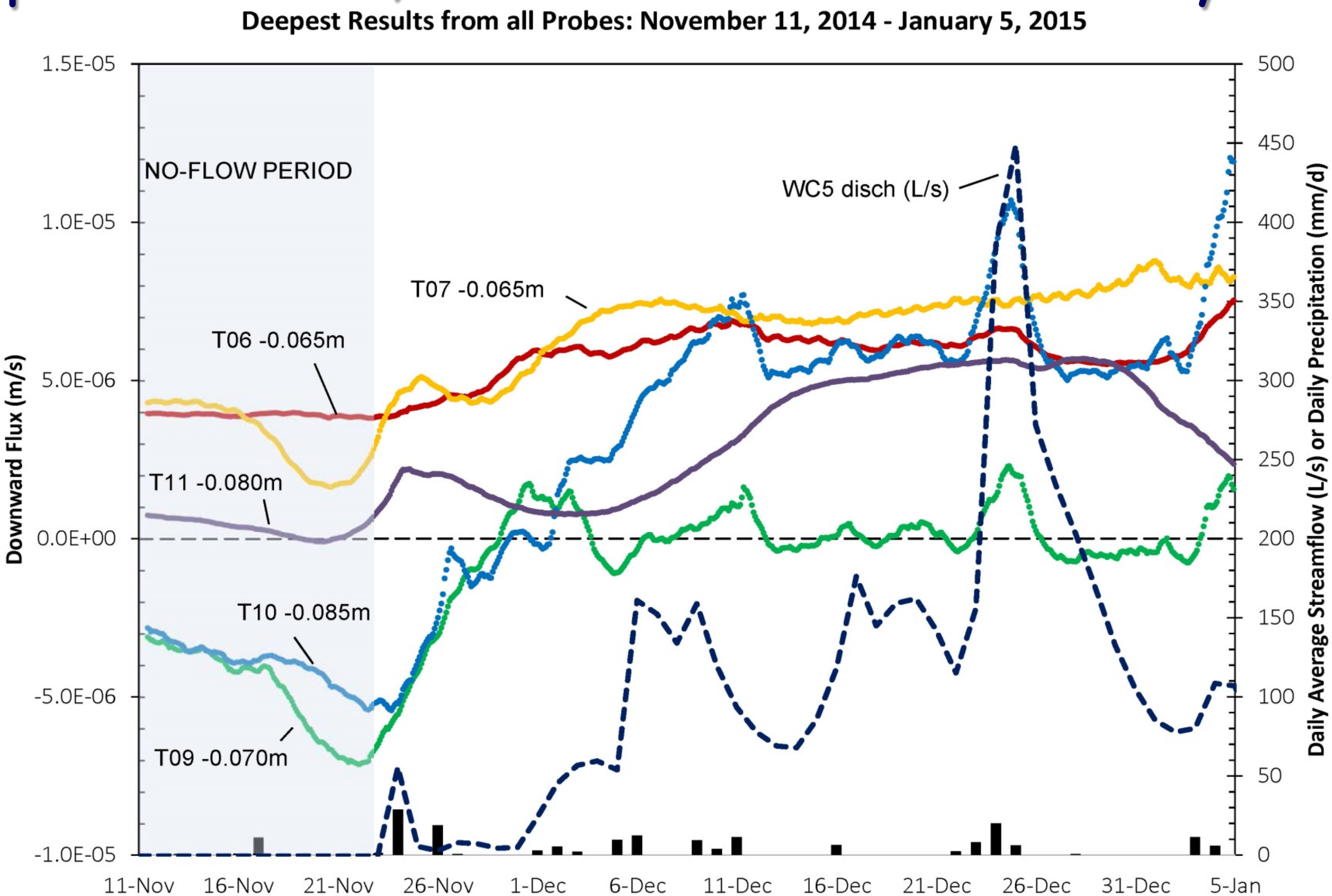


West Creek Streambed Temperature Probes, Hyporheic Flux, September – November 2014



Temperature probes within the hyporheic zone of the intermediate segment indicated spatially and temporally variable fluxes to 2.1×10^{-5} m/s (downward) during flowing conditions.

West Creek Streambed Temperature Probes, Hyporheic Flux, November 2014 – January 2015



Downward, but variable, fluxes were indicated for all probes during continuously flowing conditions.

NOTE: Average downward flux estimate of 1.70×10^{-5} m/s was computed based on cumulative streamflow losses along the entire 2.1-km segment between WC4 and WC9

West Creek Flow Loss “Seepage” Surveys 2012-15

Table A2. Measured streamflow at selected stations on West Creek during seepage runs in 2012-2015, including the estimated total gains and total losses between stations WC4 and WC5 or WC9 and the comparison of losses from West Creek with discharge from Oak Hill Boreholes.

Date of Seepage Run	WC4, measured (L/s)	WC5, measured (L/s)	WC5-WC4, change in streamflow (L/s)	WC9, measured (L/s)	WC9-WC4, cumulative total gains [a] (L/s)	WC9-WC4, cumulative total losses [b] (L/s)	WC9-WC4, cumulative total losses as percentage of total gains	OAK, daily average flow (L/s) [c]	WC5-WC4, upstream losses as percentage of OAK	WC9-WC4, cumulative total losses as percentage of OAK
20120313	17.93	3.71	-14.22	5.19	25.90	-20.71	80.0%	234.29	6.1%	8.8%
20120418	6.40	0.00	-6.40	1.43	7.83	-6.40	81.7%	171.56	3.7%	3.7%
20120427	8.04	0.00	-8.04	0.03	8.04	-8.01	99.6%	169.72	4.7%	4.7%
20120913	3.35	0.00	-3.35	2.52	6.00	-3.48	58.0%	123.73	2.7%	2.8%
20120930	29.96	23.82	-6.15	21.33	32.46	-11.13	34.3%	133.39	4.6%	8.3%
20121109	97.73	96.40	-1.33	133.47	155.64	-22.17	14.2%	222.79	0.6%	10.0%
20130118	241.97	97.68	-144.29	187.26	383.43	-196.17	51.2%	235.28	61.3%	83.4%
20140512	81.59	61.74	-19.85	101.31	160.72	-59.40	37.0%	325.37	6.1%	18.3%
20140807	6.29	0.00	-6.29	4.30	16.71	-12.40	74.2%	252.36	2.5%	4.9%
20141107	3.40	0.00	-3.40	2.35	5.75	-3.40	59.1%	134.21	2.5%	2.5%
20150423	398.46	457.66	59.20	537.40	804.68	-267.29	33.2%	381.19	-15.5%	70.1%
20150612	21.58	11.36	-10.22	64.14	101.64	-37.50	36.9%	214.55	4.8%	17.5%
20150724	28.86	14.84	-14.02	28.04	73.66	-45.62	61.9%	277.17	5.1%	16.5%
AVERAGE:	72.73	59.02	-13.72	83.75	137.11	-53.36	55.5%	221.20	6.9%	19.3%
MEDIAN:	21.58	11.36	-6.40	21.33	32.46	-20.71	58.0%	222.79	4.6%	8.8%
MAXIMUM:	398.46	457.66	59.20	537.40	804.68	-3.40	99.6%	381.19	61.3%	83.4%
MINIMUM:	3.35	0.00	-144.29	0.03	5.75	-267.29	14.2%	123.73	-15.5%	2.5%

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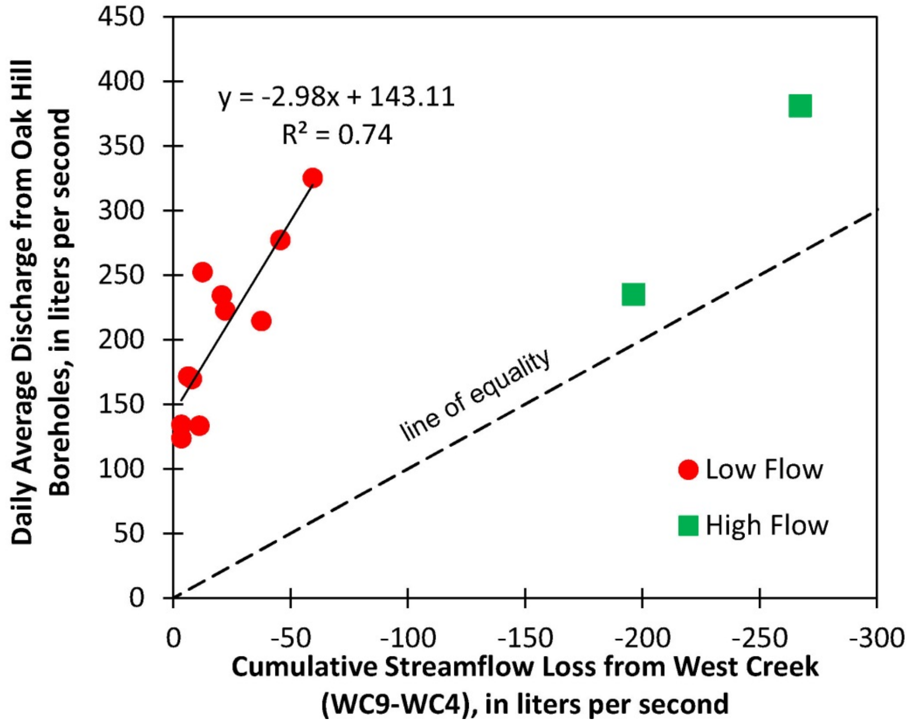
a. Cumulative gains is the sum of flow at WC4 plus all inflows indicated by increased streamflow between measurement points from WC4 to WC9.

b. Cumulative losses is the sum of all outflows indicated by decreased streamflow between measurement points from WC4 to WC9.

c. The average discharge from OAK during seepage runs was comparable to the average daily discharge of 224 L/s during January 1, 2012-September 30, 2015 (Figure 5) and 216 L/s during the 12-month period of July 1, 2014-June 30, 2015 (Table 1).

Seepage surveys involved streamflow and water-quality measurements at ~150-m intervals from upper through lower reaches. Cumulative total loss was greater than simple difference between flows at uppermost and lowermost gages because of gains between these points that also were lost.

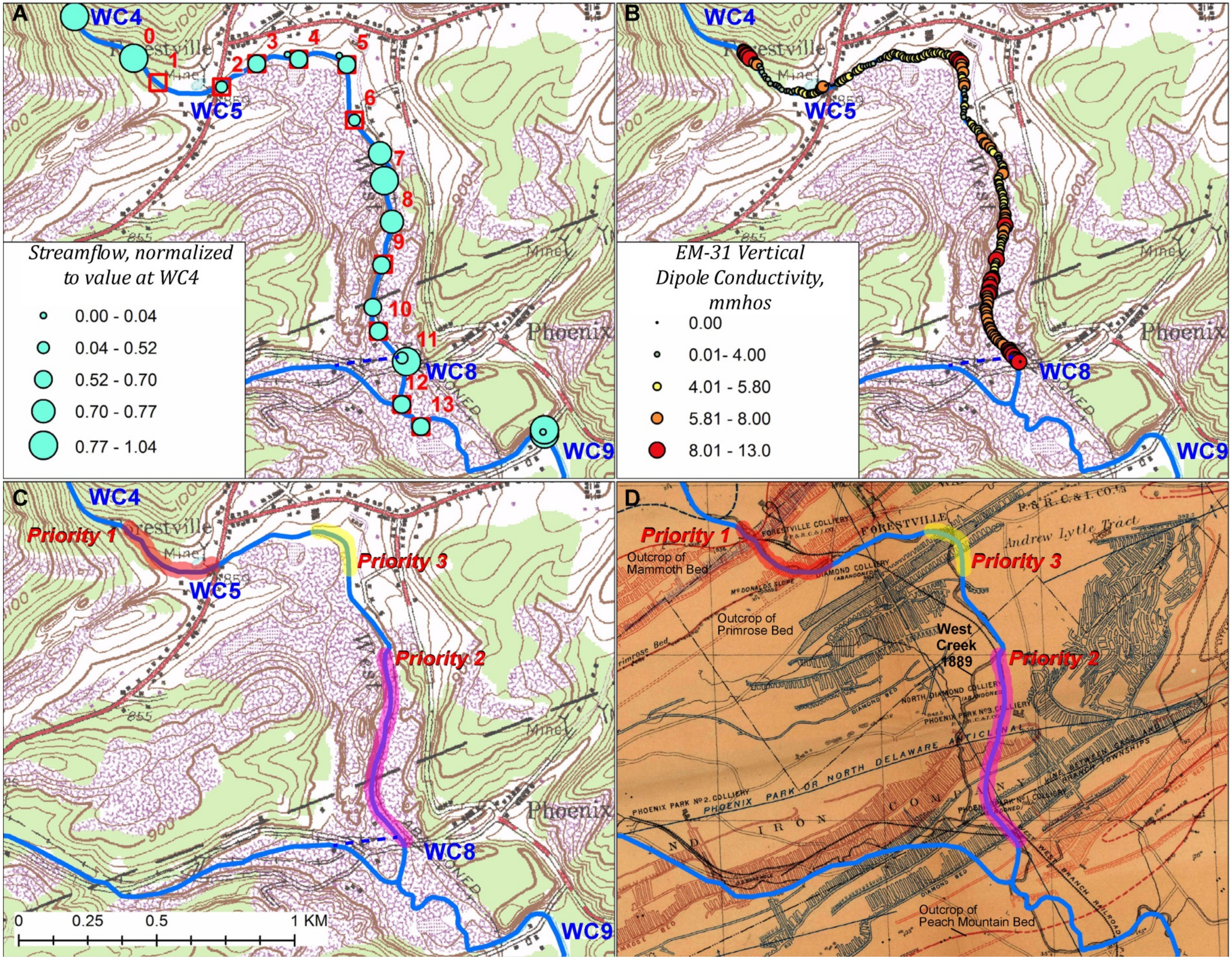
Comparison of Daily Discharge from Oak Hill Boreholes with Cumulative Streamflow Lost from West Creek, 2014-2015



Discharge from the Oak Hill Boreholes was sustained at approximately 140-150 L/s (intercept) during low-flow conditions and correlated to streamflow lost through the West Creek streambed.

NOTE: During high-flow conditions, the cumulative losses from West Creek deviated from low-flow correlation and approached the magnitude of the discharge from Oak Hill Boreholes.

West Creek Stream Restoration Priorities



Specific Conclusions

- Hydrograph analysis and seepage runs indicated:
  - ✓ Inter-basin transfer of groundwater through underground mines resulted in diminished streamflow yields of West Creek and West West Branch (downstream), and greater streamflow of West Branch (adjacent) than expected based on their topographic drainage areas.
  - ✓ Contaminated discharge from Oak Hill Boreholes was sustained during low flow and correlated to streamflow lost through the West Creek streambed.
  - ✓ Streamflow was lost (and gained) along the 2.1-km segment of West Creek that overlies the underground Oak Hill Mine complex.
  - ✓ Because of local gains, the pH and SC increased downstream and the cumulative streamflow lost exceeded the difference between measured streamflows at downstream (WC9) and upstream (WC4) gages.

Specific Conclusions

- Historical topographic and mining maps indicated:
  - ✓ Locations of streamflow losses from West Creek coincided with historical coal outcrops and historical underground mine workings.
  - ✓ Perennial streamflow coincided with historically undisturbed reaches.
- Streambed hyporheic temperature probes indicated:
  - ✓ Leakage through the West Creek streambed varied spatially and temporally; downward fluxes increased with stream discharge.
- Electrical resistivity and electromagnetic surveys indicated:
  - ✓ A low-conductivity zone beneath streambed to 5 to 10 m depth is interrupted locally by high conductivity zones to 30+ m depth, which are locations of streamflow loss or groundwater inflow to the stream.