South River Geomorphology Update
Fall 2008 Expert Panel Meeting

I. Historic Hg Concentrations on Particles in the South River

Sediments in "Fine-Grained Channel Margin" (FGCM) represent samples of suspended particles carried by the South River. New samples and analyses provide a detailed record of the ages of sediments and mercury concentrations in these deposits. Approximately 50% of the deposits are less than 5 years old, but about 10% date from the period of Hg release from the plant in Waynesboro (i.e., 1930-1950)(Figure 1). A parallel analysis of mercury concentrations in these deposits show an abundance of low concentrations with values of a few 10s of ppm. However, about 10% of the concentrations are greater than about 100 ppm, with some values up to 900ppm. Where dates are available for sediments with very high Hg concentrations, these samples all date from the period of mercury release from the plant. Averaging the data from these two populations of mercury concentrations suggests that typical release age mercury concentrations (on particles) were about 350 ppm, while typical post release concentrations on particles have averaged around 15 ppm. These data suggest that 75% of the mercury still stored in FGCM deposits dates from the period of direct mercury release from the plant.

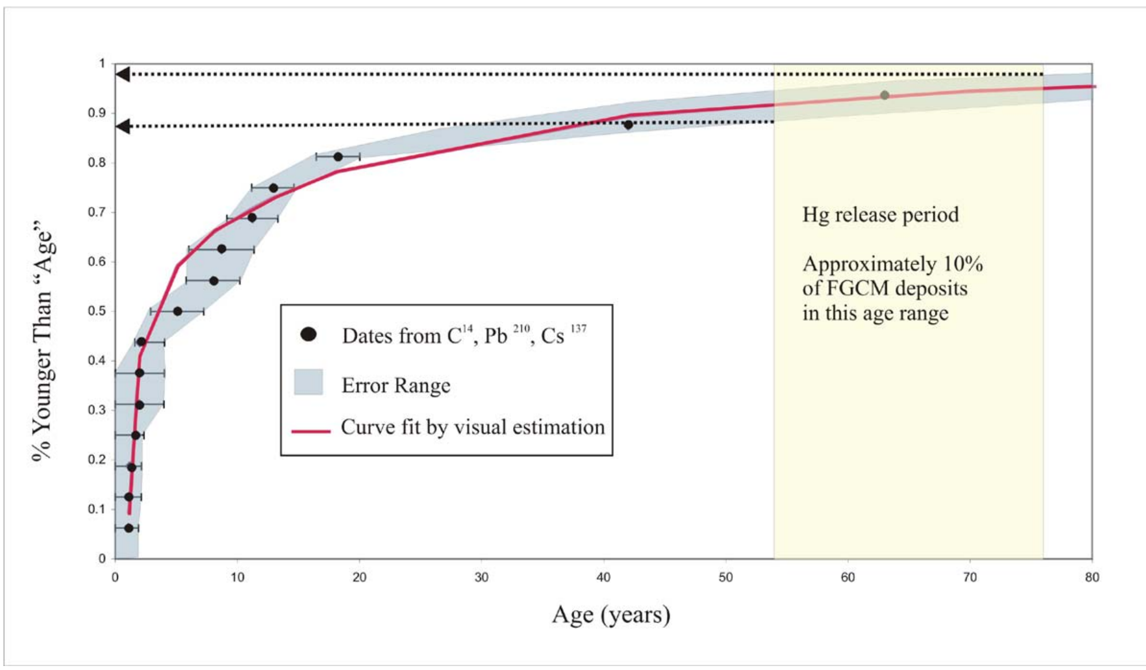

Figure 1. Age distribution of sediments in Fine-Grained Channel Margin deposits.

II. Modeling the Changes in Hg Concentration and Mass in Fine-Grained Channel Margin Deposits

We have developed a simple modeling approach for computing changes in the mass of mercury in FGCM deposits through time. Concentrations of mercury on particles suspended in the water column are specified, and the mass and age distribution of sediments in FGCM deposits are assumed to be constant. The modeling predicts that about 400 kg of mercury was stored in these deposits in 1950 at the end of the release period (Figure 2). The current mass of mercury stored in these deposits is only about 12% of this value, but because the mercury is associated with sediments in the deposits that are rarely remobilized, the model predicts that this stored mercury will persist in place for many decades (possibly centuries). Lowering ambient mercury concentrations in the water column (on particles) will not greatly accelerate the removal of mercury stored in FGCM deposits.

III. Improved Sediment Budget, RRM 2.5-5.43

Following the floodplain mercury sampling, we assembled a comprehensive sediment budget for the reach of the river (RRM 2.5-5.43) where we have the best data. We estimated the total mass of sediment transported or deposited from 1937-2005. The sediment budget results are listed in Table 1.

Table 1. Mass of sediment transported, deposited, or "released" from 1937-2005 along the South River from RRM 2.5-5.43.

Process	Mass of Sediment (kg)
Suspended Sediment Transport	3.75E+08
Floodplain Sedimentation	1.01E+08
Released from Fine-Grained Channel Margin Deposits	2.40E+07
Meas. And UnMeas. Fluvial Bank Erosion	1.15E+07
Tributary Confluence Sedimentation	2.80E+06
Released from Storage in the Bed	5.30E+05
Bank Erosion Caused by Animals	5.00E+05

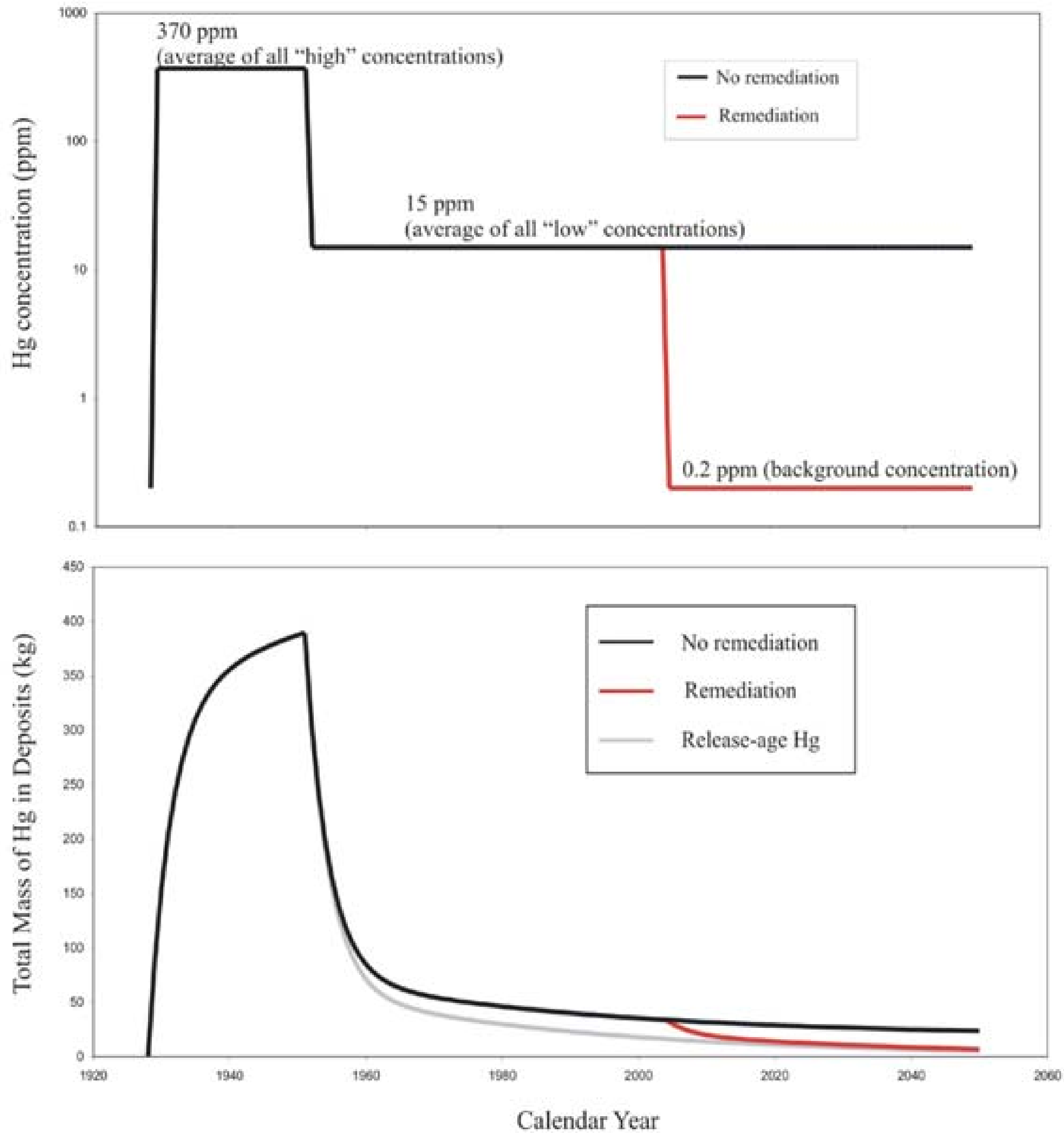

Figure 2 (Above). Assumed "loading curve" of Hg on particles suspended in the water column from 1930-2050. The red curve represents reduced concentrations in the water column that could be created through successful remediation. (Below). Predicted mass of Hg stored in FGCM deposits through time. Gray line indicates Hg remained in the deposits from the release period, while the red curve indicates predicted mass of stored Hg that would arise as a result of remediation.

IV. Hg Concentrations in Eroding Banks

As part of the floodplain sampling program, we measured Hg concentrations in eroding banks along the river. Vertically averaged and maximum Hg concentrations are listed in Table 2. When data from RRM 1.55-1.75 are excluded (these banks were created in the mid-1970s by an artificial cutoff), concentrations decrease exponentially with distance downstream of the plant site (Figure 3). For example, the maximum concentration follows the relation $y = 127e^{-0.152x}$, where x is in miles and y is in ppm (r^2=0.51).

Table 2. Maximum and average Hg concentrations in eroding banks along the South River.

RRM	Max THg (ppm)	Average THg (ppm)
0.1	584	
1.55	3	2
1.75	5	2
1.75	10	1
2.18	61	8
2.2	515	140
2.6	88	23
2.96	110	43
3.54	29	9
4.75	18	6
5.36	120	31
5.4	18	2
7.4	83	23
7.7	117	43
8.25	8	3
8.5	26	7
8.78	9	4
8.8	16	3
9.75	80	24
11.58	37	10
13.13	3	2
15.4	8	2
19.84	30	5
22.3	5	3
22.58	3	2
22.61	6	1
23.1	13	4

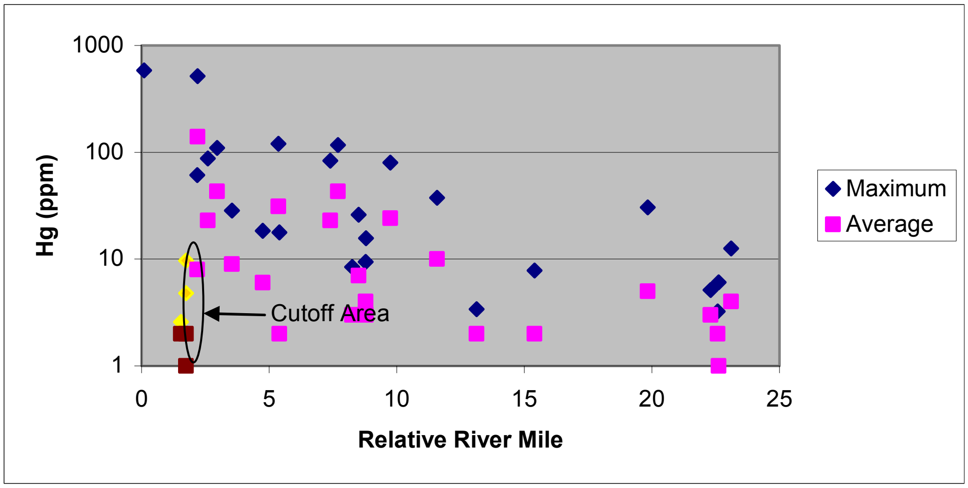

Figure. 3. Variation in maximum and average Hg concentration i eroding banks with relative river mile.

V. Hg Concentrations in “Channel Margin” Floodplain Deposits

As part of the floodplain sampling program, we sampled floodplain deposits located adjacent to the edges of the stream that we believed might have formed during the period of Hg release from the plant (1930-1950). We classified the deposits in to the following categories: point bar deposits, benches, floodplains (sediments deposited on the valley flat), and deposits at tributary confluences. Some of the bench deposits and a few floodplain deposits are associated with mill dams. Most of the deposits are located in two distinctive areas, between RRM 2-5.5 and RRM 7-9 (Figure 4)

Ten of these deposits had very high Hg concentrations that suggested deposition during direct Hg release from the plant at Waynesboro (Table 3). All of these deposits were located between RRM 2.95 and RRM 8.8. Four of these are classified as “currently eroding”.

The mercury concentration in these floodplain deposits adjacent to the river channel decrease exponentially with increasing distance downstream. The data plot along a trend that is similar to the trend for eroding banks (Figure 4).

Table 3. Maximum and average Hg concentration in floodplain deposits sampled near the margins of the river channel. HRADs are “Hg Release Age Depoits”.

HRADs with release age Hg deposits
Eroding HRADs with release age Hg deposits

HRAD	RRM	Bank	HRAD Type	Max Hg (ppm)	Ave. Hg (ppm)
1	2.95	right	bench	432	102
3	3.09	right	bench	18.4	13
4	3.39	right	point bar	75	31
5	3.53	left	point bar	204	49
6	3.68	left	point bar	839	247
7A	3.9	left	bench	10.5	7
7B	3.9	left	bench	78	11
8	4.11	right	point bar	14.7	8
9	4.76	right	tributary	1	1
10A	4.85	right	floodplain	26.6	5
10B	4.85	left	floodplain	29.9	11
11	5.14	left	point bar	11.9	4
12	5.69	right	tributary	27.8	19
14A	7.4	right	bench	96.6	47
14B	7.4	right	floodplain	2.6	0
15	7.8	right	bench	26.2	17
16	8.05	right	floodplain	270	65
17A	8.25	right	point bar	17.5	15
17B	8.25	right	floodplain	196	49
18	8.8	left	point bar	144	54
19	8.49	left	floodplain	52.9	30
20	8.5	right	point bar	26.6	12
21	8.6	right	floodplain	163	77
22	8.65	left	point bar	8.1	6
23	8.78	right	tributary	5.3	5
24 (100)	9.2	right	floodplain	62.3	10
24(101)	9.27	right	floodplain	15.3	10
26A	9.42	right	bench	129	58
26B	9.54	right	floodplain	25	10
28	13.72	right	floodplain	30.7	14
29	15.3	right	point bar	4.3	4
39	23.13	left	point bar	1.5	0
40A	23.44	right	point bar	0.3	0
41	23.44	left	floodplain	15.7	12

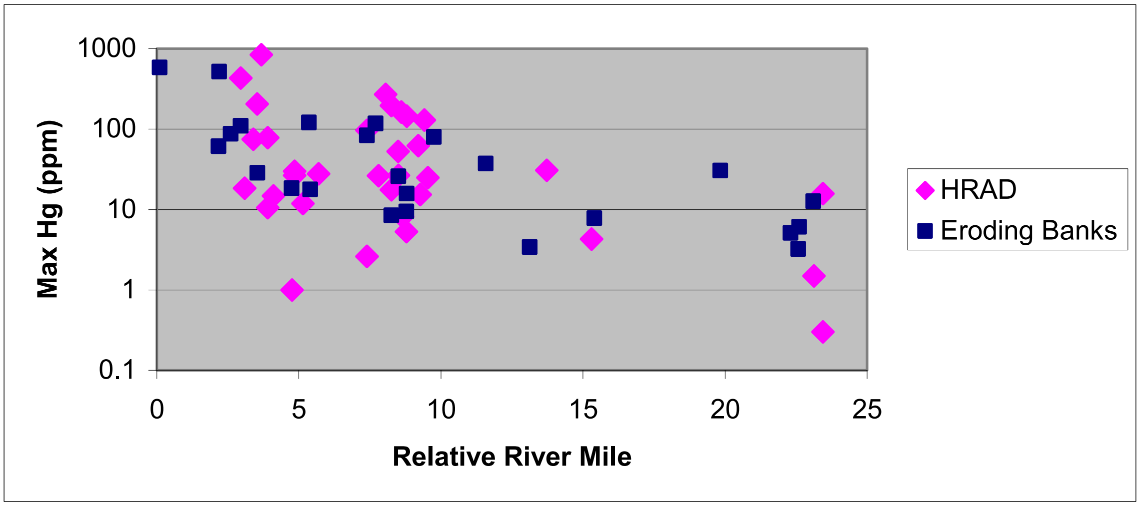

Figure 4. Maximum Hg concentrations in Hg release age deposits (HRAD) and eroding banks.

VI. Explanation For "The Hump"

It has been often observed that concentrations of mercury in many samples from the South River follow a similar pattern when plotted as a function of the distance downstream of the plant site in Waynesboro (Figure 5). Concentrations are initially low, and then they gradually rise, reaching a maximum value between RRM 5-10, and then they gradually decrease to lower values at Port Republic. This pattern has been observed in samples of water, sediment, clams, "herps", fish, and bats. It has been referred to colloquially as "The Hump".

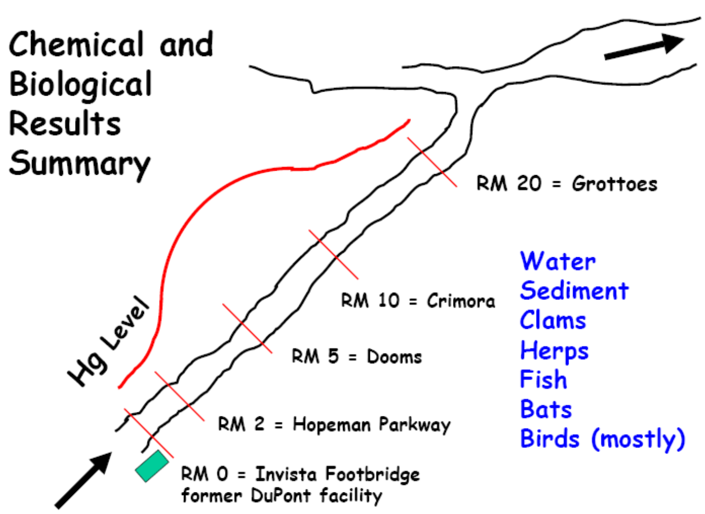

Figure 5. The "Hump" of mercury concentration observed in a variety of samples.

Here I provide a simple working hypothesis that could explain the existence of the "hump" in mercury concentration. The basic idea is that the distribution of mercury in the different types of samples should follow the balance of supply and dilution of mercury carried on particles down the river. The two important processes involve a continuous supply of mercury to the river from bank erosion, and a suite of processes that combine to cause dilution of mercury in transport on particles with distance downstream. Dilution processes could include supply of "clean sediment" from tributaries, exchange of contaminated sediment with relatively uncontaminated sediment through erosion and deposition during transport, and other processes.

Potential rates of these processes and their associated Hg concentrations are illustrated in Figure 6. Clean sediment is supplied in large amounts to the study reach in suspension from the watershed upstream of the plant. Bank erosion supplies contaminated sediment whose concentrations decrease exponentially downstream. Clean sediment is also supplied with increasing distance downstream – this rate of supply is idealized as a constant rate of input with distance. The rates of these different sources and the concentrations of Hg associated with each are specified by previous studies of the river's sediment and Hg budgets (Pizzuto et al., 1996, and other studies).

The concentration of Hg on particles computed from the model illustrated in Figure 6 is shown in Figure 7. Concentrations follow a humped distribution, with a peak of about 10 ppm around RRM 10, similar to that observed (Figure 5).

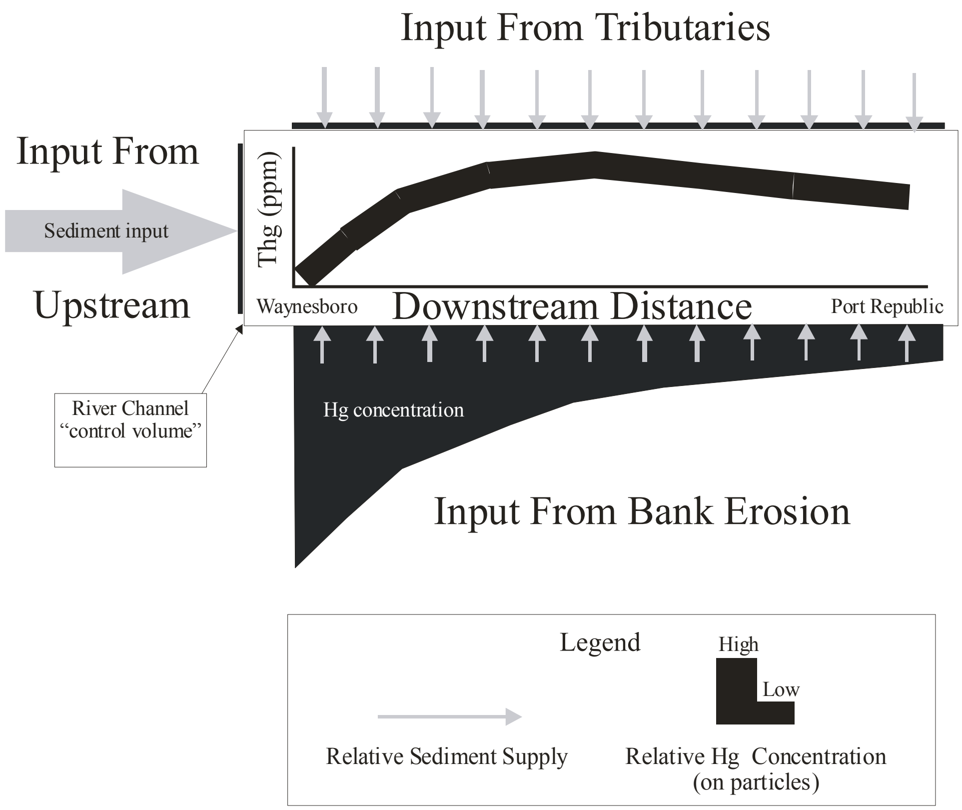

Figure 6. Rates of supply of sediment and Hg that could explain the observed “hump” in mercury concentrations sampled along the river in the study area.

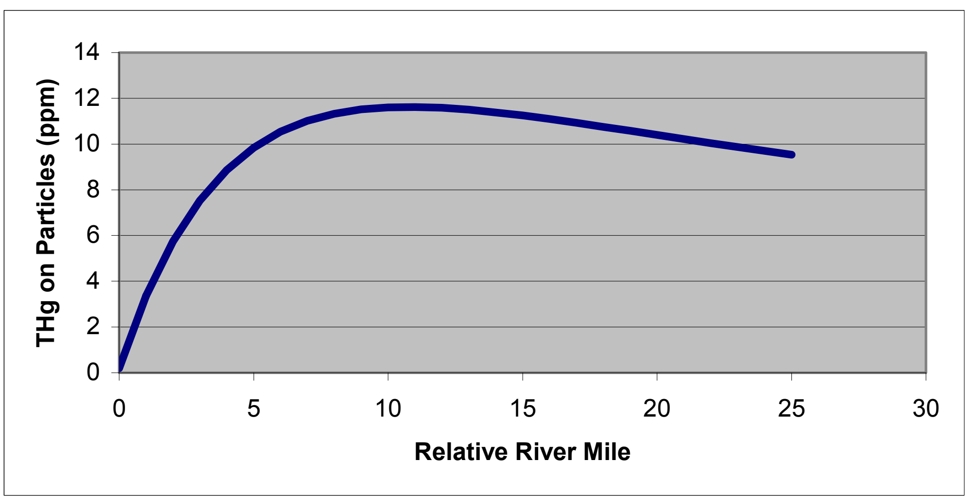

Figure 7. Concentration of total Hg on particles as a function of relative river mile computed from the model illustrated in Figure 6.

VII. Accelerating Bank Erosion Over the Last 75 Years

We have quantified rates of river bank erosion using historical aerial photographs over decadal timescales and repeat surveys using tripod mounted lidar over annual timescales.

Rates of bank erosion appear to have increased from early in the 20th Century to present. Figure 8 illustrates bank erosion rates averaged from 1937-2005, 1957-2005, and 2005-2007. Decadal bank erosion rates were measured from aerial photographs, while the more recent rates were measured using tripod LiDAR surveys. From 1937-2005, the modal bank erosion rate is about 0.05 m/yr (Rhoades et al., in press), and nearly all the erosion rates are less than 0.25 m/yr. From 1957-2005, erosion rates cover a much wider range, with values from 0.1-0.7 m/yr occurring frequently. The annual erosion rates are a much smaller database, but they generally follow a similar range as the rates measured from 1957-2005, though one measurement is extremely high at 2.3 m/yr.

Pizzuto and O'Neal document an increase in bank erosion rates after 1957 by a factor of 3 or so compared to rates observed from 1937-1957 at 14 sites along the South River (Pizzuto and O'Neal, in press). They argue that increased bank erosion rates are best explained by the demise of mill dams along the river.

VIII. Revised Geomorphic Conceptual Models for the South River

The South River as a "Bedrock River"

A new classification defines bedrock rivers as any channel that "cannot substantially widen, lower, or shift its bed without eroding bedrock" (Turowski et al., 2007). Field mapping has demonstrated that bedrock exposures occur frequently along the channel perimeter of the South River. A new longitudinal profile for the river for RRM 2.0-5.5 suggests that about 40% of the vertical drop of the river in this reach occurs where the river is flowing over bedrock (Figure 9). These observations suggest that Turowski et al's definition of a "bedrock river" is appropriate for the South River.

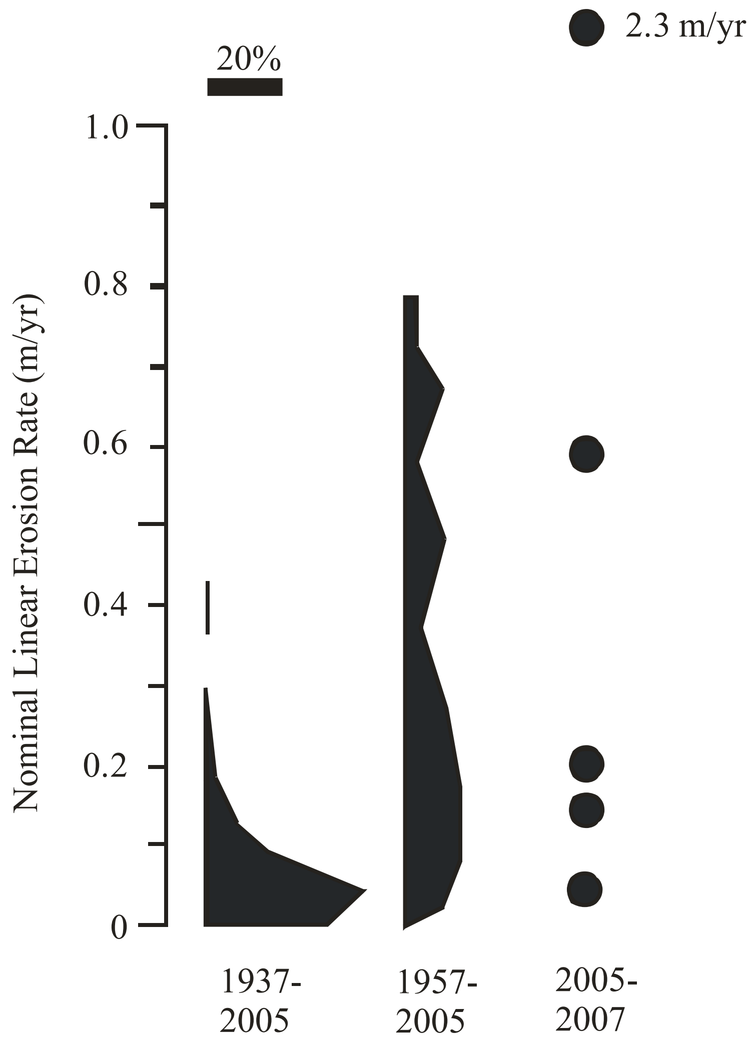

Figure 8. Distributions of bank erosion rates measured over three different time periods. Decadally averaged erosion rates were measured from aerial photographs, while the annually averaged erosion rates were measured using tripod mounted LiDAR.

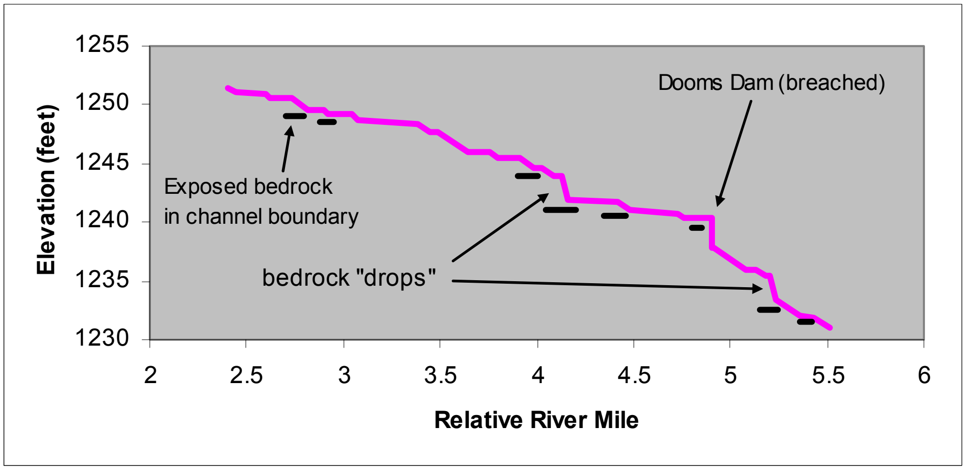

Figure 9. Longitudinal profile of the South River RRM 2-5.5 showing pools, riffles, bedrock exposures and drops, and Dooms Dam. 38% of the vertical drop in this reach occurs when the river is flowing over bedrock.

Evolution of the South River From an "Impounded" To an "Eroding" Condition

Analysis of historical sources demonstrates that mill dams were present at intervals of about every two miles along the South River in the early decades of the 20th Century (Pizzuto and O'Neal, in press). Hydraulic analyses suggest that about 80% of the length of the river from Waynesboro to Grottoes experienced reduced velocities during periods of high flow due to these dams. After about 1960, however, almost all of these dams ceased to exist. Thus, during the early part of the 20th Century, the river was in an "impounded" state, with reduced rates of bank erosion and other sediment transport processes. In the latter part of the 20th Century and the early 21st Century, velocities have likely increased along the river, leading to an "eroding" state. Changes along the river that may have occurred (Figure 10) include an increase in bank erosion rates, a lowering of the level of the bed upstream of the dams, an increase in the amount of large woody debris in the channel as a result of increased trees falling from the banks, and a decrease in the rate of overbank sedimentation. Most of these hypothetical changes, unfortunately, cannot be directly verified by observation.

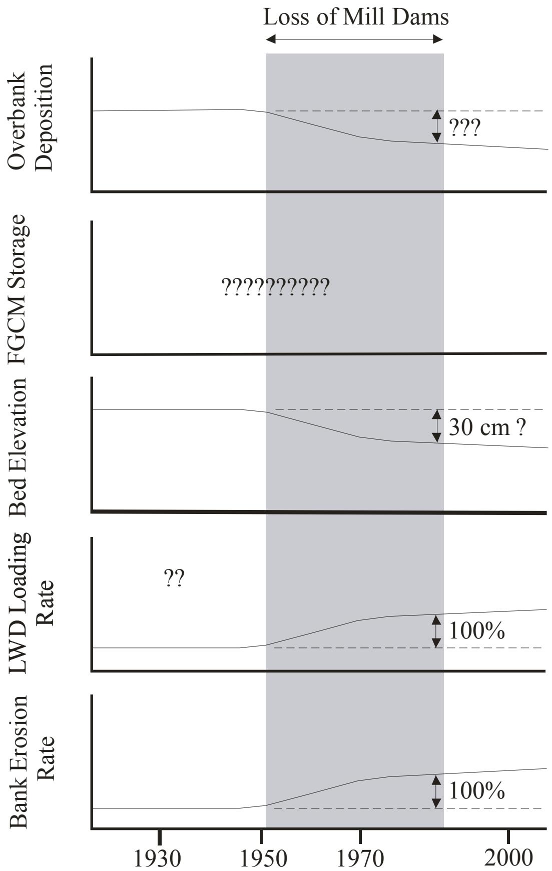

Figure 10. Some hypothetical changes to the South River as a result of the loss of mill dams circa 1950, changing the river from an "impounded" state to an "eroding" state.

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Rhoades, E/L/. O'Neal, M.A., and Pizzuto, J.E., in press. Quantifying bank erosion on the South River from 1937 to 2005, and its importance in assessing Hg contamination. Applied Geography.

Pizzuto, J. and O'Neal, M. in press. Increased Mid-20th Century River Bank Erosion Rates Related to the Demise of Mill Dams, South River, Virginia. Geology.

Turowski, J., Hovius, N., Wilson, A., and Horng, M., 2007, Hydraulic geometry, river sediment and the definition of bedrock channels. Geomorphology, doi:10.1016/j.geomorph.2007.10.001