Sediment Generation Rates in the Potomac River Basin

A Thesis Proposal Presented
by
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Master of Science specializing in Geology

The Following Members of the Thesis Committee have read and approved this document before it was circulated to the faculty:

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Date Accepted:__________________

Abstract

My research will determine long-term sediment generation rates in the Potomac River Basin. First, I will synthesize all of the relevant studies of sediment generation and sediment yield that have been done in the area. Then, I will use meteoric ^{10}Be in bulk river sediment and in situ ^{10}Be in quartz separated from that sand to estimate rates of sediment generation in the Potomac River Basin. I will compare these rates with modern sediment yield rates found by Gellis et al. (2004). I will also do a comparison of the rates I find between basins of differing size and relief. Then, I will compare the meteoric and the in situ data to determine how land use affects the concentration of meteoric ^{10}Be in river sediment. With my main analysis complete, it should be possible to help decide whether total maximum daily loads (TMDLs) of suspended sediment that are currently being created for the Potomac River by the EPA are reasonable based on the long-term sediment generation rates.

1.0 Introduction

> *"The Potomac River has long been viewed as the Nation's River because of its pivotal role in the development of the United States and as the seat of our national government (US EPA, 2001)."*

Today, the Potomac River (37995 km^2) contributes a significant amount of sediment to the Chesapeake Bay (Stanton, 1993; Gellis et al., 2004). Because the Bay is a valuable natural resource and because large amounts of money, time and energy are being spent protecting it, responsible management requires good estimates not only of current rates of sediment delivery to the bay but also background (pre-disturbance) rates of sediment generation from major river basins feeding the Bay. The Potomac River is one of two major rivers, the other being the Susquehanna that feed sediment to the bay (Figure 1). The Potomac provides 44% of the riverine sediment to the Bay while the Susquehanna provides 27% (Gellis, et al., 2004). Both the current sediment yield (Gellis, et al., 2004) and background rate of sediment generation (Reuter et al., 2006) have been determined for the Susquehanna. My Masters research will determine long-term sediment generation rates for the Potomac River Basin, which I will then compare with contemporary sediment yields (Gellis, et al., 2004). This comparison will allow me to infer how the sediment generation rates have changed since western settlement of the Potomac

Watershed. In addition, I will test for differences in sediment generation rates among basins of different size, relief, and in different physiographic provinces within the Potomac River Basin. This test will help determine what variable effects sediment generation rates the most. Then, I will compare results of meteoric ^{10}Be and in situ ^{10}Be analysis to determine how land use affects the concentration of meteoric ^{10}Be. This comparison can help future studies that are unable to use in situ ^{10}Be and a forced to use meteoric ^{10}Be. Lastly, I will compare the Potomac River Basin sediment generation rates with others in the southern Appalachians including those in the Susquehanna River Basin (Reuter, et al., 2006), the Shenandoah River Basin (Duxbury et al., accepted), the Blue Ridge (Sullivan et al., accepted), and the Great Smokey Mountains (Matmon et al., 2003). My analysis will present a clearer understanding of how the Appalachians are eroding.

2.0 Physical Setting

The Potomac River basin occupies 37,995 km^2 (Stanton, 1993). It is a major watershed in four states and the District of Colombia (Virginia, 14846 km^2; Maryland, 9889 km^2 in, West Virginia, 9039 km^2; Pennsylvania, 4,066 km^2; District of Columbia, 179 km^2; ICPRB 2009). About 5.8 million people, estimated from the 2005 census, live in the Potomac River Basin, with ¾ of those in the metropolitan area of Washington, D.C. (ICPRB, 2009).

The Potomac River begins in Fairfax Stone, WV as a small spring and then flows 616 km to the Bay (Stanton, 1993). It eventually reaches an average flow of 28,163 million liters per day, near Washington, D.C. (Gerhart, 1991) before discharging into Chesapeake Bay near Point Lookout, MD (ICPRB, 2009). The tidal portion of the river starts where it crosses the Fall Line moving into the Coastal Plain province, several km upstream from Washington, D. C. (Gerhart, 1991). From 1930 to 1989, the maximum flow of the Potomac was 1,184,076 million liters per day on March 19, 1936, and the minimum flow, which occurred on September 10, 1966, was

1,469 million liters per day (ICPRB, 2009). The Potomac River provides about 15% of the water that flows into the Chesapeake Bay (Gerhart, 1991). About 44% of the river sediment entering the Bay comes from the Potomac (Gellis et al., 2004).

The Potomac River has 10 major tributaries; the North Branch Potomac, South Branch Potomac, Shenandoah, Monocacy, Savage, Cacapon, Anacostia and Occoquan Rivers, and the Antietam and Conococheague Creeks (ICPRB, 2009). Dams only regulate about 3% of the drainage area in the Potomac River basin (Gerhart, 1991).

Five physiographic provinces, the Appalachian Plateaus, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain, are included in the Potomac River basin (Figure 2). The North Branch of the Potomac flows through the Appalachian Plateau (Stanton, 1993). The Appalachian Plateaus Province is an area with differential erosion of a thick, uplifted section of Paleozoic sedimentary rocks, mainly sandstone, shale and limestone, created by a series of plateaus capped by resistant rock layers, commonly sandstone (Fenneman, 1938). The Valley and Ridge Province makes up around 60% of the Potomac River Basin's area (US EPA, 2001). The ridges are made of strongly consolidated sandstone and conglomerate while the valleys are easily eroded layers of limestone, dolomite and shale (Trapp and Horn, 1997). The surface of the Blue Ridge is a narrow line of highlands (US EPA, 2001), the surface rocks in the highlands are mainly composed of metamorphic and igneous rocks, while the valleys are low-grade metamorphic and sedimentary rock (Milici, 1995). The Piedmont is underlain by metamorphic and igneous rocks, which range in age from Precambrian to Paleozoic. In addition, areas of this province contain sedimentary basins, which formed along failed rifts. These contain shale, sandstone and conglomerate of early Mesozoic age. The sedimentary rocks are interbedded with basaltic lava flows and some coal beds. In places, dikes and sills crosscut the sedimentary rocks and basalt flows (Trapp and Horn, 1997; Milici, 1995). The Coastal Plain is underlain by semiconsolidated to unconsolidated silt, clay and sand in most areas. A portion of the area contains consolidated beds of limestone and sandstone.

The Potomac River Basin has a temperate climate, with average annual temperatures ranging between 9° C in the western part of the basin to 14° C in the east. The central portions of the basin experience the lowest average annual rainfall, around 89 cm, while the western mountains and the coastal plain average around 112 cm (Gerhart, 1991).

The Potomac River has existed for about 30 million years (Stanton, 1993). About 6 to 7 million years ago, sea level significantly decreased in the DC area to near modern levels (Reed et al., 1980). As the sea retreated, silt, sand and gravel were deposited over the Coastal Plain by many small rivers. Slow uplift started to occur about 2 million years ago in the Piedmont and the Appalachian Plateau. This steepened the land surface and caused all of the small rivers to flow into the modern Potomac River (Reed et al., 1980). Around this same time continental glaciation began, which greatly lowered sea level. At the height of glaciation, the shoreline was 120 km east of the modern position. The falling of sea level during glaciation caused the Potomac to cut deep valleys through all of the sediment down to the Piedmont Rocks (Reed et al., 1980).

Nomadic tribes started to inhabit the Potomac River Basin around 12,000 BP (Stanton, 1993) and around 1800 BP Native Americans began practicing agriculture in the Potomac Watershed (Stanton, 1993). In 1634, the Colony of Maryland was established on the banks of the Potomac (Stanton, 1993) and in 1791, Washington DC was founded. Forest and agriculture are the dominant land use for the Potomac River Basin. In 1997, about 54 percent of the basin was forested, 29 percent was used for agriculture and 14 percent was urban (Figures 3 and 4; Gerhart, 1991).

3.0 Estimating Erosion Rates: Cosmogenic Nuclides

Analysis of ^{10}Be concentration in fine quartz sand carried by rivers has become an important technique for understanding long-term erosion rates (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). This project will focus solely on ^{10}Be, using it to estimate rates of sediment generation, because ^{10}Be has a relatively long half-life and can be easily measured in quartz (Lal and Arnold, 1985), which has great resistance to weathering and little reactivity to many acids (Kohl and Nishiizumi, 1992).

Beryllium-10 is found both in and on mineral grains. In situ ^{10}Be, that within the grains, is created when high-energy, fast cosmic ray neutrons interact with nuclei (Bierman, 1994; Lal, 1998). Meteoric ^{10}Be forms in the atmosphere where cosmic rays interact with oxygen and nitrogen atoms; ^{10}Be rains out and absorbs to soil grains, including clay and organic particles (Pavich, 1984). Once the ^{10}Be is absorbed to the soil grains, it does not leave the grain during transport (Pavich, 1984; Jungers et al., in review). The concentration of in situ ^{10}Be changes based on how long the sediment has been exposed to cosmogenic radiation, both in rock and as material on slopes. Meteoric ^{10}Be concentration appears to reflect how long the sediment resides on hill slopes before entering the river channel (Jungers et al., in review). Sediment with a higher concentration of ^{10}Be has been exposed longer and generated under a slower erosion rate. Sediment with a lower concentration of ^{10}Be was exposed for a shorter period and indicative a faster erosion rate.

Calculation of erosion rates from measured ^{10}Be concentrations requires several assumptions and is subject to some uncertainties. The sediments that are being generates must contain ^{10}Be in measurable quantities that can be determined by an accelerator mass spectrometer (AMS) (Elmore and Phillips, 1987). Erosion must be approximately constant over time but not space (Bierman, 1994). Meteoric ^{10}Be must adhere and remain on the surface of the sediment (Jungers et al., in review). In situ ^{10}Be must remain in the quartz in which it is produced (Kohl and Nishiizumi, 1992). ^{10}Be in river sediment can be used to estimate erosion rates over a 10^3 to 10^6

year time scale (Brown et al., 1995; Bierman and Stieg, 1996; Granger et al., 1996). The latitude and altitude of the location from which the sample came (Nishiizumi et al., 1989) must be known so that production rates can be calibrated (Lal, 1988; Dunai, 2000; Desilets and Zreda, 2000; Lifton, 2008). The main uncertainty with applying meteoric ^{10}Be is determining its delivery rate from the atmosphere to the surface. This has been estimated many ways (Monaghan et al., 1985). The nominal value of 1.2×10^6 atoms g^{-1} y^{-1} is generally accepted for humid regions (Pavich et al., 1984).

4.0 Controls on Sediment Generation (erosion) and Yield

Sediment yield is controlled by three main factors, land cover, climate and rock erodability (Holeman, 1968). Modern rates of sediment yield are typically estimated using suspended sediment concentrations measured at gaging stations (e.g. Judson, 1968; Judson and Ritter, 1964; Gellis et al., 2004). Many contemporary land-use practices, including; agriculture, construction, mining and the clear-cutting of forests, increase short-term sediment yields (Costa, 1975; Hewawasam et al., 2002; Jennings et al., 2003; Noren et al., 2002; Wolman and Schick, 1967). Damming rivers and streams temporarily lowers sediment yields downstream from the dams (Merritts and Walter, 2003). Much of the sediment eroded from hill slopes resides on colluvial footslopes, in alluvial fans, and in river terraces for centuries or more, slowing transport out of the basin (Schumm, 1977; Trimble, 1977; Walling, 1983) Conversely, some sediment can rapidly move through the system because of agriculture, construction, or mining (Wilkinson and McElroy, 2007).

Sediment yield is a quantification of how much sediment is exported from a basin (Evans et al., 2000). Sediment generation rates describe how rapidly sediment is created in the basin. Equating sediment yield and sediment generation implies steady-state behavior and assumes no change in the volume of sediment stored within a basin, an assumption repeatedly questioned (Meade, 1969; Trimble, 1977, 1999; Walling, 1983). When sediment generation rates are high but sediment yield is low, a large amount of sediment is being produced and is being stored in the basin. When sediment yield is high and sediment generation rates are low, sediment is being removed from storage faster than it is being generated. Brown et al. (1988) examined this problem by first calculating how much meteoric ^{10}Be was being deposited in a basin using the global average delivery rate. The amount of meteoric ^{10}Be leaving the basin was determined by convolving measured ^{10}Be concentration river sediment with contemporary sediment yields. If more ^{10}Be were entering the basin than leaving, sediment yield would be lower than sediment generation. If less ^{10}Be was entering the basin then leaving it, the sediment yield would be higher than the sediment generation. Applying this approach to a single sample from the Potomac River Basin, Brown et al. (1988) found that slightly more sediment is being generated than is leaving the basin.

In the southern and central Appalachian highlands, sediment yield and sediment generation rates appear to be well matched, indicating that they are in long-term equilibrium (Matmon et al., 2003; Reuter et al., 2006). Other regions show large differences between sediment yield and sediment generation, including previously glaciated regions of Europe (Schaller et al., 2001), parts of Idaho (Kirchner et al., 2001), agriculturally affected tropical highlands (Hewawasam et al., 2002), and the heavily farmed mid-Atlantic Piedmont (Reuter et al., 2006). These findings suggest that both human modification of landscapes (Hewawasam et al., 2002; Reuter et al., 2004), and natural variability in sediment delivery (Kirchner et al., 2001), are responsible for these differences.

^{10}Be has been used extensively to estimate the erosion rates in the Appalachian Mountains (Matmon et al., 2003; Reuter et al., 2006; Duxbury et al., accepted; Sullivan et al., accepted). Matmon et al. (2003) found that erosion rates averaged 25–30 m/My in the Great Smokey Mountains. Reuter et al. (2006) estimated erosion rates from 4–54 m/My in the Susquehanna River Basin. Duxbury et al. (accepted) determined erosion rates between 3.8–24 m/My in the

Shenandoah River Basin and Sullivan et al. (accepted) found erosion rates between 6.5–38 m/My in along the Blue Ridge Escarpment in North Carolina and Virginia.

Thermochronology has also been used to determine erosion rates in the Appalachian Mountains; Naeser et al. (2004) found erosion rates to be 20 m/My in the Blue Ridge Province. Pazzaglia et al. (1996) found an average erosion rate of 29 m/My for the entire Appalachians. Doherty and Lyons (1980) found an erosion rate between 32 m/My–49 m/My in and around New Hampshire. Spotila et al (2003) found erosion rates between 9 m/My–29 m/My in the Blue Ridge escarpment. Roden et al. (1991) found erosion rates of 16 m/My–36 m/My in the Southern Appalachian Basin.

5.0 Work Completed

In November 2008, I traveled to 13 USGS current or former gaging sites on the Potomac River and collected sediment samples from 10 (Figure 1). These sites were selected because each has a record of suspended sediment discharge over time (Gellis et al., 2004). Such records will allow me to compare short-term sediment yields with long-term sediment generation rates. At the sampling sites, I collected fluvially transported sand attempting to avoid local inputs. I wet sieved the sample on site to between 850 and 250 microns. Photodocumentation was used to record the condition and general location of each site. I used GPS to establish sample locations. Three samples were taken on the main branch of the Potomac River. One sample (Sample POT-01) was upstream from tidal influence. Another sample came from central Maryland near Point of Rocks (sample POT-06); the third came from near Cumberland, MD on the North Branch (sample POT-11). Seven other samples were taken from tributaries of the Potomac River. Not all of the USGS gaging or former gaging sites were possible to sample, due to either inaccessibility or lack of native quartz. Returning samples to UVM, I dried them. Then, samples were sieved again between 850 and 250 microns. Next, I took out an aliquot from each sample to use for meteoric ^{10}Be. Finally, each sample was run through a magnetic separator to remove magnetic minerals.

During the fall semester of 2008, in Applied Geostatistics with Dr. Donna Rizzo, we created Matlab programs to use for geostatistical analysis. So far, my geostatistical analysis of the modern sediment load has shown that there are possible relationships in space among the samples (Figure 5).

6.0 Work Plan and sample site selection rationale

The USGS has provided us the resources necessary to prepare and analyze 50 samples for both meteoric and in situ ^{10}Be. I have devised a sampling plan to maximize our understanding of erosion rates in the Potomac River basin and the affect of basin slope, time and lithology and basin area. My samples will include 40 from the river network and 10 from a dated core.

Using GIS, a set of small (5-15 km^2) basins of the Potomac and its tributaries have been chosen for sampling (Figure 2; Table 1). The sites contain a variety of development levels and land uses. This will aide in understanding how these variables affect the measured concentration of meteoric and in situ ^{10}Be. In addition, I have selected basins with different levels of relief, basin areas, and in different physiographic provinces. With these data, I will compare the rates statistically, using mean slope, province, development, and basin area as variables. I will collect samples in May and June.

In addition, samples will be taken from a core of Potomac River sediments deposited in the Hybla Valley (Figure 6), a Coastal Plain palaeochannel adjacent to the present Potomac River. The core is held by the USGS. The palaeochannel is filled with >25m of late Quaternary sediment. Most of the sediment is estuarine silt that filled the valley during successive sea level high stands between ~125 ka and ~32 ka. Figure 7 shows dated samples and descriptions of the core. I will analyze the sandier sections of the core, which should represent fluvial intervals, for both meteoric and in situ ^{10}Be, to compare with more recent Potomac alluvium. I will sample at 10 locations in the core, including the four dated locations; 1.8 m, 4.7 m, 12.2 m and 22.5 m; these locations contain quartz sand and have dates. I also plan to sample six other sandy sections spread throughout the core; 8.5 m, 11 m, 14.3 m, 16 m, 20 m, and 26.5 m, for meteoric ^{10}Be. These sections were chosen because they contain quartz sand.

After collection, all samples will be brought to UVM for processing. In order to measure in situ ^{10}Be, quartz must be extracted and purified, (link) which includes drying, sieving, and magnetically separating all samples. The sample will be repeatedly etched in HCl and dilute HF/HNO3, which dissolves most minerals except quartz (Kohl and Nishiizumi, 1992). Then, the sample will be tested for purity and ^{10}Be can be extracted. Finally, the ^{10}Be is measured on an accelerator mass spectrometer (AMS) at the Lawrence Livermore Laboratory. Meteoric ^{10}Be, which is adhered to the surface of sediment and soil grains, is extracted using a flux method described here link. A quick outline of what is done includes powdering the sediment and spiking it with ^{9}Be. Then KHF_2 and NA_2SO_4 are added to the sample and it is fused with a >800°C flame. Then K is removed from the sample using $HClO_4$ and B is removed through perchloric acid fuming. Finally, $Be(OH)_2$ is formed with NH_4OH and burn to form BeO.

After getting isotopic data from Livermore Laboratory, we will calculate sediment generation rates using the interpretive equations of Granger et al. (1996), Brown et al. (1995) and Bierman and Steig (1996). I will do statistical analysis of the data to determine what variables influence sediment generation rates in the Potomac River Basin and the differences between measured concentrations of in situ and meteoric ^{10}Be. I will complete a statistical analysis on each of the variables, basin size and relief, in relation to the concentration of both meteoric and in situ ^{10}Be and derived sediment generation rates. I will also do a geostatistical analysis to determine the differences in sediment generation rates among the physiographic provinces.

Finally, I will do a full analysis of pre-human sediment generation rates (derived from the isotopic data) and compare them to modern sediment yields (Gellis, 2004).

7.0 Significance of Results

This research will allow me to determine long-term sediment generation rates in the Potomac River Basin. Our findings will help determine if the modern total maximum daily loads (TMDLs) for sediment that the government has in place are realistic. I can make these determinations by comparing our long-term sediment generation rates with the modern sediment yields. I also will be able to determine what variables affect sediment generation in the Potomac River Basin, basin size, relief or physiographic province. Finally, I will be able to determine how land use affects measured concentration meteoric ^{10}Be by comparing it with in situ ^{10}Be.

Timeline

Collect initial samples (done)

Use GIS to determine future sampling sites (done)

Initial data analysis of modern sediment fluxes (in progress)

Process initial samples (in progress)

Collect more samples, including samples from core (May and June 2009)

Prepare quartz (Summer 2009)

Extract, measure ^{10}Be and progress report (Fall 2009)

Data analysis and writing (Spring 2010)

Present thesis (End of Spring 2010)

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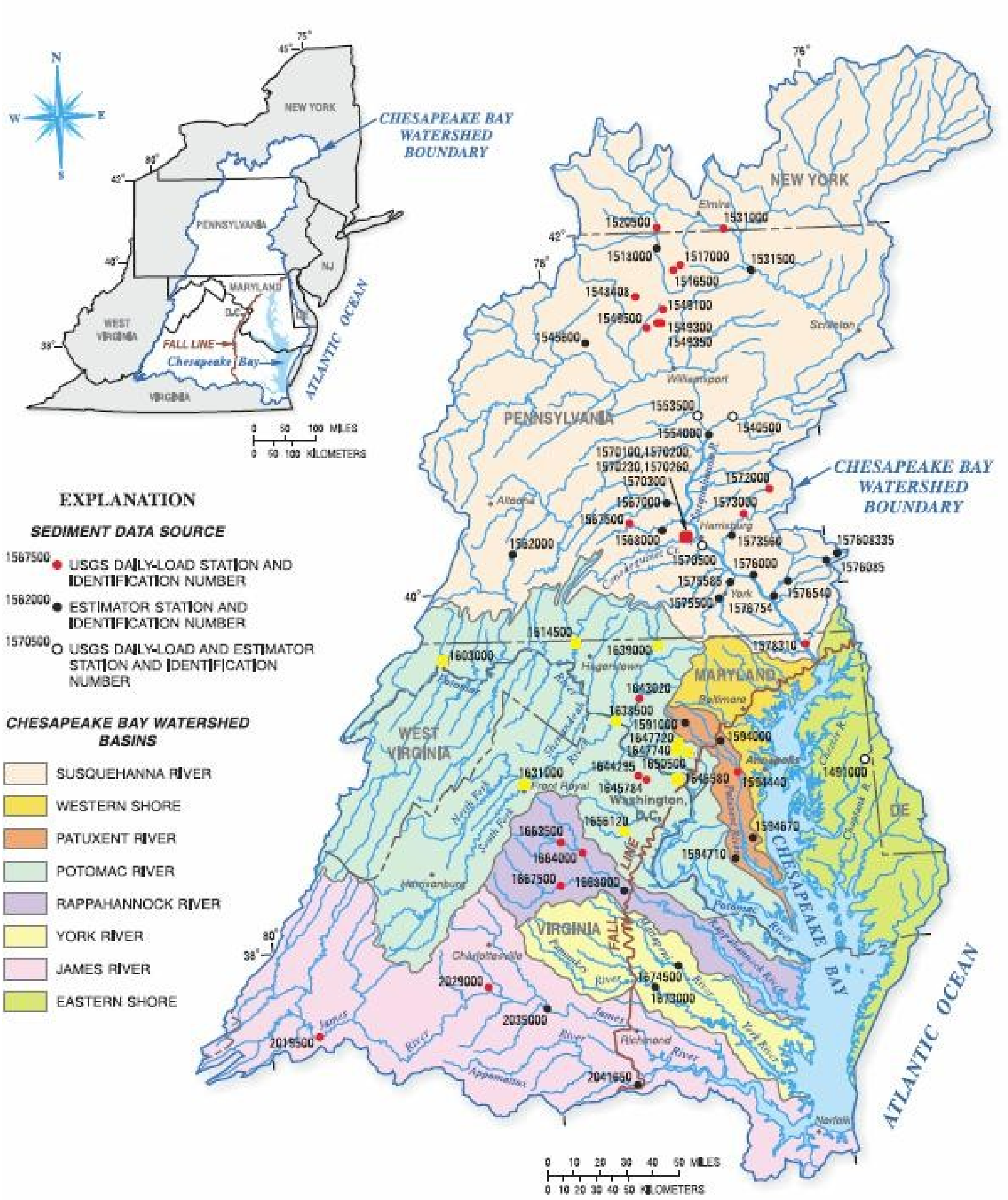

Figure 1

Chesapeake Bay Watershed. The tan Northern section is the watershed of the Susquehanna River; the light green section is the Potomac Watershed. The red white and black dots are USGS gauging stations or former gauging stations. I sampled 10 of the gaging stations in the Potomac River basin (1603000, 1614500, 163900, 1631000, 1656126, 1645580, 1650500, 1647740, 1647720 and 1638500), I did not sample from (1643020, 1645784 and 1644295). (Gellis et al., 2004).

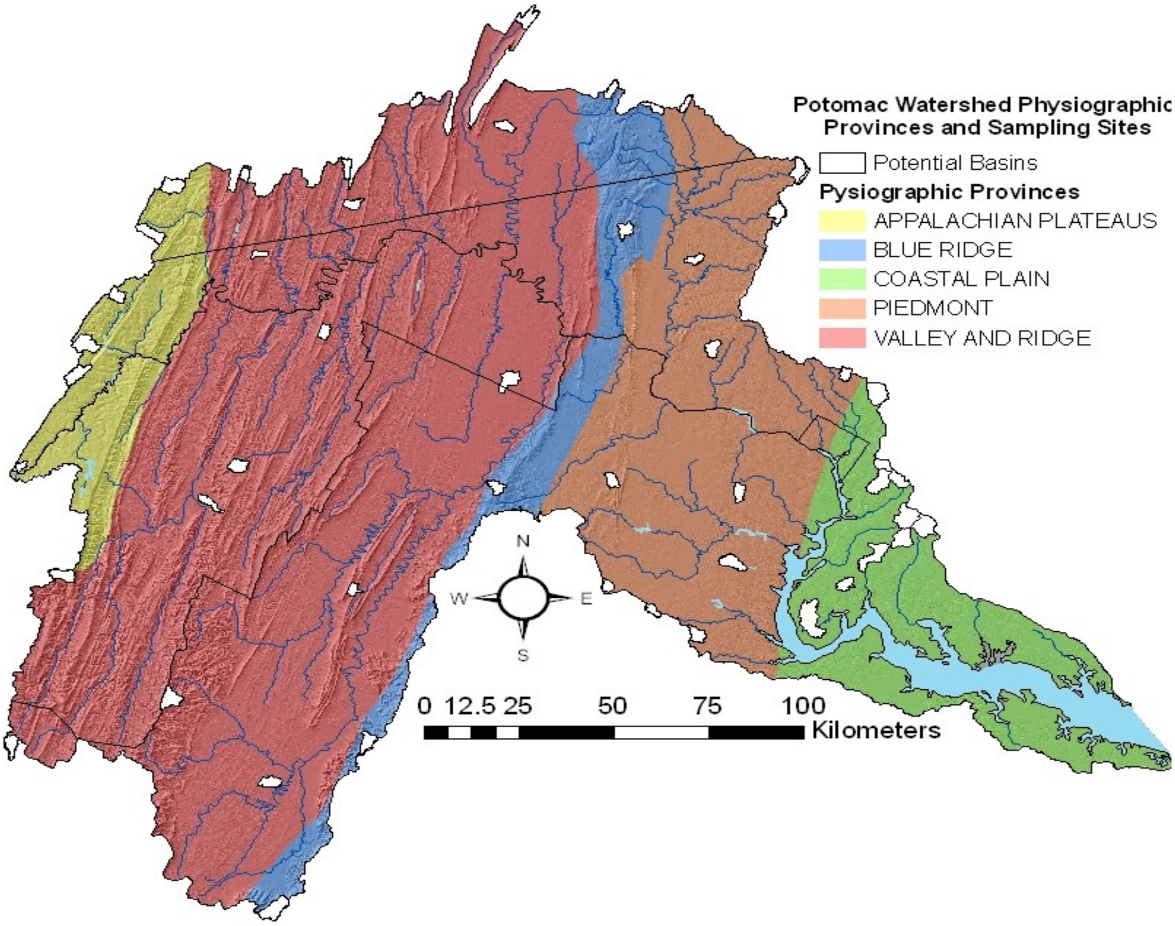

Figure 2
Proposed sample basins (n= 50, white outlines) shown with physiographic provinces of Potomac River Basin from West to East are the Appalachian Plateau (Yellow), Valley and Ridge (Red), Blue Ridge (Blue), Piedmont (Orange) and Coastal Plain (Green). Pennsylvania is to the north, West Virginia is to the west, Virginia is to the south, Maryland is in the center and east and DC is where the river starts to widen (Data from USGS).

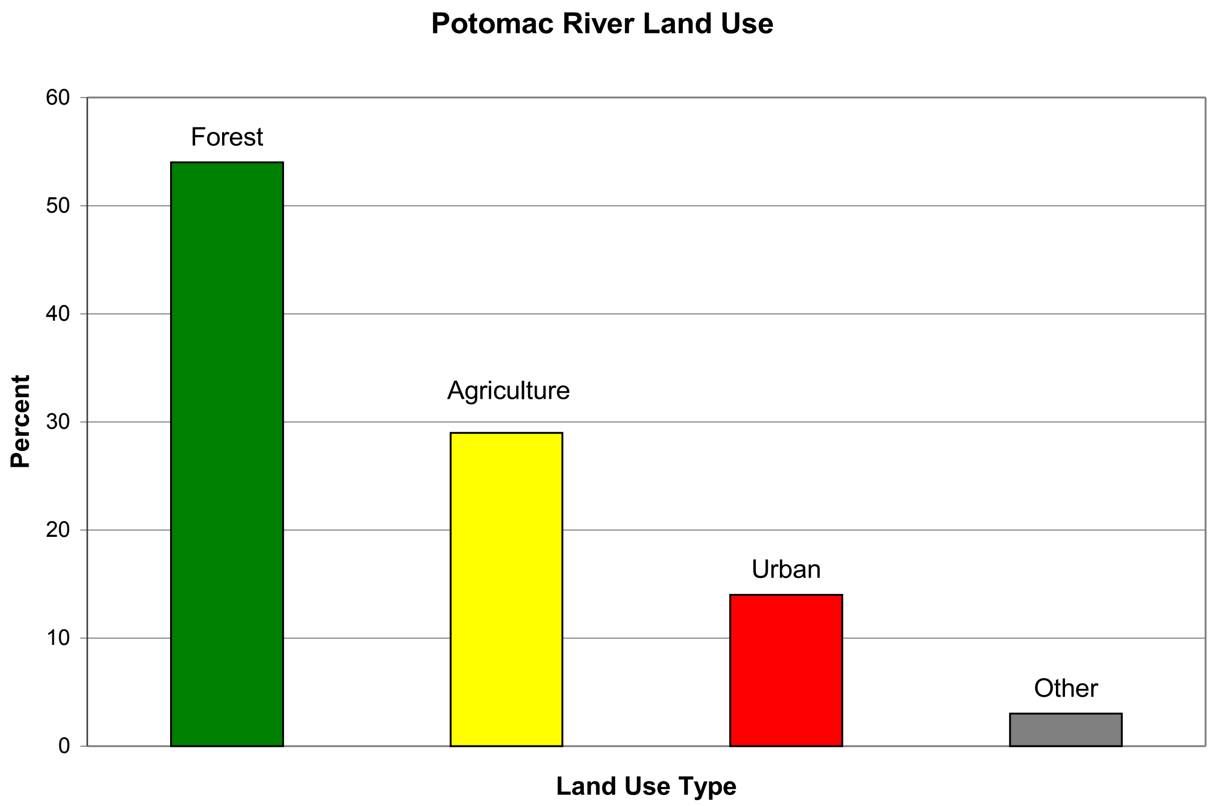

Figure 3
Land use percentages from the Potomac River Basin (Data derived from Gerhart, 1991).

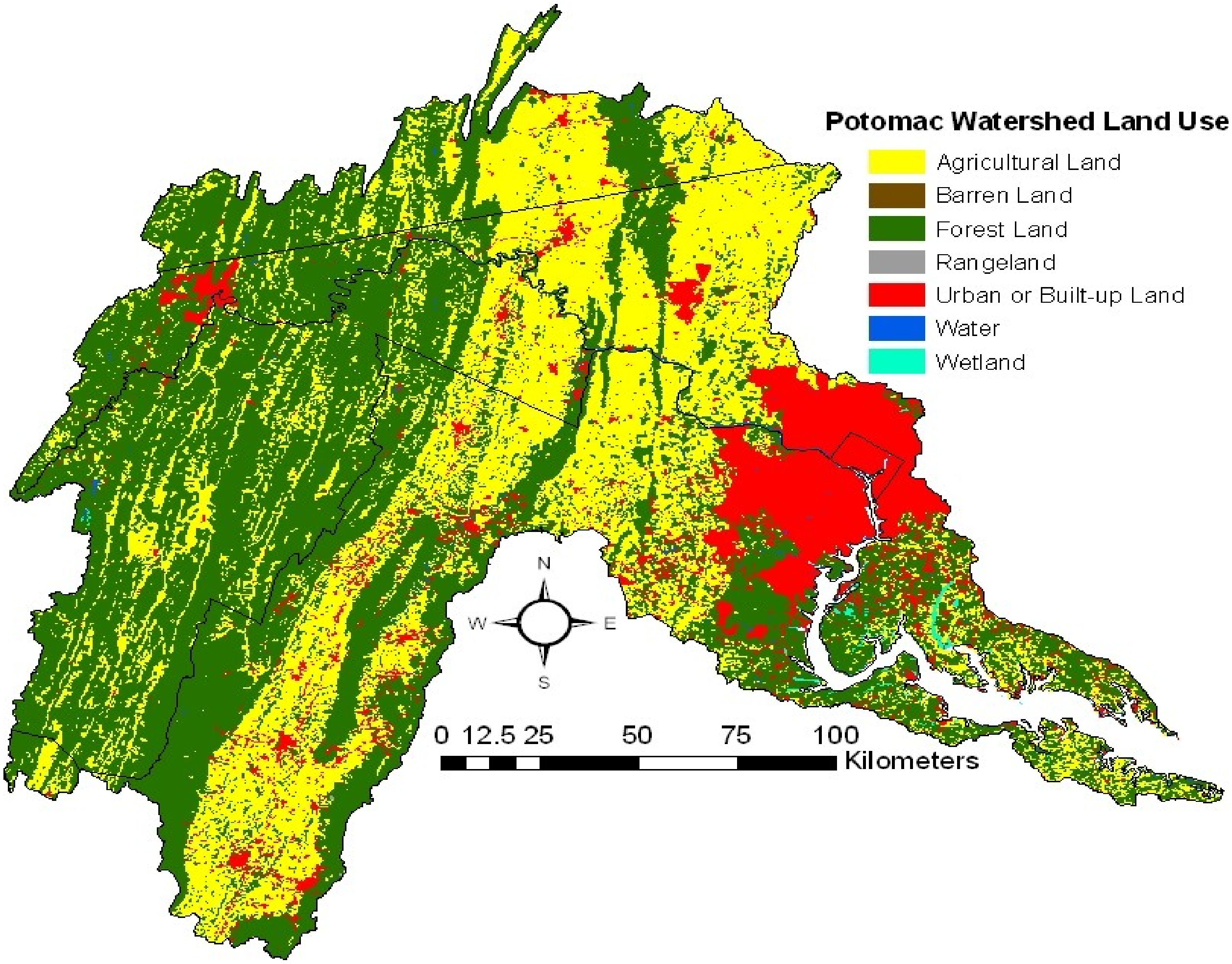

Figure 4

Map of land use in the Potomac River Basin. The green areas are forest, the red areas are urban and the yellow areas are agriculture (Data from USGS and NOAA).

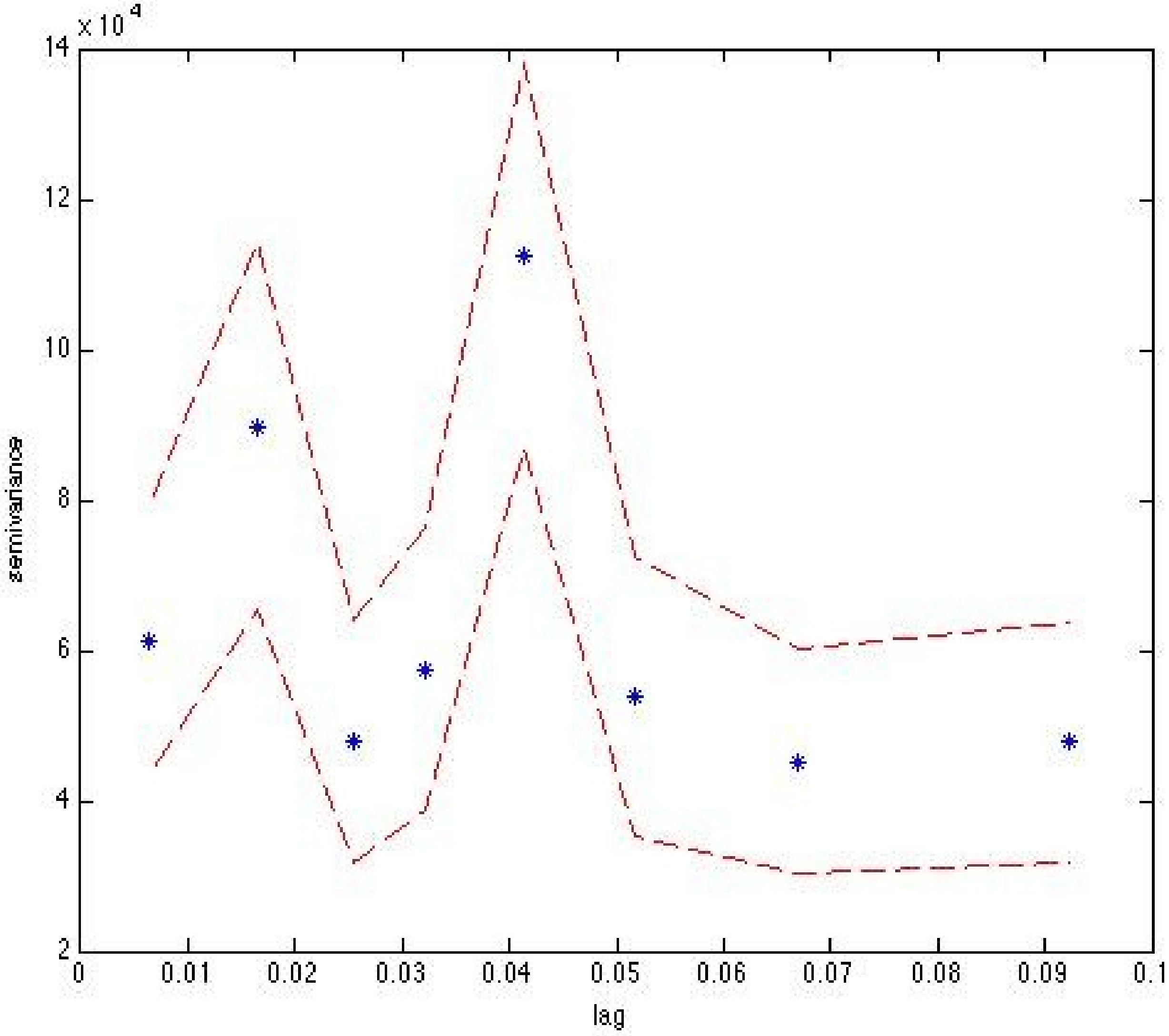

Figure 5

Semivariogram showing spatial relationship of modern sediment yield (Gellis et al., 2004) in the Chesapeake Watershed. The dashed lines the 95% confidence interval. Each symbol (*) is a bin of 8 basins. The Y-axis is the level of difference in sediment yield. The X-axis is the distance between basins. The low point at the beginning of the graph shows that neighboring basins have similar sediment yields. The first peak shows that basins, which are separate by a few basins, are dissimilar. The next low point potentially shows that basins with a good distance between them are similar. The final high point then shows that eventually basins are too different to have similar sediment yields and the low points after that are basin to far apart to be compared (Data derived from Gellis et al., 2004).

Figure 6

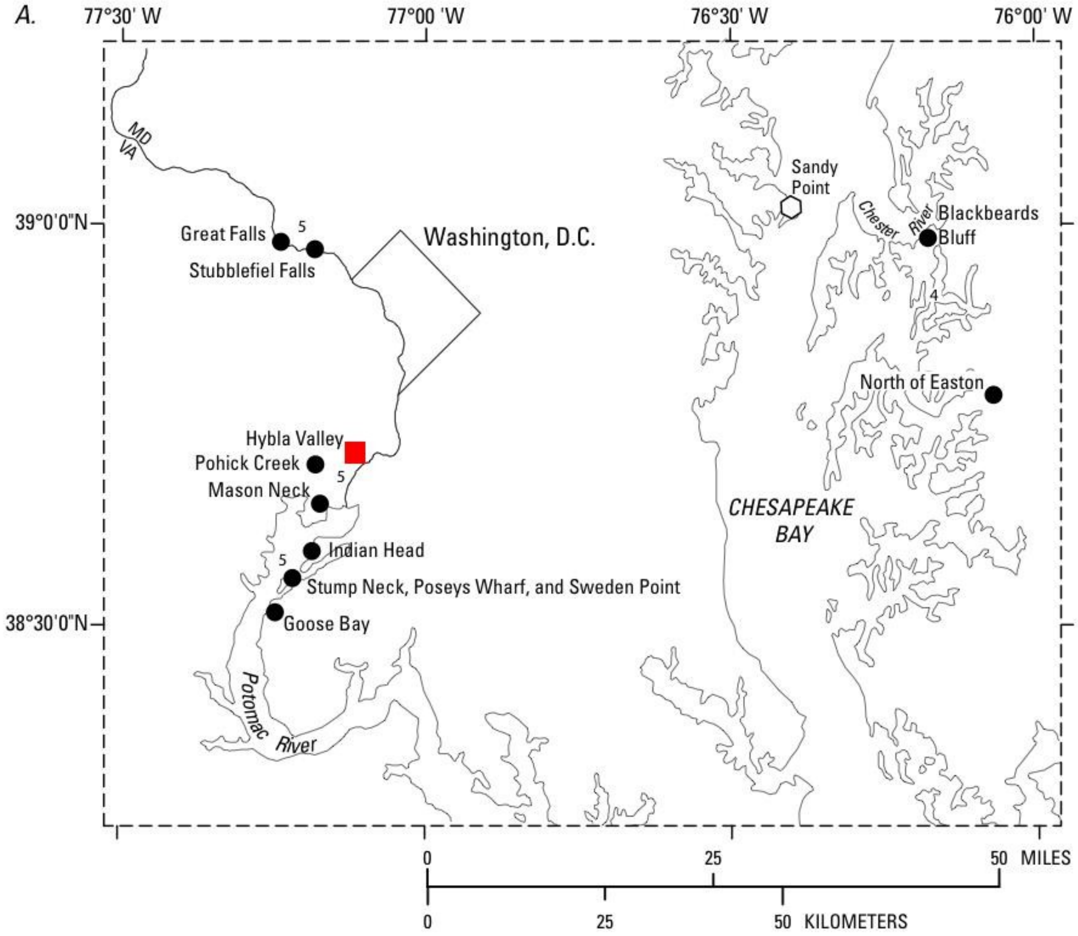

Figure 6

This map (correspondence with Milan Pavich, USGS) shows the location of the core that will be sampled. The core was taken at Hybla Valley (Red Square) on the left central portion of the map next to the Potomac and below DC.

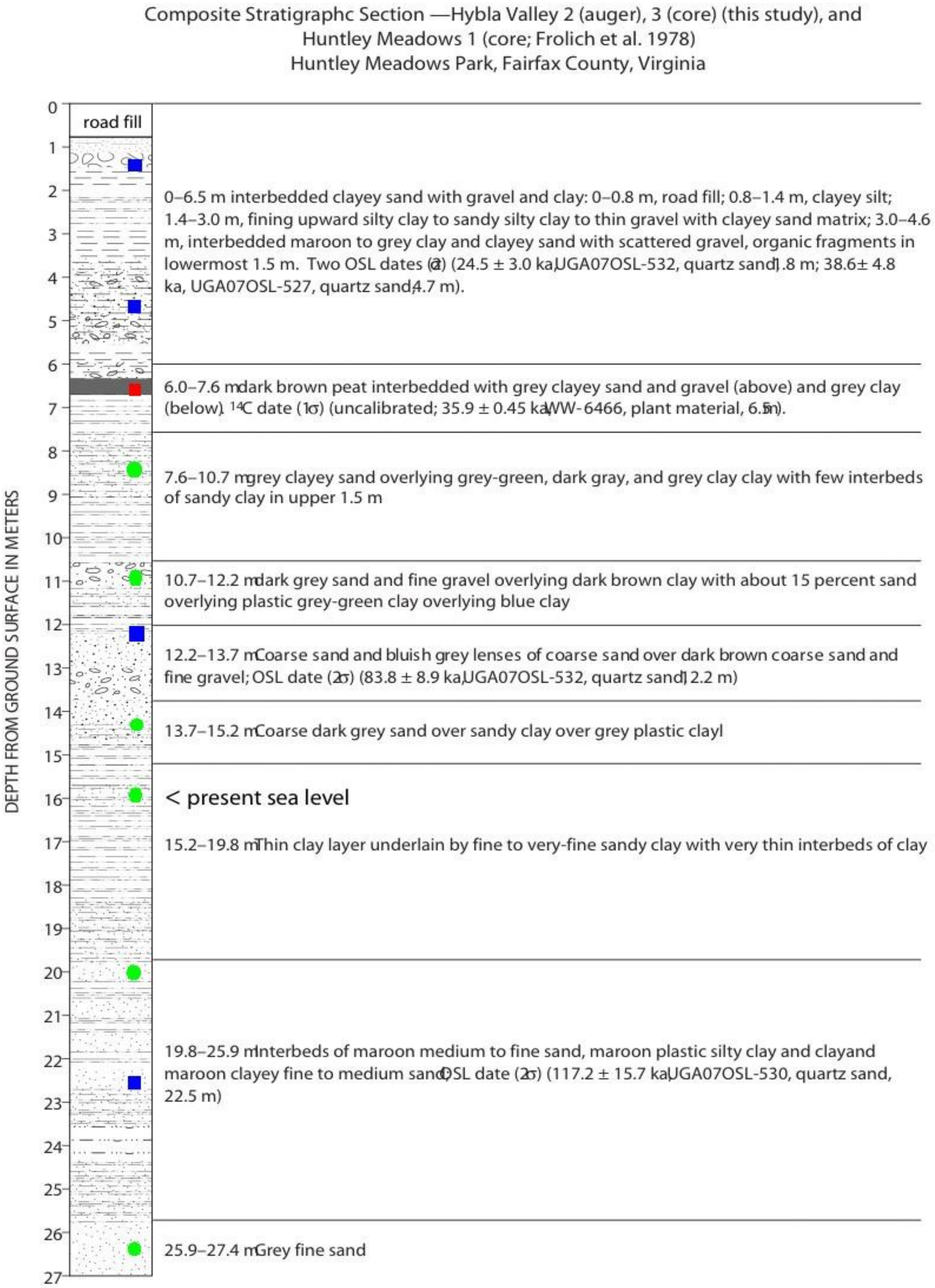

Figure 7

Proposed core sampling depths. The blue squares on the core are sections that have been dated and will be sampled. The green circles are sections that will be sampled for quartz sand (Correspondence with Milan Pavich, USGS).

Site	Selected Sites	Complete Samples	Potential Total	Samples to be Processed	Total
Core	10	0	10	7	7
Costal Plain	10	0	10	5	5
Piedmont	12	7	19	8	15
Blue Ridge	6	0	6	5	5
Valley and Ridge	16	2	18	10	12
Appalachian Plat	6	1	7	5	6
Total	60	10	70	40	50

Table 1

This table shows how many samples I will take and where. The “Selected Sites” column is how many samples I will plan in case I am not able to get all of the samples. The “Complete Samples” column shows how many samples I have already taken from each province. The “Potential Total” is how many total samples I have selected and already taken form each location. The “Samples to be Processed” column is actually how many stream samples I will process from each location. The “Total” column is how many total samples I will take from each location.