The Use of the Chesapeake Bay Program's Watershed Model in the Susceptibility Analysis for the District of Columbia's Source Water Assessment

6.1 The Watershed Model's Role in the Source Water Assessment

The Potomac River drains into the Chesapeake Bay, the largest estuary in the United States. In the face of deteriorating water quality and living resources in the bay, the states of Maryland, Pennsylvania, and Virginia, the District of Columbia, and the Federal Government entered into a partnership, the Chesapeake Bay Program, to restore water quality in the bay. Excess nutrient loads are blamed for the deterioration of water quality. Excess nutrients lead to excess algal growth; the subsequent decay of algae leads to decreases in oxygen levels in the bay. CBP has primarily focused on reducing nutrient loads to the bay from wastewater treatment plants, agricultural activities, and other nonpoint sources. Sediments, which decrease water clarity, and toxic contaminants, have also become concerns of the CBP.

CBP maintains several computer simulation models to help understand the impact of nutrient and sediment loads on water quality in the bay and to evaluate management scenarios for nutrient and sediment reduction. The Watershed Model is an HSPF (Hydrological Simulation Program--Fortran) model of all the watersheds, including the Potomac River Basin, which drains into Chesapeake Bay. The Watershed Model simulates the flow, sediment transport, and nutrient dynamics, which determine the nutrient and sediment loads to the bay. These loads are used to drive the Water Quality Model, a computer simulation model of water quality in the bay itself. The Watershed Model can also be used to predict the flows, nutrient, and sediment loads that would occur under different scenarios for nutrient reduction, or if, for example, nothing is done to limit nutrient loads as population in the basin grows. The loads from these management scenarios can then be fed into the Water Quality Model to determine the impact that the loading scenarios have on the bay.

HSPF is a flexible model. It can simulate both point and nonpoint sources. It can simulate many types of pollutants, although it has special modules for simulating sediment and nutrient dynamics. It is capable of simulating all elements of the hydrological cycle--precipitation, interception, infiltration, runoff, interflow, percolation, and ground water discharge. It also can simulate the fate and transport of pollutants through all these phases of the hydrological cycle. It is capable of simulating both pervious and impervious surfaces, and it can take the flows and the pollutant loads from these land surfaces and route them through river channels and reservoirs. HSPF also simulates the processes that occur in transport in channel reaches, such as erosion, deposition, or the uptake of nutrients by algae. Bicknell et al.(1996) provide a full description of HSPF's capabilities.

HSPF's flexibility comes at the price of complexity. It requires a great deal of information to run the model. Many parameters have to be set; many are determined by calibrating the model against observed data. Watersheds must be divided into land uses, which are treated as homogeneous areas for the sake of the simulation. Constituent loads must be determined for each type of land use. The hydrological simulation in HSPF is driven by hourly meteorological data. HSPF uses a "level pool" method of routing flow through reaches, in which the outflow of each reach is determined as a single-valued function of storage. Information must be collected on each channel to determine the routing function and other reach characteristics.

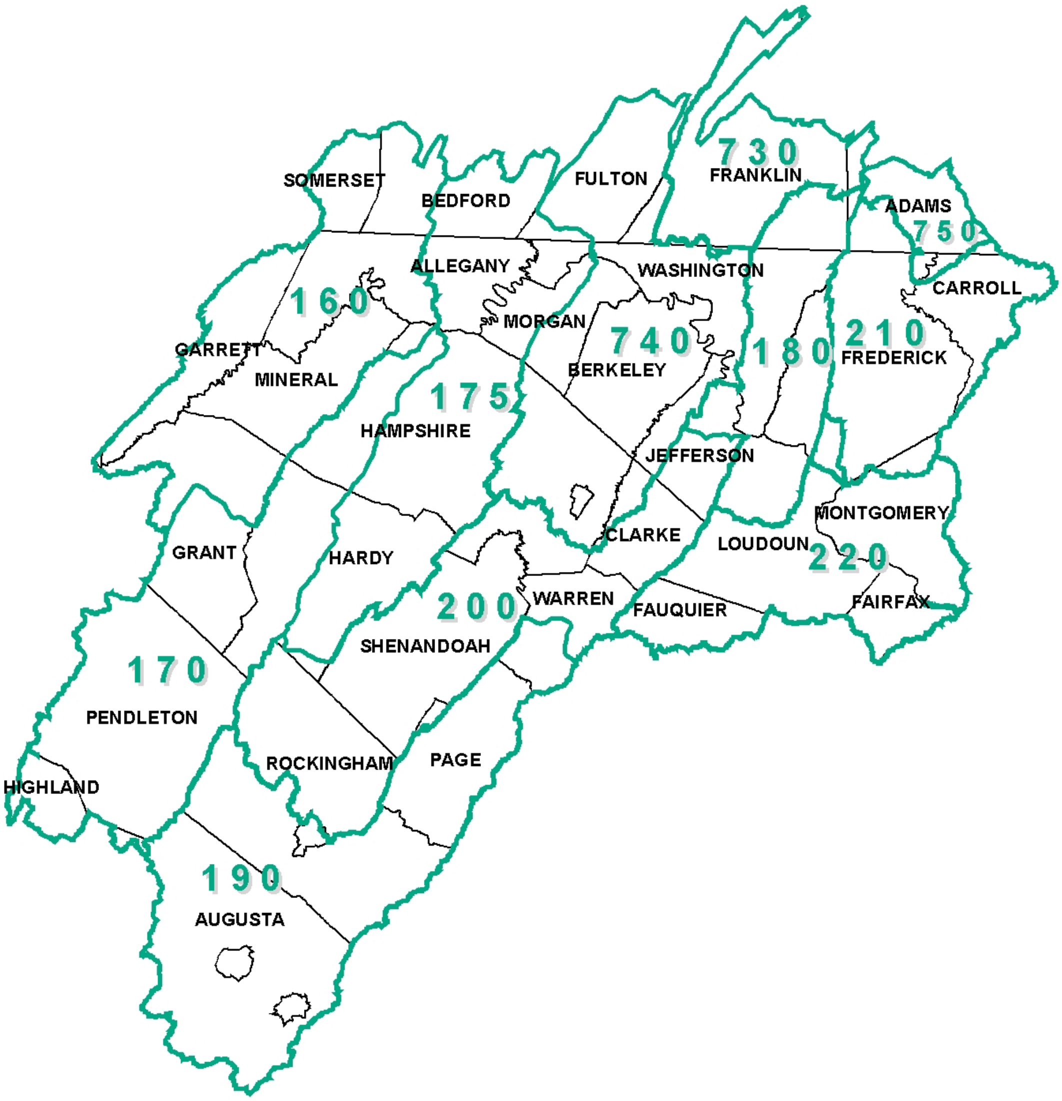
To cover an area the size of the Chesapeake Bay Basin, the size of model segments, which represent watersheds, and the river reaches draining them, is very large. There are 11 model segments in the Potomac River Basin above the Potomac fall line. Figure 6.1.1 shows the location of the model segments. Table 6.1.1 shows the watersheds associated with each segment number. The average size of a segment is almost 1000 square miles, and the corresponding river reaches range from 21.5 to 139 miles in length.

Table 6.1.1 Watershed Modeling Segments

Segment	Watershed
160	North Branch of the Potomac River
170	South Branch of the Potomac River
175	Upper Potomac River
180	Point of Rocks
190	South Fork of the Shenandoah River
200	North Fork and Mainstem of the Shenandoah River
210	Lower Monocacy River
220	Lower Potomac River
730	Conococheague Creek
740	Middle Potomac River
750	Upper Monocacy River

Six pervious and two impervious land use types are represented in each segment: forest, hay, pasture, conventional tillage (high till), conservation tillage (low till), pervious urban, impervious urban, and "manure" acres, which represent impervious areas of feedlots and concentrated animal operations that have the potential to produce runoff with high concentrations of nutrients. Calculation of how much of a segment belongs to land use type is a complicated procedure, described more fully in Appendix E of model documentation (Modeling Subcommittee, 1998). The land use is primarily based on the EPA's EMAP (Environmental Monitoring and Assessment Program) land use/land cover. Information from the U. S. Department of Agriculture's Agricultural Census was used to determine the areal extent of agricultural land uses. The Agricultural Census provides information on a county level. County acreages were apportioned among modeling segments by determining what fraction of a county's herbaceous acreage, outside of urban areas, is in a modeling segment. Herbaceous land cover is the EMAP land cover associated with crops and grassed areas like pastures and lawns. Essentially, if 25% of a county's herbaceous acres are in a segment, 25% of the acreage of crops and pasture in that county would be apportioned to that segment. For the most part, there are more acres of herbaceous land cover in the watershed than agricultural land recorded by the census. The additional herbaceous acres are classified as "mixed open" land, but simulated as urban pervious land.

Figure 6.1.1 Modeling Segments in the CBP Watershed Model



The determination of model segment characteristics on the basis of county-level information is typical of the challenge the CBP faced in developing an HSPF model on the scale of the Chesapeake Bay Basin. On the whole they have been successful in developing a methodology to account for nutrient and sediment loads in the basin from a variety of sources: wastewater treatment plants, septic systems, animal operations, crop management, and even atmospheric deposition. And on the whole, though not without some controversy, the Watershed Model has been accepted as a management tool in developing strategies for nutrient reduction in the watersheds of the basin.

The District of Columbia is interested in finding common ground between the protection of its drinking water supply and the CBP's strategies to reduce nutrient, sediment, and toxic contaminant loads to the bay. For that reason, the Watershed Model and the CBP methodology behind it were used to help perform the susceptibility analysis for the source water assessment. The Watershed Model is geared towards predicting nutrient and sediment loads entering the Potomac estuary at the fall line. It is calibrated against observed flows at the [REDACTED] intake and against water quality data collected [REDACTED] at Chain Bridge, which connects D. C. with Arlington, VA. The Potomac portion of the Watershed Model is, on a regional scale, a computer simulation model of water quality at the source water intakes. It would be negligent not to use the Watershed Model to help determine the upstream sources of nutrient and sediment loads, which potentially effect source water quality.

Second, the sources of nutrient and sediment loads--wastewater treatment plants, septic systems, agricultural operations--are also sources of other constituents that can have an impact on source water quality. Pathogens, for example, are associated with livestock, manure disposal, failing septic systems, and wastewater treatment plants. Pesticides are applied as part of the same agronomic schedule of planting, fertilizing, and harvesting that is already represented in the Watershed Model. For this reason, the Watershed Model was extended so it can provide a regional analysis of the sources of other constituents that could adversely impact drinking water supplies. Modifying the Watershed Model to represent these other constituents extends a recognized management tool that has already been used to develop strategies for pollution reduction and prevention. It provides a way of evaluating how these strategies might impact source water quality and a common language for explaining that impact to stakeholders and regional partners in the Bay Program. This is especially important, since the watershed for the intakes encompasses a large geographic area lying wholly outside the boundaries of the District of Columbia. D. C. can take advantage of its participation in a regional partnership to reduce pollutant loads which flow pass their intakes--entering the estuary less than [REDACTED] downstream.

The Watershed Model will therefore be used for three tasks in the susceptibility analysis:

1. The Watershed Model will be used to characterize the size and sources of nutrient and sediment loads, both under current conditions and in the face of

population growth;

2. The Watershed Model will be modified to represent the fate and transport of fecal coliform bacteria, which serve as indicators of water-borne pathogens; and

3. The Watershed Model will be modified to evaluate the susceptibility of D. C.'s source water to contamination by pesticides.

Version 4.3 of the Watershed Model, available through the CBP as the Community Model, was used in the susceptibility analysis. The Reference or Calibration Scenario was used as the basis for the modifications for representing fecal coliforms and pesticides. The scenarios used to analyze nutrient and sediment loads will be explained below.

6.2. Nutrient and Sediment Loads at the Source Water Intakes

Nutrient and sediment loads can adversely impact source water quality. Sediment and particulate organic matter must be removed from finished drinking water. Excess nutrient loads can lead to algal growth, which in turn can lead to taste and odor problems.

6.2.1 Current Nutrient and Sediment Loads

The CBP 2000 Progress Scenario was used to calculate nutrient and sediment loads delivered to the Potomac estuary just below Chain Bridge, [REDACTED].
The Progress 2000 Scenario is a fourteen-year simulation, using meteorology and hydrology from 1984-1997, but representing current nutrient and sediment loadings. It thus represents current conditions independent of hydrological variations that can affect the quantity of nutrient or sediment loads in any given year. Table 6.2.1 shows simulated average annual sediment loads, Table 6.2.2 shows simulated average annual total nitrogen loads, and Table 6.2.3 shows simulated average annual total phosphorus loads. The loads ten-year averages from the period 1985-1994. In the tables the nonpoint source loads from conventional till crops, conservation till crops and hay have been combined under the "crops" category; the nonpoint source loads from pervious and impervious urban land have also been combined.
As Table 6.2.1 shows, a total of 1.6 million tons of sediment are delivered each year. Half of the load comes from crops and hay. A quarter of the load comes from pasture. Only 11% comes from forest and 14% comes from urban land. About a third of the load comes from the Shenandoah Valley, Segments 190 and 200. The Middle Potomac region, Segment 740, is also a large source of sediment. Cropland in the Shenandoahs, the Middle Potomac, and the Monocacy all produce over 100,000 tons of sediment a year.

Table 6.2.1 Simulated Annual Average Sediment Loads Under Current Conditions (tons/yr)

Segment	Forest	Pasture	Crop	Urban	Total
160	17,296	26,311	18,004	10,999	72,610
170	17,297	95,479	26,973	18,274	158,023
175	16,034	49,189	30,731	15,309	111,263
180	6,361	15,992	73,239	14,878	110,470
190	21,560	89,590	154,692	28,913	294,755
200	35,109	49,000	100,785	29,360	214,253
210	6,708	12,020	100,316	19,321	138,364
220	15,719	21,615	63,581	22,114	123,030
730	9,529	8,165	73,650	11,969	103,313
740	29,554	35,720	114,740	42,037	222,051
750	1,549	2,738	28,209	4,459	36,955
Total	176,715	405,818	784,921	217,635	1,585,088

Table 6.2.2 Simulated Annual Average Total Nitrogen Loads Under Current Conditions (lbs/yr)

Segment	Forest	Pasture	Crop	Feedlot	Urban	Point Source	Septic	Total
160	1,037,212	412,485	494,983	53,243	459,590	343,404	74,979	2,875,896
170	627,448	790,415	977,509	111,340	309,083	190,302	44,443	3,050,540
175	829,318	450,314	725,171	87,089	252,898	2,544	63,298	2,410,631
180	184,204	363,038	1,605,615	159,073	450,521	365,229	212,956	3,340,636
190	277,717	618,687	700,680	97,878	331,872	328,270	112,474	2,467,578
200	361,508	697,410	1,481,107	124,671	432,231	539,119	164,029	3,800,075
210	262,261	310,612	1,839,654	68,260	540,881	511,274	276,619	3,809,562
220	324,534	531,446	1,356,321	26,563	1,379,245	399,105	283,951	4,301,167
730	224,576	375,881	1,746,416	477,199	305,514	107,027	88,503	3,325,115
740	606,948	632,983	1,271,126	106,322	961,857	395,397	313,736	4,288,369
750	44,179	64,824	511,870	31,761	106,806	24,954	34,662	819,056
Total	4,779,904	5,248,095	12,710,452	1,343,400	5,530,499	3,206,626	1,669,649	34,488,625

Table 6.2.3 Simulated Annual Average Total Phosphorus Loads Under Current Conditions (lbs/yr)

Segment	Forest	Pasture	Crop	Feedlot	Urban	Point Source	Total
160	12,402	63,992	39,359	7,312	33,027	80,645	236,737
170	9,613	112,648	68,355	15,160	22,809	40,326	268,912
175	9,695	48,107	41,254	9,934	15,352	456	124,799
180	1,351	27,857	90,736	15,720	43,856	66,173	245,693
190	5,260	218,194	155,498	24,320	75,408	177,723	656,404
200	6,000	115,970	186,993	16,753	57,966	112,062	495,745
210	3,159	39,933	161,846	7,843	63,481	73,792	350,055
220	4,118	77,985	91,566	2,538	134,099	30,678	340,985
730	2,219	18,648	89,420	55,876	18,475	28,083	212,720
740	5,809	40,879	77,392	11,418	53,335	46,907	235,739
750	715	10,743	54,827	4,195	15,579	3,156	89,216
Total	60,343	774,956	1,057,246	171,070	533,387	660,002	3,257,004

The loads of total nitrogen come from a wider variety of sources. As table 6.2.2 shows, crops are the largest source of nitrogen, accounting for 16% of the total average annual load of 35 million pounds. But urban nonpoint source loads constitute the second largest source, accounting for 15% of the total. Point sources, such as wastewater treatment plants, contribute 9% of the load. Agricultural sources still dominate urban sources. Fifty-six percent of the load comes from crops, pasture, or runoff from feedlots. Thirty percent of the load comes from point sources, septic systems, and urban land. Forests account for only 14% of the total delivered nitrogen loads. The sources are also more geographically diverse. The largest source of loads is the heavily urbanized Lower Potomac (220), delivering 12% of the load. Crops still contribute the largest share of the load in the Lower Potomac. The Middle Potomac (740) has almost the same load with less urbanization. Nonpoint source loads from crops in Conococheague (730), Middle Potomac (740), Mainstem Shenandoah (200), Point of Rocks (180), Lower Monocacy (210), and Lower Potomac all contribute more than one million pounds per year to the total nitrogen load. Among the other sources, only urban land in the Lower Potomac and forests in the North Branch (160) contribute over one million pounds per year.

Crops also contribute nearly one-third of the annual total phosphorus load of 3.2 million pounds. The next largest source is pasture, delivering nearly 25% of the annual load. Point sources are the third largest source, contributing 20% of the load, and nonpoint sources from urban land contribute 16% of the load. The contribution from forests is almost negligible. Inorganic phosphorus is transported primarily bound to sediments, so it is not surprising that the 35% of the delivered load comes from the Shenandoahs (190 and 200). Point source loads from the Shenandoahs are also the highest in the basin. The Lower Moncacy (210) and the Lower Potomac (220) each also deliver over 10% of the total annual load. The dominant source in the Monocacy is crops; the dominant source in the Lower Potomac is urban land.

6.2.2 Projected Population Growth and Land Use Changes

The CBP has projected the population growth in modeling segments for the years 2010 and 2020. The projection is based upon estimates by the U. S. Census Bureau and the basin states. Table 6.2.4 shows the population of each model segment in the Potomac Basin in 2000, the projected populations for 2010 and 2020, and the percent change with respect to the 2000 population. Growth is the story, at least in the downstream segments which are rapidly becoming part of the Washington metropolitan area. The basin population of nearly 2 million is expected to increase by nearly 10% in each decade. The percent change is greatest in the Lower Monocacy, Frederick County in Maryland, which is expected to grow by over 30% in the next twenty years. The rate of growth is over 10% per decade in the Lower Potomac (220), which already has three-quarters of a million people, nearly 37% of the basin total. Other segments growing by more than 10% a decade are the Middle Potomac (740) and the mainstem Shenandoah (200).

Table 6.2.4 Projected Population Changes 2010 and 2020

Segment	2000	2010	% Change	2020	%Change
160	116,427	116,832	0%	117,145	1%
170	29,659	30,687	3%	31,582	6%
175	31,062	33,297	7%	35,149	13%
180	174,256	190,291	9%	201,838	16%
190	195,750	205,076	5%	214,667	10%
200	130,347	144,682	11%	158,291	21%
210	232,364	275,914	19%	304,417	31%
220	736,917	821,212	11%	890,241	21%
730	84,536	87,913	4%	89,597	6%
740	213,705	241,043	13%	265,489	24%
750	33,160	36,225	9%	38,493	16%
Total	1,978,183	2,183,172	10%	2,346,909	19%

Table 6.2.5 shows the CBP estimates of current land use, its projections for land use in 2010, and the percent change in land use over the decade. As might be expected from the population growth, there is considerable expansion of urban land. Overall, there is a 9% increase projected in urban land, roughly consistent with the population increase. The percent of the basin that is urban land will grow from 15% to 17% over the next decade, with the addition of almost 100,000 acres. The net loss of forest is about 1%. Forest will cover just over 50% of the basin into the next decade. Loss of forest will account for at most 25% of the growth in urban land. The rest will come from agricultural land.

Superimposed on the growth in urban land is a shift in the use of agricultural land. There will be a net loss of pasture of almost 8% and a net gain in crops of 2%. Hay production will increase by 8% and conventionally-tilled crops will decrease by 18%. Conservation till will increase by 6%. The gain in acres under conservation till is less than the acres lost in conventional till. The overall net decrease in crop land, excluding hay, is about 10%.

Table 6.2.5 Projected Land Use Changes 2010

Segment	2000				2010				Percent Change			
	Forest	Pasture	Crop	Urban	Forest	Pasture	Crop	Urban	Forest	Pasture	Crop	Urban
160	627,995	86,960	58,807	86,704	625,387	82,034	65,661	87,386	0%	-6%	12%	1%
170	619,599	201,942	50,193	78,102	622,294	194,067	52,741	80,734	0%	-4%	5%	3%
175	617,543	82,018	49,306	50,558	614,637	79,975	52,858	51,956	0%	-2%	7%	3%
180	148,322	56,860	123,666	77,013	145,946	54,677	124,380	80,857	-2%	-4%	1%	5%
190	509,150	221,670	153,487	159,711	504,011	192,817	161,255	185,953	-1%	-13%	5%	16%
200	453,435	159,924	146,238	140,556	451,961	142,270	148,010	157,923	0%	-11%	1%	12%
210	184,273	46,207	170,324	99,064	176,132	34,910	174,053	114,853	-4%	-24%	2%	16%
220	208,614	89,644	105,483	189,066	203,820	89,075	98,421	208,607	-2%	-1%	-7%	10%
730	134,735	21,960	113,494	49,757	135,668	18,832	115,365	50,011	1%	-14%	2%	1%
740	439,604	96,909	160,863	170,214	438,526	87,944	160,937	180,186	0%	-9%	0%	6%
750	37,238	8,423	46,569	20,715	35,479	5,823	50,318	21,336	-5%	-31%	8%	3%
Total	3,943,269	1,064,093	1,131,861	1,100,745	3,918,382	976,601	1,153,681	1,198,466	-1%	-8%	2%	9%

6.2.3 Estimated Nutrient and Sediment Loads Under 2010 Conditions

A modeling scenario was developed to estimate nutrient and sediment loads under the population increase and land use changes projected for 2010. The scenario was intended to represent future conditions under current levels of BMP implementation for agricultural and urban nonpoint sources and current levels of point source controls. The scenario was constructed from two existing Bay Program scenarios. The first is the 2000 Progress Scenario described in section 6.2.1. The second is a scenario representing 2010 land use and population growth but no controls on point or nonpoint sources: the 2010 No BMPs Scenario. Using the Community Model pre- and post-processors, the following steps were taken to construct what might be called the 2010 Progress Scenario:

1. Land use distributions were taken from the 2010 No BMPs Scenario;
2. The level of nonpoint source controls per acre in the 2000 Progress Scenario were applied to urban and agricultural land;
3. Point source flows were taken from the 2010 No BMPs Scenario;
4. Point source loads were calculated by assuming the same concentrations as the 2000 Progress Scenario;
5. Acres under nutrient management were assumed to be the same as the 2000 Progress Scenario;
6. Loads from atmospheric deposition took into account reductions yielded by Clean Air Act; and
7. Septic system loads were taken from the 2010 No BMPs Scenario.

The simulated average annual sediment loads under 2010 conditions are shown in Table 6.2.6. Simulated average annual total nitrogen loads are shown in Table 6.2.7 and simulated average annual total phosphorus loads are shown in Table 6.2.8.

Both simulated annual sediment loads and simulated average nitrogen loads decrease slightly during 2010 conditions. Sediment loads decrease by less than 1%. The increase in loads from urban land is balanced by a decrease in loads from agricultural land. Urban loads increase by 13%, but that is an increase in overall load of about 1%. Sediment loads remain dominated by agricultural sources. Annual total nitrogen loads also decrease by about 1%. There is only a 2% increase in the load from urban nonpoint sources, but a 23% increase in loads from point sources. They now constitute 12% of the total annual load. Agricultural loads decrease by 7%. Forest loads also decrease by 8% due to the decrease in load from atmospheric deposition.

Total phosphorus loads under 2010 conditions increase by 10%. Point source loads increase by 23% and total phosphorus loads from urban nonpoint sources increase by 36%. Losses from agricultural sources decrease by only 1%.

If urban growth only converted agricultural land and forest to urban land, at a ratio of 0.75 acres of agricultural land and 0.25 acres of forest to every acre of land developed, nutrient loads would decrease. The average phosphorus loading rates on forest, agricultural, and urban lands are 0.015, 0.86, and 0.45 lbs/ac, respectively, while the average nitrogen loading rate on these lands are 1.2, 8.6, and 4.6 lbs/ac, respectively. Population growth also raises point source nutrient loads. In the case of phosphorus, the additional load from point sources more than outweighs the loss in load from the land use changes. With no additional point source controls, that trend will only increase as the population increases 2010-2020.

It is difficult to determine whether the increase in phosphorus load will have an impact on surface water quality. If algal growth in the Potomac River is phosphorus-limited, as most free-flowing streams are, then an increase in phosphorus will potentially lead to an increase in algal growth and an increase in taste and odor problems. But the TN/TP ratio in the lower Potomac, as predicted by the Watershed Model, may even be less than 10:1, suggesting if not that algal growth in the Potomac might be nitrogen limited, at least that the matter requires further investigation.

An analysis of the impact of population growth on source water quality using the Watershed Model indicates that the growth in population upstream of the intakes will have little impact on sediment loads. If algal growth in the Potomac River does turn out to be phosphorus limited, population growth may cause an increase in algae and a corresponding increase in taste and odor problems. Otherwise, the increase in phosphorus will not have adverse effects on surface water quality.

Table 6.2.6 Simulated Annual Average Sediment Loads Under 2010 Conditions (lbs/yr)

Segment	Forest	Pasture	Crop	Urban	Total
160	18,001	26,047	20,674	11,536	76,259
170	18,156	95,990	26,868	19,736	160,750
175	16,678	50,177	30,115	16,281	113,251
180	6,541	16,159	70,488	16,078	109,265
190	22,305	81,442	151,771	35,777	291,295
200	36,573	45,557	94,056	34,553	210,739
210	6,700	9,490	96,693	23,170	136,054
220	15,680	22,046	48,063	25,297	111,086
730	10,027	7,317	88,493	12,499	118,337
740	30,810	33,842	102,777	46,000	213,429
750	1,542	1,968	25,458	4,749	33,717
Total	183,013	390,035	755,456	245,676	1,574,182

Table 6.2.7 Simulated Annual Average Total Nitrogen Loads Under 2010 Conditions (lbs/yr)

Segment	Forest	Pasture	Crop	Feedlot	Urban	Point Source	Septic	Total
160	943,119	374,709	576,502	51,449	416,447	434,693	78,620	2,898,306
170	589,710	726,452	969,603	109,619	293,622	231,069	45,285	2,978,070
175	772,692	422,063	727,755	86,376	240,806	2,952	68,963	2,343,978
180	171,128	345,865	1,551,413	168,156	460,008	392,718	237,536	3,345,579
190	244,139	519,678	620,591	83,721	345,096	379,202	108,275	2,312,408
200	338,176	628,769	1,376,962	113,507	478,893	506,098	177,369	3,646,331
210	216,760	216,800	1,106,825	38,346	571,132	933,533	318,465	3,412,479
220	286,406	463,250	727,434	19,529	1,508,239	372,361	316,476	3,745,761
730	215,695	374,433	2,142,773	568,492	283,137	119,117	91,665	3,801,789
740	572,321	581,280	1,651,590	102,081	938,482	548,568	354,247	4,782,000
750	36,476	53,539	409,339	21,463	101,594	27,321	36,048	689,185
Total	4,386,622	4,706,838	11,860,787	1,362,739	5,637,456	3,947,632	1,832,949	33,955,886

Table 6.2.8 Simulated Annual Average Total Phosphorus Loads Under 2010 Conditions (lbs/yr)

Segment	Forest	Pasture	Crop	Feedlot	Urban	Point Source	Total
160	10,975	82,435	39,690	7,124	50,664	103,105	295,732
170	8,734	131,431	63,050	14,796	35,401	48,540	303,034
175	9,116	57,919	39,669	9,747	24,577	523	143,095
180	1,201	29,056	90,748	16,332	49,852	70,080	258,328
190	4,000	198,288	177,885	22,126	93,376	218,357	715,782
200	5,460	110,062	186,006	15,307	80,364	106,578	505,945
210	1,945	21,720	156,861	4,578	78,581	139,978	404,347
220	2,676	49,140	72,329	1,828	189,869	27,992	346,584
730	2,193	23,659	98,425	65,342	25,782	30,680	246,486
740	6,005	48,802	72,777	10,787	79,552	62,000	281,967
750	546	8,291	51,634	2,970	18,979	3,620	86,307
Total	52,851	760,803	1,049,074	170,937	726,997	811,453	3,587,607

6.3. Fecal Coliform Bacteria

To better understand the sources of fecal coliform bacteria observed at the WAD intakes, the CBP Watershed Model was modified to simulate the fate and transport of fecal coliform bacteria. The same segmentation, land uses, and hydrology used in the reference scenario of the Watershed Model were used in the Fecal Coliform Model, and a similar methodology was used to estimate input loads of fecal coliform bacteria. Loads from agricultural sources were derived from information available on a county level from the agricultural census, and distributed to the model segments on the basis of the fraction of a county's herbaceous land that was in each modeling segment. Loads from human sources such as wastewater treatment plants or septic systems were calculated on the basis of flows and loads already accounted for in the Watershed Model. Other sources, such as wildlife, were added on a county or regional basis.

HSPF has been used to simulate the fate and transport of fecal coliform bacteria in the development of Total Maximum Daily Load (TMDL) allocations for impaired waterbodies in Virginia (VA DEQ and VA DCR, 2000 a, b, c) and West Virginia (U. S. EPA, 1998 a, b, c, d). Tetra Tech, on behalf of West Virginia DEP and the U. S. EPA Region III, has developed fecal coliform TMDLs for the North Fork and South Forks of the South Branch of the Potomac River, their tributaries, and the Lost River, a tributary to the Cacapon River. Numerous fecal coliform TMDLs have been developed in Virginia, including TMDLs for three small tributaries to the Shenandoah River-- Mill Creek, Dry River, and Pleasant Run developed by Virginia Tech. These TMDLs were used to guide the adaptation of HSPF to the simulation of the fate and transport of fecal coliform bacteria. They were also used to guide the estimation of input loads to the model. The EPA (U. S. EPA, 2001) has also published guidance on the development of pathogen TMDLs. Every effort was made to keep the Fecal Coliform Model consistent with both the practices of the Bay Program and the methodology used in the fecal coliform TMDLs.

The purpose of the Fecal Coliform Model is to help quantify the sources and geographic origin of fecal coliform bacteria observed at the WAD's water supply intakes. This will help to identify the source and origin of fecal material that is a potential source of pathogens. Loads from the following sources were developed as inputs into the model:

8. Bacteria from livestock waste deposited on pasture and transported in runoff;
9. Bacteria, transported in runoff, from manure and poultry litter applied to crops and hay;
10. Bacteria in runoff from feedlots and concentrated animal operations;
11. Bacteria in runoff from urban land;
12. Bacteria in deer scat and geese droppings, deposited in forests and agricultural land and transported in runoff;
13. Bacteria discharged in effluent from wastewater treatment plants;
14. Bacteria draining directly into waterbodies from failing septic systems;
15. Bacteria from cattle directly defecating into streams; and

16. Bacteria from geese and other waterfowl directly defecating into streams.

An attempt was made to estimate the impact of bacteria loads from Combined Sewer Overflows (CSOs) and Sanitary Sewer Overflows (SSOs) in the North Branch of the Potomac, around Cumberland, where these discharges have been documented. Loads from CSOs and SSOs are not represented in other segments.

The sources of fecal coliform bacteria fall into two groups. Some sources (1-5) only deliver loads to waterbodies in runoff. Bacteria from these sources will only appear during storm flows or high flows. The loads from other sources (6-9) are delivered almost constantly and can be expected to constitute the load observed in base flow or low flow conditions. There exists a significant amount of monitoring data for fecal coliform bacteria in the Potomac River Basin under a variety of flow conditions. As will be described more fully below, the observed data show variation in concentration with flow conditions. The mean concentration at high flows tends to be larger than the mean concentration at low flows, although generally there are several orders of magnitude in the range of observed concentrations under all flow conditions. The Fecal Coliform Model was calibrated to replicate mean concentrations at different flow conditions; it was not intended to simulate the observed data on an event-by-event basis, or even to capture the range of variability observed under different flow conditions. Demonstrating, however, that the model faithfully replicates the mean fecal coliform concentrations under different flow conditions throughout the basin will enable the model to explain the relative contribution of sources at different locations to the observed bacteria concentrations at the intakes.

The development of the model and its use to analyze the potential for pathogen contamination of source water will be described in the following six sections. The first section will describe the observed monitoring data that were used to calibrate the model. The next section will outline how HSPF was adapted to represent the processes relevant to the fate and transport of bacteria and what parameters were used to calibrate the model. It will also explain how the scale of the Watershed Model was taken into account in calibrating the model. The third section will describe the estimation of input loads. The fourth section will give the results of the calibration. The next section will analyze the relative contribution of the sources to the observed fecal coliform concentrations at the intakes. The final section will assess the susceptibility of source water to pathogens on the basis of the results of the simulation.

6.3.1. Monitoring Data

The Fecal Coliform Model was calibrated against the geometric mean of the observed data for different flow conditions at or near the outlet of each modeling segment. Using the daily discharge record for a USGS gage near the outlet of a segment, the 90^{th}, 74^{th}, and 50^{th} percentile flow for the period 1984-2000 was calculated, where the 90^{th} percentile flow is a flow which is larger than 90% of the observed flows. Table 6.3.1 shows the USGS gages that were used to make the calculations and table 6.3.2 shows the results. The gage at Hancock was used for both the Upper Potomac (175) and Middle Potomac (740) segments.

Table 6.3.1 USGS gages used to determine flow percentiles

Watershed	Segment	USGS Gage	Location
North Branch	160	1603000	North Branch Potomac River Near Cumberland, MD
South Branch	170	1608500	South Branch Potomac River Near Springfield, WV
Upper Potomac	175	1613000	Potomac River At Hancock, MD
Point of Rocks	180	1638500	Potomac River at Point of Rocks
S.Fk. of Shenandoah	190	1631000	South Fork Shenandoah River at Front Royal, VA
Mainstem Shenandoah	200	1636500	Shenandoah River at Millville, WV
Lower Monocacy	210	1643000	Monocacy River at Jug Bridge Near Frederick, MD
Lower Potomac	220	1646500	Potomac R. near Washington, D.C. Little Falls Pump Station
Conococheague	730	1614500	Conococheague Creek at Fairview, MD
Middle Potomac	740	1613000	Potomac River At Hancock, MD
Upper Monocacy	750	1639000	Monocacy River at Bridgeport, MD

Table 6.3.2 Modeling segment flow percentiles

Watershed	Segment	90th Percentile	75th Percentile	50th Percentile
North Branch	160	3,080	1,595	444
South Branch	170	3,250	1,540	292
Upper Potomac	175	9,652	4,820	1,120
Point-of-Rocks	180	22,100	11,100	2,915
S.Fk. Shenandoah	190	3,490	1,880	612
Mainstem Shenandoah	200	6,223	3,320	950
Lower Monocacy	210	2,050	1,050	236
Lower Potomac	220	27,800	13,700	2,960
Conococheague	730	1,340	708	172
Middle Potomac	740	9,652	4,820	1,120
Upper Monocacy	750	457	185	24

Fecal coliform data from monitoring stations near the outlet of each segment were collected and paired with the gaged flow for each segment. Table 6.3.3 shows the monitoring stations used for each segment. Where multiple stations were used which had observations on the same day, the arithmetic average was used as a value for the segment on that day. Each segment's observed data were then divided by the following four flow categories: (1) observations taken on days whose daily flow was greater than the 90th percentile flow, (2) observations with flows between the 75th and 90th percentile flows, (3) observations with flows between the 50th and 75th percentile flows, and (4) observations taken on days whose daily average flow was below the 50th percentile flow. These flow classes will be referred to as high, medium high, medium, and low-to-medium flows, respectively. For each segment, the geometric mean and the median of the observed data available for the period 1984-2000 was calculated for each flow class. Table 6.3.4 shows the geometric mean and median for each flow class by segment. Generally, the mean and the median value were not strikingly different.

Table 6.3.3 Monitoring stations used to calibrate the Fecal Coliform Model

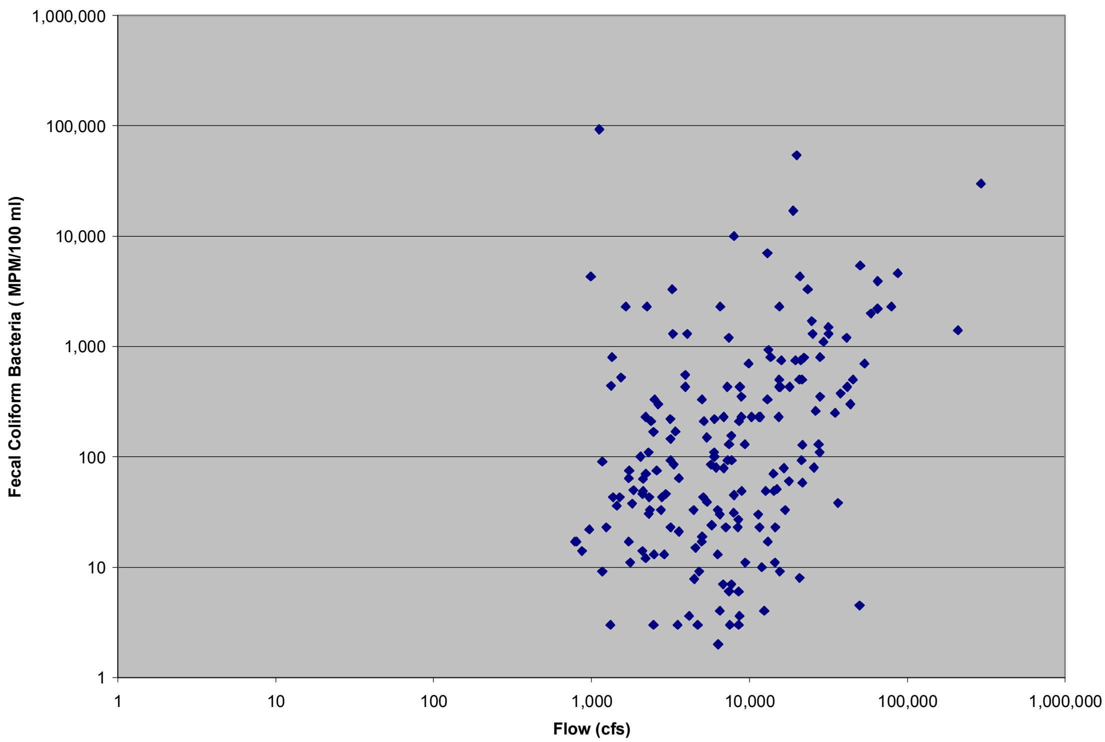
Segment	Agency	Station	Number of Observations	Location
160	DNR	NBP0023	175	West Of Moores Hollow Rd. And Route 51
170	WVDEP	550468	132	South Branch of Potomac River near Springfield
	WVDEP	WA96-P03	12	South Branch of Potomac River near Springfield
175	DNR	POT2386	178	Potomac R. At Gag Sta; 0.5m Bel Br On Rt 522
180	DNR	POT1595	137	Potomac R. E End Of Bird., U.S. Rt. 15
	DNR	POT1596	138	Potomac River VA Side Point Of Rocks
190	VADEQ	1BSSF000.19	91	Approx. 0.4 Mile Below Rt340/522 Bridge
	VADEQ	1BSSF000.58	52	Three Islands
	VADEQ	1BSSF003.56	147	Rt. 619 Bridge At Gaging Station
200	WVDEP	550471	122	Shenandoah River at Harpers Ferry, WV
	USGS	1636500	49	Shenandoah R At Millville, WV
	WVDEP	WA96-S01	12	Shenandoah River at Harpers Ferry, WV
	VADEQ	1BSHN022.63	137	Rt. 7 Bridge, Castlemans Ferry Bridge
210	DNR	MON0020	132	Monacacy R.Bridge On Md.Route 28
220	DNR	POT1184	141	Potomac R At Chain Bridge, At Wash, DC
	USGS	1646580	51	Potomac R At Chain Bridge, At Wash, DC
730	DNR	CON01830	179	Conoco. Cr. Gag. St. 0.7m. Ab. Br. On Fair.Rd
740	DNR	POT1830	136	Potomac River At Gag. Sta. Be. Br. On Rt. 34
	USGS	1618000	50	Potomac River At Gag. Sta. Be. Br. On Rt. 34
750	DNR	MON0518	132	Monocacy R At Bridgeport Br On Md Rt 97 Gag

Table 6.3.4 Geometric mean and median fecal coliform concentrations by flow condition (cfu/100 ml)

Watershed	Segment	High Flows		Medium High Flows		Medium Flows		Low-to-Medium Flows	
		Mean	Median	Mean	Median	Mean	Median	Mean	Median
North Branch	160	2,432	2,300	1,195	1,050	1,384	1,300	252	225
South Branch	170	198	185	45	63	21	10	22	10
Upper Potomac	175	687	700	275	230	141	93	50	43
Point of Rocks	180	2,019	2,325	312	280	95	75	86	60
S.Fk. Shenandoah	190	346	250	171	100	112	100	116	100
Mainstem Shenandoah	200	503	500	141	100	135	100	121	100
Lower Monocacy	210	2,705	3,000	1,072	930	325	230	162	160
Lower Potomac	220	769	1,100	270	345	74	86	64	46
Conococheague	730	1,955	1,700	692	490	379	430	312	230
Middle Potomac	740	707	495	117	93	77	75	46	49
Upper Monocacy	750	2,815	3,000	1,161	2,200	339	230	162	170

Several generalizations emerge. The mean of high flow observations are usually at least an order of magnitude higher than the mean of low-to medium observations, and generally, there is a trend toward higher observed means for higher flow classes. The strong trend towards increasing concentrations with increasing flow coexists with enormous variability in the observed data at each flow level. Figure 6.3.1 shows a scatter plot of observed fecal coliform concentrations against flow on a log-log scale for the Lower Potomac (220). There is a pronounced upward trend in concentration with flow, but concentrations have range of almost five orders of magnitude over a wide range of flows. The slope of a log-log regression line between flow and concentration is 0.7 and is strongly significant, but the coefficient of determination is only 0.14.

Figure 6.3.1 Observed fecal coliform concentrations vs. flow for Lower Potomac



Some geographic trends are also apparent from the monitoring data. Upstream portions of the basin, such as the North Branch (160), Conococheague (730), and Upper Monocacy (750), tend to higher mean fecal coliform concentrations for all flow classes than downstream segments. The South Branch(170) and the South Fork of Shenandoah (190) don't follow this trend because the mean segment concentrations represent stations near the outlet of the segment. Much of the South Branch, and many streams in the South Fork, are impaired by fecal coliform bacteria, but high fecal coliform concentrations are more rare downstream near the watershed outlet. The North Branch of the Potomac has mean concentrations of fecal coliforms above 1000 cfu/100 ml for three of the four flow classes. Downstream concentrations drop in the middle Potomac (740), however, according to monitoring data collected near Shepherdstown, WV. Fecal coliform concentrations on the Monocacy River remain high up to its confluence with the Potomac below Point of Rocks.

There is one important anomaly in the observed data. The mean high flow concentration at Point of Rocks (180) is above 2000 cfu/100 ml, despite the fact that high flow concentrations are relatively low in upstream segments on the mainstem of the Shenandoah and the Middle Potomac River. The observed concentration is inconsistent with high-flow concentrations observed upstream both at Shepherdstown on the Potomac and on the mainstem of the Shenandoah. The high-flow loads from neither of these upstream sources can explain the concentrations at Point of Rocks. The observed geometric mean of high flow concentrations in Antietam Creek, which flows into the Middle Potomac (740) downstream of Shepherdstown, is 681 cfu/100 ml, and the 90^{th} percentile flow on Antietam Creek is only about 5% of the flow at Shepherdstown. The observed concentrations on the Catoctin Creeks tend to be high, but they deliver relatively small loads because their flows are also relatively small. The observed concentration at Point of Rocks is the average of near-shoreline observations, and it is possible that they are unduly influenced by the flows from the Catoctin Creeks, which are just upstream of the monitoring station locations.

6.3.2 Modifications to the Watershed Model

Modifying the Watershed Model to represent fecal coliform bacteria is straight forward. HSPF modules are added to the Watershed Model to simulate the deposition and death of fecal coliform on the land surface, their washoff in runoff, and their transport downstream. The scale of the Watershed Model, however, poses some problems for faithfully representing the fate of fecal coliform bacteria. The observed rate at which fecal coliform die-off or disappear from a stream is as high as 15/day (Bowie et al., 1985). Transport processes in small tributaries not represented in the Watershed Model can have a large impact on the fate of bacteria. These processes need to be explicitly taken into account in the Fecal Coliform Model.

6.3.2.1 HSPF Modules for Simulating Fecal Coliform Bacteria

HSPF has been used to represent the fate and transport of fecal coliform bacteria for TMDLs in Virginia (VADEQ and VADCR, 2000 a, b, c) and West Virginia (U. S. EPA 1998 a, b, c, d). The PQUAL module of HSPF is used to represent the build-up, die-off, and wash-off of fecal coliform bacteria from the pervious land surfaces, such as cropland, forest, and pasture. That module, in the simple form in which it is used to represent bacteria, is characterized by three parameters: (1) ACQOP, the daily rate, in cfu/acre, at which bacteria accumulate on the surface in scat, livestock feces, or applied manure; (2) SQOLIM, the limit, in cfu/acre of bacteria build-up on the surface, and (3) WSQOP, the rate of surface runoff (in/hr) that removes 90% of the accumulated bacteria from the surface.

ACQOP can, and does, vary monthly. Its calculation, based on animal populations and manure applications, will be explained in the next section. SQOLIM functions as a decay rate, on the assumption that the accumulation of bacteria on the surface will reach asymptotic limit determined by a daily die-off rate. The soil decay rate used in Virginia TMDLs is approximately 0.1/day, which, by their calculations, led to a SQOLIM of nine times the application rate. In the Fecal Coliform Model, SQOLIM was set at ten times the smallest monthly application rate.

HSPF determines the fraction of accumulated bacteria removed from the surface at a runoff rate R (in/hr) by the formula:

$$1.0 - EXP(-2.3*R/WSQOP)$$

In the Fecal Coliform Model WSQOP was determined by calibration.

The in-stream processes used to represent fecal coliform bacteria are also quite simple. Bacteria are represented as a dissolved substance subject to temperature-corrected, first-order decay. The decay rate of bacteria for any given time step is determined by multiplying FSTDEC, the decay rate at 20 degrees Celsius, by the factor, $THST^{T-20}$, where T is the water temperature in degrees Celsius, calculated by HSPF. The decay rate, FSTDEC, was determined by calibration. Following Virginia's TMDLs, the temperature correction term, THST, was set at 1.05.

6.3.2.2 Travel Time Corrections for Low-Flow Sources

Low-flow sources, such as wastewater effluent, failing septic systems and the direct deposition of cattle and goose feces, are input directly into model reaches as external time series. Most large wastewater facilities discharge into or close to the river reaches explicitly represented in the model. The loads from cattle, geese, and failing septic systems, however, are usually transported in smaller tributaries that are not explicitly represented in the Watershed Model. The travel time from smaller tributaries to the mainstem of the Potomac or the main channel of the larger tributaries represented in the model can be considerable, and, consequently, a considerable number of the bacteria deposited in the smaller tributaries can be expected to die off before entering the main channel river reaches.

The travel time from small tributaries to the represented river reaches, and the resulting die-off of bacteria, were explicitly taken into account in the Fecal Coliform Model. An average travel time from small tributaries to river reaches was calculated using information provided in the EPA's River Reach File version 1 (RF1). RF1 is a nation-wide GIS representation of this country's stream network. The stream network is divided into reaches. RF1 contains a considerable amount of information about reach segments. Among the attributes assigned reaches in RF1 are segment length and velocity at mean flow. These attributes were used to calculate a travel time through the reach. The travel time from the RF1 reach to the reach of the segment represented in the Watershed Model was calculated and associated with the centroid of the reach.

The centroids of the RF1 reaches provide a point coverage, which was then contoured using the ArcView GIS software. This yielded a contour map of travel times to Potomac Watershed Model segments under mean flow conditions. An area-weighted travel time for each model segment was then calculated. The results are shown in Table 6.3.5.

Table 6.3.5 Travel times and annual input loads for low-flow loads

[REDACTED]

The fraction of the load which arrives at the model segment reach from failing septic systems and the direct deposit of fecal material into streams by cattle and waterfowl was calculated using the average travel time and a temperature-corrected, first-order decay rate. The temperature correction term used the same value as the model segment reach. The time series of simulated water temperature from the Lower Potomac (220) was used to calculate the temperature correction term. The base first-order decay rate was a calibration parameter.

6.3.3 Fecal Coliform Bacteria Input Loads

The information for the quantification of fecal coliform bacteria input loads comes from three sources: (1)The EPA guidance document, Protocol for Developing Pathogen TMDLs (USEPA 2001), (2) existing Virginia and West Virginia fecal coliform TMDLs (VADEQ and VADCR 2001 a, b, c, and USEPA 1998 a, b, c, d) and (3) the CBP methodology for tracking animal waste (Jeff Sweeney, personal communication). Key to the quantification of almost all loads is the animal per capita fecal coliform generation, in cfu/day. Table 6.3.6 gives the number of fecal coliform bacteria generated per day by animal. USEPA (2001) is the source for all these estimates, except for geese, where the EPA's per capita rate seemed unusually high. The geese fecal coliform per capita production rate was derived from the TMDL for Mill Creek (VADEQ and VADCR, 2000b). As the table shows, beef and dairy cattle have the highest per capita fecal coliform generation rate, more than two orders of magnitude higher than humans. The estimates used here generally follow the average weight of the species. It should be noted that published estimates of fecal coliform generation rates can vary by two orders of magnitude.

Table 6.3.6 Per capita fecal coliform generation rates, storage fractions, and storage decay rates

Animal Name	Fecal Coliform Generation Per Capita (cfu/day)	Fraction on Pasture	Fraction Confined And Stored	Fraction Confined But not Stored	Decay Rate in Storage (1/day)
Beef	1.04E+11	80 - 100%	0	0 - 20%	0.863
Dairy	1.01E+11	20%	40%	40%	0.115
Swine	1.08E+10	0%	85%	15%	0.787
Poultry	1.36E+08	0%	100%	0%	0.081
Turkeys	9.30E+07	0%	100%	0%	0.081
Deer	5.00E+08	NA	NA	NA	NA
Geese	7.99E+08	NA	NA	NA	NA
Humans	2.00E+09	NA	NA	NA	NA

6.3.3.1 Accumulation Rates on Forest, Cropland, Hay, and Pasture

The daily accumulation rate for forest, cropland, hay, and pasture from livestock was calculated using the Bay Program's methodology for tracking animal waste products, with one difference: Animal populations were based solely on the 1992 Agricultural Census and kept constant throughout the simulation; no attempt was made to change deposition rates by estimating changes to the animal population throughout the simulation period. Table 6.3.7 gives the animal population for each segment. County animal populations, as reported in the 1992 Census, were proportioned to the model segments based on the fraction of a county's herbaceous acres, as given by the MRLC land cover layer, that were in the model segment. Poultry populations are larger than any other species except in the Lower Potomac (220), where people dominate. Table 6.3.8 shows the total daily fecal coliform generated by species for each modeling segment. Poultry produce the largest amount of fecal coliform bacteria in every segment except 220, where beef cattle dominate. Beef cattle generally produce the second largest total of fecal coliform per day, followed by dairy cattle everywhere except 220, where the human population ranks third.

Table 6.3.7 Human and animal populations by modeling segment

Segment	Beef	Dairy	Poultry	Turkeys	Swine	Deer	Geese	Human Population
160	24,358	5,270	1,281,367	61,040	2,572	62,971	1,748	114,179
170	47,641	713	5,877,942	1,158,129	4,654	63,165	1,928	28,606
175	27,596	3,266	2,393,273	7,222	4,504	62,396	1,627	28,267
180	41,015	23,389	590,678	14,666	16,453	24,122	827	152,924
190	156,878	25,184	15,685,491	3,990,569	12,825	39,894	2,058	183,490
200	101,262	17,450	9,030,176	2,370,513	10,038	51,531	1,833	114,613
210	41,058	30,961	884,440	63,394	8,736	20,479	5,078	178,694
220	42,268	4,332	3,431	107	1,493	30,256	5,938	631,651
730	33,685	28,906	1,417,590	38,159	48,573	13,272	650	79,867
740	54,600	16,946	323,757	47,447	33,146	50,487	1,755	182,218
750	7,746	3,775	695,916	175,939	8,750	4,984	1,150	29,507

Total	578,108	160,193	38,184,059	7,927,185	151,743	423,557	24,594	1,724,016

Table 6.3.8 Daily total fecal coliform generation by species (cfu/day)

Segment	Beef	Dairy	Poultry	Turkeys	Swine	Deer	Geese	Human	Total
160	2.5E+15	5.3E+14	1.4E+16	8.3E+12	2.4E+11	3.1E+13	1.4E+12	2.3E+14	1.7E+16
170	5.0E+15	7.2E+13	6.3E+16	1.6E+14	4.3E+11	3.2E+13	1.5E+12	5.7E+13	6.9E+16
175	2.9E+15	3.3E+14	2.6E+16	9.8E+11	4.2E+11	3.1E+13	1.3E+12	5.7E+13	2.9E+16
180	4.3E+15	2.4E+15	6.4E+15	2.0E+12	1.5E+12	1.2E+13	6.6E+11	3.1E+14	1.3E+16
190	1.6E+16	2.5E+15	1.7E+17	5.4E+14	1.2E+12	2.0E+13	1.6E+12	3.7E+14	1.9E+17
200	1.1E+16	1.8E+15	9.8E+16	3.2E+14	9.3E+11	2.6E+13	1.5E+12	2.3E+14	1.1E+17
210	4.3E+15	3.1E+15	9.6E+15	8.6E+12	8.1E+11	1.0E+13	4.1E+12	3.6E+14	1.7E+16
220	4.4E+15	4.4E+14	3.7E+13	1.5E+10	1.4E+11	1.5E+13	4.7E+12	1.3E+15	6.2E+15
730	3.5E+15	2.9E+15	1.5E+16	5.2E+12	4.5E+12	6.6E+12	5.2E+11	1.6E+14	2.2E+16
740	5.7E+15	1.7E+15	3.5E+15	6.5E+12	3.1E+12	2.5E+13	1.4E+12	3.6E+14	1.1E+16
750	8.1E+14	3.8E+14	7.5E+15	2.4E+13	8.1E+11	2.5E+12	9.2E+11	5.9E+13	8.8E+15
Total	6.0E+16	1.6E+16	4.1E+17	1.1E+15	1.4E+13	2.1E+14	2.0E+13	3.4E+15	4.9E+17

The fate of animal waste is depends on the type of animal and model segment. Animals are either confined or in pasture. Pastured animals deposit wastes with fecal coliform bacteria on pasture land daily. The waste from confined animals is either stored or unstored. If the waste is unstored, it is applied to crops and hay on a daily basis. If it is stored, it is applied to crops only in the spring (April, May) before planting or in the fall (October, November) after harvesting and before planting a winter cover crop. Fecal coliform bacteria in manure or litter in storage are subject to decay. Table 6.3.6 gives the fraction of animal waste that is stored, unstored, or deposited in pasture for each animal type. It also gives the decay rate in storage for each type of animal waste. According to CBP assumptions, all poultry wastes are stored. For the most part, beef cattle are in pasture, though about 20% of the cattle are confined in the upper Potomac segments. Most of the waste from hogs is stored. Twenty percent of the waste from dairy cattle is deposited in pasture; half of the rest is stored.

The contribution of domestic animals to fecal coliform accumulation rates is calculated as follows. The pasture loading rate is equal to the number of animals of each type in pasture in a model segment, times their per capita fecal coliform generation rate, divided by the number of acres in the model segment. The pasture loading rate is corrected monthly to take into account the fecal material directly deposited by cattle into a stream, as will be explained below. Table 6.3.9 gives the total amount of fecal coliform bacteria applied on pasture annually in each segment. Almost of the load comes from beef cattle, with a smaller contribution from dairy cattle.

Table 6.3.9 Annual fecal coliform application rates (cfu/yr)

Segment	Stored				Unstored				
	Pasture	High Till	Low Till	Hay	High Till	Low Till	Hay	Geese	Deer
160	7.5E+17	2.6E+15	1.8E+15	3.7E+15	8.4E+16	6.0E+16	1.2E+17	3.8E+14	1.1E+16
170	1.4E+18	9.3E+15	6.5E+15	6.9E+15	1.5E+17	1.1E+17	1.1E+17	4.2E+14	1.2E+16
175	8.3E+17	4.2E+15	4.0E+15	2.1E+15	1.1E+17	1.0E+17	5.2E+16	3.6E+14	1.1E+16
180	1.7E+18	3.8E+15	9.7E+15	5.0E+15	7.3E+16	1.9E+17	9.6E+16	1.8E+14	4.4E+15
190	5.9E+18	1.9E+16	4.6E+16	1.3E+16	9.4E+16	2.2E+17	6.3E+16	4.5E+14	7.3E+15
200	3.8E+18	1.1E+16	2.6E+16	1.1E+16	5.9E+16	1.4E+17	6.2E+16	4.0E+14	9.4E+15
210	1.7E+18	6.7E+15	1.3E+16	4.9E+15	1.3E+17	2.4E+17	9.2E+16	1.1E+15	3.7E+15
220	1.6E+18	6.6E+14	1.4E+15	9.4E+14	1.4E+16	3.1E+16	2.0E+16	1.3E+15	5.5E+15
730	1.4E+18	8.4E+15	1.2E+16	5.0E+15	1.5E+17	2.2E+17	8.8E+16	1.4E+14	2.4E+15
740	2.1E+18	2.8E+15	5.7E+15	5.2E+15	5.6E+16	1.1E+17	1.0E+17	3.8E+14	9.2E+15
750	3.1E+17	1.9E+15	2.3E+15	1.3E+15	2.0E+16	2.6E+16	1.5E+16	2.5E+14	9.1E+14
Total	2.2E+19	7.0E+16	1.3E+17	5.9E+16	9.3E+17	1.5E+18	8.2E+17	5.4E+15	7.7E+16

Unstored animal waste is applied daily to conventional tillage cropland, conservation tillage cropland, and hay land according to a CBP formula for dividing animal manure among the land uses. The total number of bacteria in unstored waste is calculated for a model segment. It is simply the product of the population of animals with unstored waste times their per capita fecal coliform generation rate. The bacteria are then proportioned among the land uses by the CBP formula. The daily application rate is calculated by dividing the bacteria from unstored waste generated daily for each land use type by the number of acres of each land use. Table 6.3.9 gives the total number of bacteria from unstored waste applied to each land use annually by model segment. Almost all of the unstored waste comes from dairy cattle, except in the North Branch (160), South Branch (170), and Upper Potomac (175) segments, where 70%, 96%, and 80% of waste, respectively, comes from beef cattle.

It is assumed that stored waste asymptotically approaches a limiting fecal coliform population determined by dividing the daily accumulation rate by the decay rate. According to that formula, the die-off rate for fecal coliform bacteria in stored beef, dairy, swine, and poultry rate is 99%, 95%, 97%, and 93%, respectively. The remaining population is then apportioned among the land uses according to the CBP formula, and a daily rate is determined by dividing the apportioned population by the area of each land use over 61 days, to take into account the two-month, twice-a-year application period. Table 6.3.9 shows the daily application rate for each land use by model segment. Bacteria from dairy cattle waste constitute the largest fraction of stored load in the Lower Potomac (220), Lower Monocacy (210), Point of Rocks (180), Middle Potomac (740), and Conococheague (730) segments, accounting for 98%, 87%, 87%, 86%, and 77% of the stored coliforms, respectively. Coliforms from poultry are predominant in the remainder of the segments, accounting for 54% of the bacteria in the North Branch (160), 98% in the South Branch (170), 77% in the Upper Potomac (175), 77% in the South Fork of the Shenandoah (190), and 73% in the remainder of the Shenandoah watershed (200). The contribution from swine was greater than 1% only in segments 730 (4%), 740 (6%), and 750 (4%). The source of the remainder of the stored load in segment 750, the Upper Monocacy, is split evenly between poultry and dairy cattle. It should be noted that the application rate for stored waste is another order of magnitude smaller the rate for unstored waste, and the pasture application rate is usually an additional order of magnitude higher than the rate for unstored waste. Beef cattle, and to a lesser extent, dairy cattle, have surpassed poultry as the dominant source of fecal coliform bacteria applied to agricutural lands.

Wildlife can also deposit wastes on cropland and pasture, as well as forest. Deer and geese are thought to be the largest contributors to wildlife fecal coliform loads. Deer populations were estimated by county for each state. In Virginia, DGIF supplied county deer population estimates. Pennsylvania also supplied county deer population estimates (Christopher S. Rosenberry, personal communication). In West Virginia and Maryland, deer populations were estimated from the buck harvest. According to a rule of thumb, used in West Virginia TMDLs (U.S. EPA 1998 a, b, c,d), the deer population is roughly equal to ten times the number of bucks harvested. All deer populations are estimates for 2000. Since deer populations have been increasing, this overestimates the fecal coliform load from during the 1984-1997 simulation period, but should help compensate for the fact that no other mammalian wildlife species is represented in the model. The county deer population was assumed to be homogeneously divided across all land uses. Model segment deer populations were calculated by apportioning the county deer population by the fraction of the county in each model segment. Table 6.3.7 shows the deer population in each segment. Table 6.3.9 gives the daily loading rate from deer, which was applied to forest, pasture, and cropland. As the table shows, the contribution from deer is not significant on agricultural land.

The geese population for each model segment was estimated on the basis of waterfowl survey conducted by a consortium of state conservation agencies (Heusmann and Sauer, 2000). Geese densities were estimated to be 0.01 geese/acre in the Piedmont (Segments 750, 210, and 220) and 0.002 geese/acre elsewhere, spread evenly over all land uses. The geese population was doubled in the months of November, December, and January to take into account migratory geese and other waterfowl. Table 6.3.7 shows the resident goose population by model segment. Other species of waterfowl may be significant contributors to fecal coliform loads, especially since high per capita fecal coliform generation rates are attributed to ducks and other waterfowl. On the other hand, other species of water fowl, like wood ducks, tend to be highly seasonal. The geese densities used in the Fecal Coliform Model also are higher than estimates used in any of the fecal coliform TMDLs in Virginia and West Virginia. It is hoped that generous estimates of the geese population will account for the contribution of other species of waterfowl, which are present in most of the basin in far smaller numbers than geese. In Virginia TMDLs, it is assumed that 25% of waterfowl feces are deposited directly into waterbodies; the rest is deposited on cropland, pasture, and forest. This assumption was adopted in the Fecal Coliform Model. Table 6.3.9 gives the goose load applied to forest, cropland, and pasture. It is smaller than the deer load and again, insignificant on agricultural land.

To summarize, the fecal coliform load on pasture is about 15 times the load from unstored animal waste, more that 150 times the load from stored animal wastes, and almost 300 times the load from geese and deer. Beef and dairy cattle are responsible for most of the bacteria deposited on pasture or applied on fields as unstored waste. Poultry generate more coliform bacteria than any other species; However, because poultry waste is stored and is subject to decay before being applied to fields, fewer bacteria from poultry waste are applied to the fields where they are subject to runoff. The number of fecal coliform bacteria from wildlife applied on agricultural land is small compared to the number from domestic animals.

6.3.3.2 Low-Flow Loads From Small Tributaries

Failing septic systems and the direct deposition of feces by cattle and waterfowl contribute fecal coliform bacteria loads during low-flow conditions. Section 6.3.2 already described how these loads are input into the model as a time series with a temperature-corrected first-order decay rate based on the estimated average travel time from smaller tributaries to the main channel of the modeling segment. Septic system loads were calculated on the basis of the per capita human fecal coliform generation rate and the CBP estimates of the population served by septic systems in a model segment. A failure rate of 2.5%, which was used in West Virginia TMDLs, was assumed. Table 6.3.5 shows the annual septic system load by model segment before correcting for travel time.

As explained above, it was assumed that 25% of the fecal coliform bacteria from geese were deposited directly into waterbodies. The annual low-flow load from a model segment was calculated on the basis of the geese population shown in Table 6.3.7. Table 6.3.5 shows the annual low-flow load from geese by model segment before correcting for travel time. The goose population, and therefore the load, was assumed to double during the months of November, December, and January.

Direct deposition of fecal coliform bacteria to waterbodies by cattle was assumed to be proportional to the time cattle spent in stream. The assumptions used in Virginia TMDLs were adopted. Cattle spend 3.5 hours a day in streams during June, July, and August, 1.0 hour/day in May and September, 0.75 hours/day in April and October, and 0.5 hours/day the remainder of the year. Table 6.3.6 shows the annual fecal coliform load attributable to cattle by model segment, before the travel time correction.

6.3.3.3 Fecal Coliform Loads in Wastewater, Urban Runoff, and Drainage from Confined Animal Operations

Wastewater treatment plants are usually permitted to discharge effluent with concentrations up to 200 cfu/100 ml, but most discharge much less than that under normal operations. Most of the fecal coliform effluent concentrations reported to MDE under state permitting process were 20 cfu/100 ml or less, so on that basis the concentration of fecal coliforms in wastewater was set at 20 cfu/100 ml. The Watershed Model already represents wastewater flows by model segment as an input time series for those plants with flows 0.5 mgd or greater.

The Watershed Model estimates runoff from feedlots and other types of confined animal operations. The estimate is based on assigning each model segment a number of impervious acres proportional to the animal population in the segment. The simulated runoff from the manure acres carries with it a concentration of nitrogen and phosphorus. This nutrient load is not subtracted from the total nutrients generated by animals in confinement. In the Fecal Coliform Model, a fecal coliform concentration of 1.35 $x10^6$ cfu/100 ml (EPA, 2001) was assigned to runoff from feedlots and confined animal operations. The fecal coliform load from confined animals was not corrected for these losses. In general the losses represent less than 5% of the fecal coliform bacteria generated by confined animals.

Urban sources of fecal coliform bacteria include fecal wastes from pets, waterfowl, and wildlife, as well as sanitary sewer overflows and cross-connections between storm water and sanitary sewers. Distinct types of sources, however, were not represented in the Fecal Coliform Model. The low-flow urban load, attributable to waterfowl, is already represented as part of the base flow load. The fecal coliform load from urban sources during storm water events was represented by assigning a fixed concentration to the simulated runoff from both pervious and impervious urban land. The concentration of fecal coliform bacteria in urban runoff was determined by the methodology used by Gruessner et al. (1997) in estimating the load of toxic chemicals in urban runoff for the CBP Toxics Loading Inventory. For the Toxics Loading Inventory, all of the monitoring data available from NPDES stormwater application permits for communities in the Chesapeake Bay basin were collected into a single database. The geometric mean of all observations in the database was used to represent the concentration of a constituent in urban stormwater in the Chesapeake Bay basin. The geometric mean of observed fecal coliform bacteria concentrations in the database was 1775 cfu/100 ml, and that number was used in the Fecal Coliform Model to represent the fecal coliform concentration in urban storm water.

Combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) are a known problem in the North Branch of the Potomac in a near Cumberland, MD. MDE maintains a database of reported CSOs and SSOs, but it was not possible to find a simple relationship between reported CSO or SSO volumes and either precipitation or simulated urban runoff. Annual reported overflow volumes were approximately 67 million gallons for 1996, 45 million gallons for 1997, 41 million gallons for 2000, and 90 million gallons, January through May of 2001. The annual overflow volume for 1996 could be approximated if it were assumed that every inch of daily urban runoff over 0.3 inches produced 2 million gallons of overflow. This assumption does not capture reported volumes on a daily basis. A time series of overflow volumes was developed for the simulation period 1984-1997 using this assumption. The overflow load was calculated by assuming that the concentration of fecal coliforms in CSOs is 4.2×10^6 cfu/100 ml (U. S. EPA, 2001).

SSOs are not explicitly represented in other model segments and may not be captured by the urban runoff concentration developed from stormwater monitoring data. It would be helpful to incorporate a simple model of SSO flows into the Fecal Coliform Model to better determine the relative magnitude of the contribution of SSOs to fecal coliform loads.

6.3.4 Model Calibration

The Fecal Coliform Model was calibrated by adjusting the pervious land washoff rate, WSQOP, the main channel first-order decay rate, FSTDEC, and the low-flow decay rate until the geometric means of simulated fecal coliform concentrations matched the geometric means of observed concentrations at the four different flow classes. In general, WSQOP controls the high flow class concentrations, the low-flow decay rate controls the medium-to-low flow class concentrations, and the fit to the other flow classes was controlled by the main channel decay rate.

Table 6.3.10 compares the observed and simulated geometric means of the four flow conditions. Figure 6.3.2 shows the same information graphically. Overall, good agreement was achieved between observed and model values, with two exceptions. Observed fecal coliform concentrations in the North Branch (160) remain above 1000 cfu/100 ml in the medium flow class, where the simulated values fall to 400. The high concentrations at all flows above the 50^{th} percentile probably represents the influence of CSO and SSO loads that are not being fully captured by the model. The model also fails to capture the high flow class concentration at Point of Rocks. As discussed in section 6.3.2, the observed fecal coliform concentrations during high flows at Point of Rocks seem to be an anomaly.

Table 6.3.10 Comparison of simulated and observed geometric mean fecal coliform concentrations by flow class

Segment	Observed vs. Simulated	High	Medium-High	Medium	Medium-to-Low
160	OBSERVED	2,432	1,195	1,384	252
	SIMULATED	2533	1044	400	248
170	OBSERVED	198	45	21	22
	SIMULATED	202	52	18	11
175	OBSERVED	687	275	141	50
	SIMULATED	716	271	105	56
180	OBSERVED	2,019	312	95	86
	SIMULATED	993	319	150	76
190	OBSERVED	346	171	112	116
	SIMULATED	355	145	134	118
200	OBSERVED	503	141	135	121
	SIMULATED	489	199	140	118
210	OBSERVED	2,705	1,072	325	162
	SIMULATED	2,633	1,161	342	160
220	OBSERVED	769	270	74	64
	SIMULATED	768	244	117	63
730	OBSERVED	1,955	692	379	312
	SIMULATED	1959	517	322	332
740	OBSERVED	707	117	77	46
	SIMULATED	692	218	89	38
750	OBSERVED	2,815	1,161	339	162
	SIMULATED	2,887	1,001	286	165

Figure 6.3.2. Comparison of observed and simulated concentrations

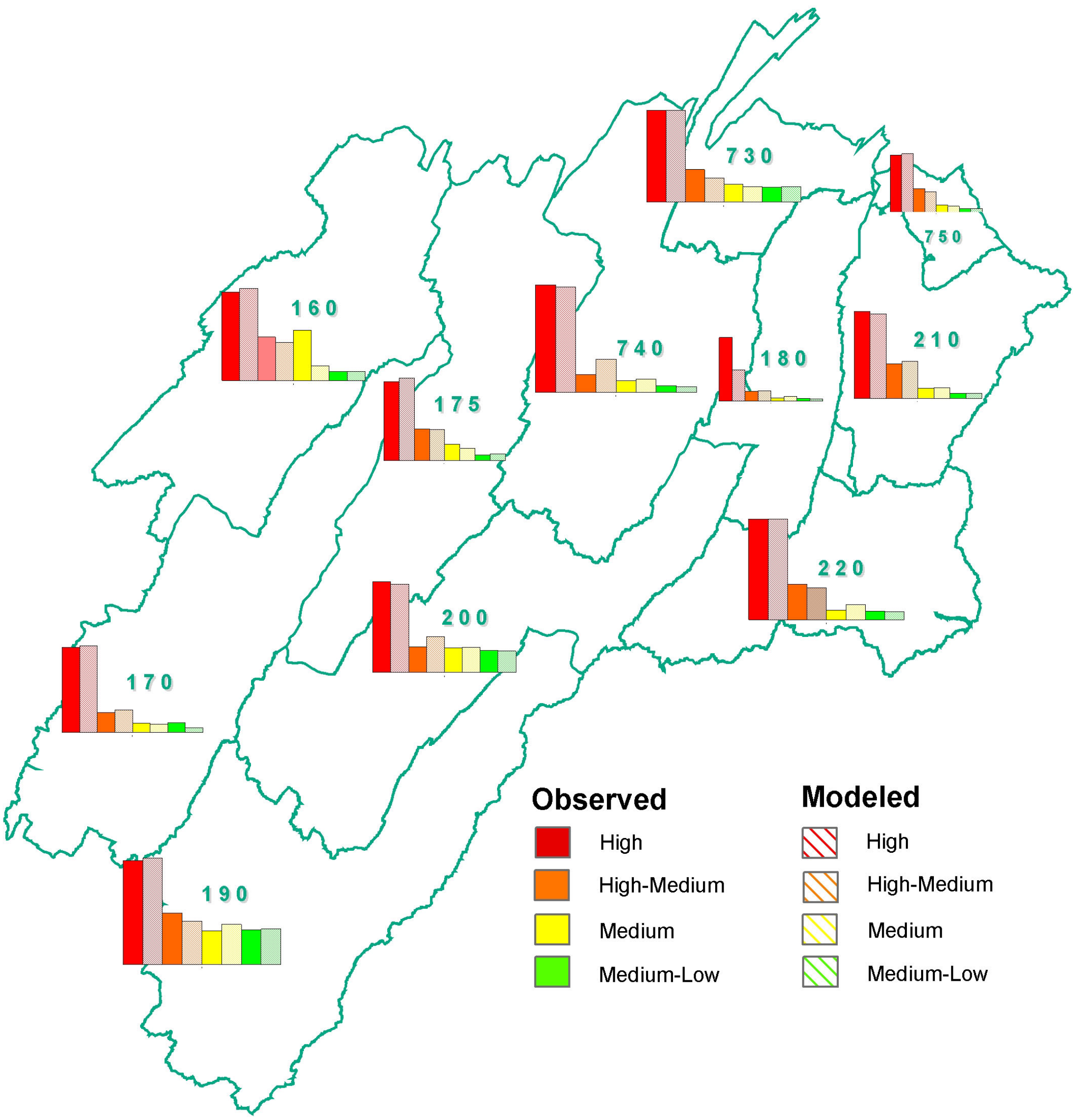


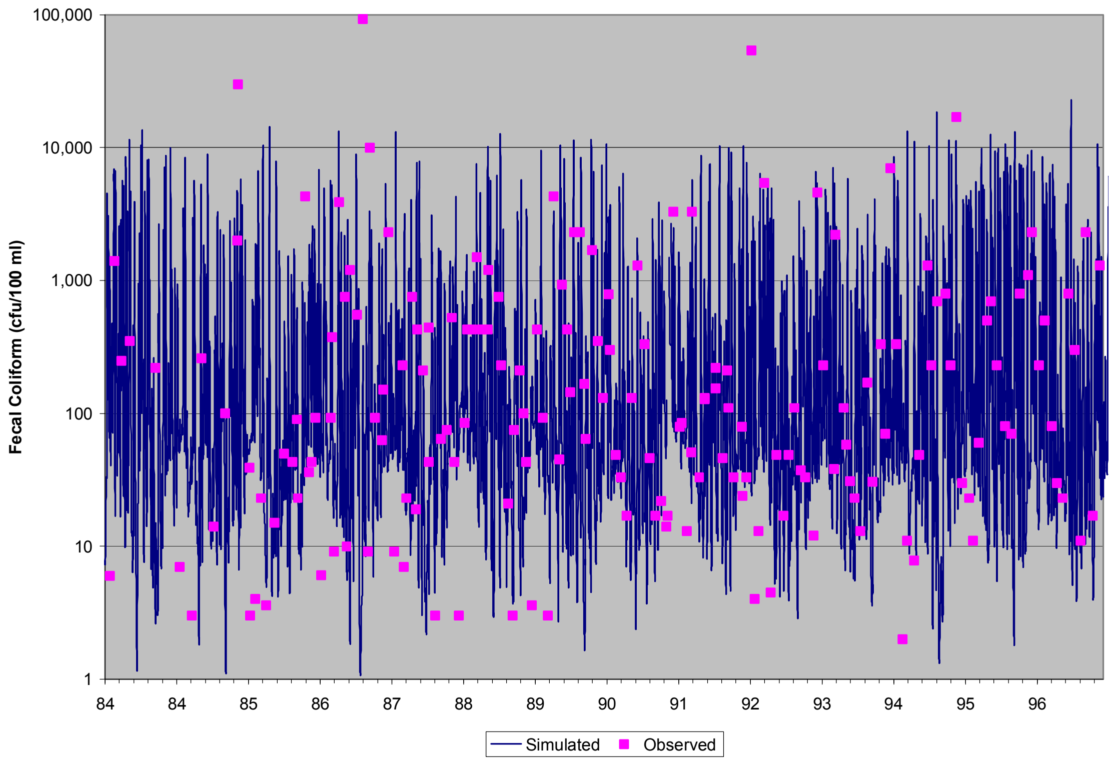
Table 6.3.11 shows the parameters used in the calibration. The main channel decay rates vary between 0.42 and 1.7 /day, tending toward high values in the mainstem of the Potomac. Low-flow tributary decay rates varied between 0.51 and 1.42 /day. Both sets of decay rates are within the observed range. The washoff parameter, WSQOP, varies more widely, from 5 in to 230 inches/hour. All other things being equal, high values of the washoff rate indicate smaller contributions to fecal coliform loads from runoff from forest and agricultural land. The higher the value, the higher the runoff rate necessary to remove equivalent amounts of bacteria from the surface, or in other words, the higher the washoff rate, the less load from the same amount of runoff. An 1 inch/hour runoff rate will wash off 37% of the bacteria accumulated on the surface when WSQOP equals 5, but only 1% when WSQOP equals 230. Most segments have washoff rates between 20 and 75, with corresponding removal rates for 1 in/hr of runoff of 10% and 3%, respectively.

Table 6.3.11 Calibration parameter values

Segment	Washoff Rate (in/hr)	Main Channel Decay Rate (1/day)	Tributary Decay Rate (1/day)
160	17	0.42	0.63
170	75	1.7	0.95
175	50	1.45	1.15
180	5	0.42	1.15
190	70	1.3	0.51
200	50	0.425	0.86
210	70	0.425	1.10
220	22	1.6	0.91
730	230	0.5	1.30
740	9	1.7	0.74
750	38	0.425	1.42

Figure 6.3.3 compares the time series of individual observed fecal coliform concentrations at Chain Bridge, [REDACTED], with simulated values. The model fails to capture either the highest or lowest observed values, but does capture the general range and trend of the observed concentrations well.

Figure 6.3.3 Observed vs.simulated fecal coliform bacteria concentrations in Lower Potomac



6.3.5 Analysis of Simulated Fecal Coliform Bacteria Loads

Simulated fecal coliform loads can be identified at three phases of the simulation. The first phase loads are the input loads discussed in Section 6.3.3. The second phase loads are the loads delivered to the main channel reaches from the land surface or from the tributaries under low-flow conditions. These are called edge-of-stream loads. They represent the simulated loads in runoff from the land surface and the low-flow loads from smaller tributaries corrected for die-off during time of travel to the main channel. Table 6.3.12 shows the average annual simulated edge-of-stream loads for land uses and major components of low-flow load. Average values were determined from the entire 14-year simulation period. The load from hay land, conventional-tilled cropland, and conservation-tilled cropland have been combined. The annual simulated CSO load in the North Branch (16), not shown on the table, is 4.6E+15 cfu. Pasture loads are the largest source of fecal coliform bacteria in all segments except the Conococheague (730), where feedlots are the largest source of loads. Generally, feedlot runoff and cropland are the next largest source of loads during high flow periods, although the annual CSO/SSO load is comparable to the feedlot load in the North Potomac (160). Loads in urban runoff are less than runoff loads from feedlots and cropland everywhere except in the Lower Potomac (220). Loads in forest runoff are always less than either urban or agricultural loads. On an annual basis, the load from cattle in streams is the largest source of loads during low-flow periods. It is roughly an order of magnitude smaller than the load in urban runoff. The load from cattle in streams is highly seasonal: during the summer months cattle are the dominant source of fecal coliform bacteria during low flow periods, while during the winter months the load from geese and failing septic systems is comparable to the load from cattle.

Table 6.3.12 Annual edge-of-stream fecal coliform loads (cfu/yr)

Segment	Forest	Geese	Pasture	Crop	Feedlots	Cattle	Septic	Point Source Load	Urban Load
160	1.5E+14	1.8E+13	3.1E+16	1.1E+16	3.1E+15	1.4E+15	6.1E+13	1.0E+13	2.6E+15
170	1.7E+13	2.7E+12	8.3E+15	2.1E+15	3.2E+15	2.8E+14	3.9E+12	2.5E+11	1.3E+15
230	3.1E+13	4.0E+11	9.0E+15	2.6E+15	2.5E+15	2.7E+13	8.2E+11	1.8E+10	9.9E+14
180	3.2E+13	1.3E+12	6.7E+16	1.8E+16	7.2E+15	3.7E+14	1.7E+13	3.3E+12	1.1E+15
190	4.2E+12	8.9E+12	2.4E+16	1.9E+15	1.1E+16	4.2E+15	6.1E+13	4.8E+12	2.6E+15
200	3.6E+12	2.5E+12	1.4E+16	1.2E+15	6.4E+15	7.6E+14	1.5E+13	1.1E+12	1.4E+15
210	7.9E+12	1.1E+13	1.4E+16	3.8E+15	9.3E+15	5.5E+14	3.2E+13	3.9E+12	2.2E+15
220	2.4E+13	3.3E+13	3.9E+16	1.6E+15	2.0E+15	1.5E+15	7.8E+13	2.3E+12	4.8E+15
730	1.7E+12	1.1E+12	4.6E+15	1.6E+15	1.1E+16	3.6E+14	9.3E+12	1.7E+12	1.4E+15
740	1.1E+14	3.8E+12	1.0E+17	1.5E+16	5.8E+15	6.7E+14	3.5E+13	3.2E+12	3.3E+15
750	3.6E+12	3.3E+12	4.8E+15	9.7E+14	1.6E+15	1.3E+14	6.6E+12	6.5E+11	5.0E+14

Table 6.3.13 Annual delivered fecal coliform loads (cfu/yr)

Segment	Forest	Geese	Pasture	Crops	Feedlots	Cattle	Septic	Point Source	Urban	Total
160	1.2E+13	1.4E+12	2.5E+15	8.7E+14	2.6E+14	1.1E+14	5.0E+12	8.4E+11	2.2E+14	4.0E+15
170	6.1E+11	9.7E+10	3.0E+14	7.7E+13	1.1E+14	1.0E+13	1.4E+11	9.2E+09	4.7E+13	5.5E+14
175	3.2E+12	4.1E+10	9.3E+14	2.7E+14	2.6E+14	2.8E+12	8.4E+10	1.9E+09	1.0E+14	1.6E+15
180	1.4E+13	6.0E+11	3.0E+16	7.9E+15	3.2E+15	1.7E+14	7.5E+12	1.5E+12	5.0E+14	4.1E+16
190	4.1E+11	8.7E+11	2.3E+15	1.9E+14	1.0E+15	4.1E+14	6.0E+12	4.7E+11	2.5E+14	4.3E+15
200	1.1E+12	8.0E+11	4.4E+15	3.8E+14	2.0E+15	2.4E+14	4.6E+12	3.5E+11	4.5E+14	7.5E+15
210	3.4E+12	4.7E+12	6.1E+15	1.6E+15	4.0E+15	2.4E+14	1.4E+13	1.7E+12	9.4E+14	1.3E+16
220	1.2E+13	1.7E+13	2.0E+16	8.3E+14	1.0E+15	7.6E+14	4.1E+13	1.2E+12	2.5E+15	2.5E+16
730	2.4E+11	1.6E+11	6.6E+14	2.4E+14	1.6E+15	5.2E+13	1.3E+12	2.5E+11	2.0E+14	2.7E+15
740	2.0E+13	6.9E+11	1.9E+16	2.7E+15	1.1E+15	1.2E+14	6.4E+12	5.8E+11	5.9E+14	2.3E+16
750	1.3E+12	1.2E+12	1.8E+15	3.6E+14	6.0E+14	5.0E+13	2.5E+12	2.4E+11	1.9E+14	3.0E+15
Total	6.9E+13	2.8E+13	8.7E+16	1.5E+16	1.5E+16	2.2E+15	8.8E+13	7.1E+12	6.0E+15	1.3E+17

Table 6.3.13 shows the fecal coliform bacteria load delivered to the intakes. The delivered load is calculated from the ratio of inflow loads to outflow loads for each main channel reach. The delivery ratio for a segment is the product of the ratio of inflow to outflow loads from segments downstream of segment. Table 6.3.14 shows the ratio of inflow to outflow loads for each segment, and the segment delivery ratio. The inflow-to-outflow ratio is a function of the main channel decay rate and the residence time of flow in the reach.

Table 6.3.14 Inflow-to-outflow ratios and delivery ratios

Segment	Inflow-to-Outflow Ratio	Delivery Ratio
160	0.79	0.06
170	0.48	0.04
175	0.62	0.08
180	0.63	0.32
190	0.54	0.12
200	0.70	0.22
210	0.83	0.42
220	0.51	0.51
730	0.79	0.10
740	0.41	0.13
750	0.86	0.36

The model predicts a perhaps unrealistically large delivered load from Point of Rocks; nevertheless, some broad conclusions can be drawn from an analysis of the delivered loads. The bulk of the simulated delivered fecal coliform, about 98% of the total load, is from runoff. Two-thirds of the load is from runoff from pasture. The largest sources of fecal coliform bacteria are from agricultural land in the Piedmont and Middle Potomac, Segments 220, 210, 750, 180, and 740. Under base flow conditions, on an annual basis, cattle in stream are the largest source of fecal coliform bacteria seen at the intakes. The largest source of these bacteria is in the Lower Potomac, but the second largest source is in the South Fork of the Shenandoah. The North Fork and mainstem of the Shenandoah (200) and the Monocacy (210) are also large sources. Human sources, point sources, failing septic systems, and urban runoff (which also contains bacteria from pets and wildlife)--delivers only 5% of the fecal coliform bacteria seen at the intakes. Almost all of this load comes from urban runoff. The largest sources of fecal coliform bacteria from septic systems are in the Lower Potomac and the Moncacy. These may be significant contributors to low-flow loads during the winter months, when cattle are not spending much time in streams. In general forests are a not significant source of fecal coliform bacteria. Geese and other wildfowl in the Lower Potomac and Monocacy may be a significant source of fecal bacteria at the intakes in the winter months.

6.3.6 Susceptibility of Source Water Supply to Pathogen Pollution

Fecal coliform bacteria are indicator organisms. Their natural habitat is the digestive system of warm-blooded animals. They are found in water primarily when fecal waste is transported there. Fecal coliforms are used to detect the presence of fecal material but they themselves are not pathogenic. There is some controversy whether fecal coliform bacteria are the best indicators of water-borne pathogens. The EPA currently recommends using *E. coli* and enterococci bacteria as indicators of pathogens, because they have been better correlated with incidences of wateborne illnesses (U.S. EPA, 2001). Nevertheless, the Fecal Coliform Model, by simulating the connection between the sources of fecal material and observed fecal coliform concentrations, provides a framework for analyzing the susceptibility of D. C.'s source water supply to water-borne pathogens.

Table 6.3.15 provides a list of pathogens, the diseases they cause, their symptoms, the species, which are potential sources, and the per capita generation rate from infected individuals. Water-borne pathogens can be divided into three classes: bacteria, viruses, and protozoans. The susceptibility of D. C.'s source water to each class of pathogen contamination can be evaluated by comparing the source of the pathogens and their die-off rate in transport to the source and die-off rate of fecal coliforms. In general, pathogens can be distinguished by whether they are specific to people or found in cattle or other animals, and whether their die-off rate in the aquatic environment is less than or great than that or fecal coliform bacteria. The first factor determines which type of source is an important potential source for the pathogen. The second factor determines whether areas of the basin are potentially relatively important sources of the pathogen. If a pathogen's decay rate is comparable to the coliform decay rate, areas in the Piedmont and the Middle Potomac region will be more important sources that the rest of the basin. If the pathogen's die-off rate is smaller, the geographic location of the source will be less important in determining the susceptibility of the District's source water to specific pathogens.

Table 6.3.15 Characteristics of waterborne pathogens

Pathogen	Disease	Symptoms	Sources	Infectious Dose (organisms)	Generation Rate (organisms/day)
		Bacteria			
Escherichia coli (pathogenic)	Gastroenteritis	Vomiting, diarrhea	humans, cattle		
Salmonella typhi	Typhoid fever	High fever, diarrhea, intestinal ulcertion	humans	$>10^3$	$10^4 – 10^{10}$
Salmonella	Salmonellosis	Diarrhea, dehydration	animals, humans		
Shigella	Shigellosis	Bacillary disentery	humans	$>10^3$	$10^8 – 10^{10}$
Vibrio chorerae	Chlolera	Heavy diarrhea, dehydration	humans	10^2 -10^8	$10^8 – 10^9$
Yersinia enterolitica	Yersinosis	Diarrhea	humans, animals		
		Viruses			
Adenovirus	Respiratory disease	Various effects	humans		
Enterovirus	heart disease, meningitis, gastroenteritis	Various effects	humans	<50	$10^8 – 10^9$
Hepatitis A	Infectious hepatitis	Jaundice, fever	humans	<50	$10^8 – 10^{10}$
Reovirus	Gastroenteritis	Vomiting, diarrhea	humans		
Rotavirus	Gastroenteritis	Vomiting, diarrhea	humans	< 50	10^{11} -10^{12}
Calicivirus	Gastroenteritis	Vomiting, diarrhea	humans		
Astrovirus	Gastroenteritis	Vomiting, diarrhea	humans		
		Protozoans			
Cryptosporidium	Crytpsporidiosis	Diarrhea, possibly death	humans, animals		
Entamoeba histolytica	Amoebic dysentery	chronic diarrhea, abscesses of liver and intestine	humans		
Giardia lamblia	Giardiasis	diarrhea, nausea, indigetion	humans, animals	<50	10^5

Sources: Battigelli, 2002; Moe, 2002

6.3.6.1 Bacteria

Pathogenic bacteria have die-off rates comparable to fecal coliforms. Typically, they are thought to be able to survive up to 60 days in the aquatic environment (Battigelli, 2002). Thomann and Mueller report, for example, that the decay rate in storm water for salmonella is 1.1 /day for the first three days and 0.1/day thereafter (U.S. EPA, 2001). Thus the Piedmont and Middle Potomac Region are more likely to have a potential impact on susceptibility. For those bacteria found in both humans and animals, such as *salmonella* and *escherichia coli*, runoff from pasture and feedlots are likely to be the dominant source of bacteria during high-flow conditions, and the in-stream deposition of waste by cattle is likely to be the dominant source during low-flow conditions. For those bacteria found only in humans, runoff from urban areas in the Lower Potomac and failing septic systems in the Lower Potomac and the Monocacy are likely to be the most important potential sources of contamination.

6.3.6.2 Viruses

Viruses have low reported decay rates and are thought to be able to survive up to five months in rivers and streams (Battigelli, 2002). Since infections can occur by ingesting only a few organisms, dilution also plays less of a factor in reducing the risk of infection, and potential sources in the basin shouldn't be distinguished solely by their location. Since humans are the primary source of viruses, the largest human sources, without regard to decay or travel time, pose the greatest potential risk. CSOs and SSOs in the North Potomac are an important potential source of viral pathogens, as well as stormwater runoff from developed areas in the Monocacy, Lower Potomac, and the South Fork of the Shenandoah.

6.3.6.3 Protozoa

Giardia and *cryptosporidium* are increasingly recognized as posing a risk to water supplies, in part due to the fact that they transported from host to host as cysts that are able to resist treatment by chlorination. Craun (1981) documented that giardiasis was the most frequently identified cause of waterborne illness in the United States in the 1970's. *Cryptosporidium* has been implicated in the outbreak of waterborne illness in major water supply systems in Milwaukee, Las Vegas, and Waterloo, Ontario. In Milwaukee there were 400,000 clinical case of cryptosporidiosis and several deaths (Sattar et al., 1999).

The factors affecting the fate and transport of *giardia* and *cryptosporidium* are not well known. U.S. EPA (2001) reports a relatively low die-off rate of 0.024/day at 15 degrees Celsius for cryptosporidium. Satter et al.(1999) tested the survival of *cryptosporidum* and *giardia* cysts in natural river water from five locations. They found a substantial die-of in *giardia* cysts after two days, but a substantial number of *cryptosporidium* cysts survived up to 30 days. The potential exists, therefore, for the transport of at least *cryptosporidium* from all reaches of the basin. Areas with high edge-of-stream loading rates for pasture and feedlot runoff, like the Conococheague and the South Fork of the Shenandoah, may contribute significantly to the susceptibility of D. C.'s source water to pathogen contamination.

6.3.7 Nutrient Reduction and Environmental Protection

Of all potential contaminants, the District of Columbia's source water is probably most susceptible to pathogens. Extensive beef and dairy cattle operations, failing septic systems, CSOs and SSOs all contribute in different ways to this susceptibility. Some of the measures promoted by Chesapeake Bay Program to reduce nutrient loads to the bay can also help reduce the potential for pathogen contamination. Better storage and handling of manure and livestock waste can reduce the number of bacteria in runoff from feedlots. The storage of animal waste, in itself, reduces the number of bacteria applied to fields. Other agricultural BMPs, like riparian buffers, may also reduce the potential for pathogen transport in runoff from crops and pasture. Perhaps more could be done to repair failing septic systems and prevent SSO and CSOs.

It was possible to use the Watershed Model and the methodology of the CBP to estimate fecal coliform loads because the sources of fecal coliform bacteria in the basin are also sources of nutrients. Programs to control nutrients also help control the potential for pathogen transport. It is important for the public to recognize that the protection of the District of Columbia's source water is not a separate problem from controlling nutrient and sediment loads to Chesapeake Bay, and that all environmental cost and benefits should be taken into account when charting the future course of environmental protection in the Potomac River Basin.

6.4. Pesticides

Pesticide contamination of surfacewaters is a major concern for the protection of human health by public drinking water utilities (Knappe et al., 1999). In the Potomac River Basin, which is the sole source of water for the District of Columbia, pesticide usage in agricultural regions has resulted in measurable concentrations of pesticides at surfacewater and groundwater monitoring stations throughout the basin (see Fisher, 1997; Ator and Ferrari, 1997; Ferrari et al., 1997; Donnelly and Ferrari, 1998; Hall, Jr. et al., 1999). In some cases, pesticide concentrations in untreated water have exceeded EPA health action levels (HALs) and/or maximum contaminant levels (MCLs).

At present, little is known regarding the potential for pesticide contamination at the intakes on the Potomac River Basin. It is generally understood that elevated concentrations of pesticides in the Potomac River Basin typically occur in pulses during the period from May through July following the application of pesticides to farm fields and residential lawns (Fisher, 1995). Furthermore, the highest concentrations are measured during periods of high streamflow following storm events (Fisher, 1995; Ferrari et al., 1997; Hyer et al., 2001). The period from May through July represents the critical period for pesticide contamination at the water intakes.

To assess the susceptibility of the District of Columbia's source water to pesticide contamination, the CBP Watershed Model was adapted to simulate the daily fate and transport of pesticides. The Watershed Model was modified to simulate the fate and transport of atrazine, a widely used herbicide, in the Potomac River Basin. The model was used to analyze what hydrologic conditions and general management practices would result in elevated pesticide concentrations at the water intakes. The analysis is described in the next four sections. The first section summarizes pesticide usage in the Potomac River Basin. The next section describes some of the general features of the fate and transport of atrazine and two other widely used pesticides, metolachlor and 2,4-D. It also summarizes the monitoring data available. The third section describes how of the Watershed Model was modified to simulate the fate and transport of atrazine. The last section uses the results of the simulation to evaluate the susceptibility of D.C.'s source water to pesticide contamination.

6.4.1 Pesticide Use in the Potomac River Basin

Pesticide use in the Potomac River Basin plays an important role in controlling unwanted organisms such as weeds and insects. Approximately 4.94 million pounds of pesticides are applied annually in the Potomac Basin for agricultural purposes (Gianessi and Puffer, 1990; 1992a-b). In 1997, agricultural pesticide use accounted for 75 percent of the total pesticide usage nationwide (Asplin and Grube, 1999). Herbicides were the most widely applied pesticides in the basin and are used to control the growth of weeds on cropland and lawns. For agricultural use, the two most frequently applied herbicides were atrazine and metolachlor (Gianessi and Puffer, 1990; 1992a-b). For nonagricultural pesticide use (e.g. lawncare), which is more difficult to quantify in terms of annual application (Donnelly and Ferrari, 1998), the most applied pesticide was 2,4-

D, another herbicide (Asplin and Grube, 1999). 2,4-D is also used on small grains and hay. Because atrazine, metolachlor, and 2,4-D represent three of the most utilized pesticides in the Potomac River Basin, they will be the focus of the susceptibility analysis.

6.4.1.1 Methods and Timing of Application for Atrazine, Metolachlor, and 2,4-D

The methods and timing of pesticide application are critical to the overall efficacy of their use. Pesticides are typically applied using one of three general methods (Scholtz and Van Heyst, 2001):

1. Soil incorporation into top 10 cm of soil
2. Spray application
3. Soil application into furrows at depths greater than 10 cm

When pesticides are applied during inappropriate weather conditions or applied in the wrong amounts, regardless of the method chosen, they are susceptible to release into the environment and may not accomplish the desired effect (U.S. Congress, 1990). Table 6.4.1 summarizes the general characteristics and recommended timing of application for atrazine, metolachlor, and 2,4-D.

Table 6.4.1: General characteristics and recommended timing of application for atrazine, metolachlor, and 2,4-D

Pesticide	Regulatory Status	Formulation	Pests Controlled	Timing of Application
Atrazine	Restricted Use	Dry flowable, flowable liquid, granular, and wettable powder	Broadleaf and Grassy Weeds	Pre-emergent[A]
Metolachlor	General Use	Emusulfiable concentrate and granular	Broadleaf and Grassy Weeds	Pre-emergent[A]
2,4-D	General Use	Emulsion, aqueous solutions, and dry flowable	Broadleaf Weeds	Pre-emergent[A] or Post-emergent[B]

Sources: EXTOXNET, 2002 and Hofstader, 2002
[A] Herbicide is applied after the crop is planted but before it emerges from the ground (Ritter et al., 2001).
[B] Herbicide is applied to the foliage of the weeds after the crop has emerged from the ground (Ritter et al. 2001).

The beginning of the growing season in the Potomac River Basin is generally during late April and early May. Because atrazine, metolachlor, and 2,4-D are usually applied prior to the emergence of crops, this represents the period during which the majority of herbicide application occurs on agricultural lands. The next critical step was to determine the typical application rates and trends for atrazine, metolachlor, and 2,4-D.

6.4.1.2 Atrazine, Metolachlor, and 2,4-D Application Rates and Trends

Information on pesticide use and trends in the Potomac River Basin can be obtained from a variety of sources. The individual states monitor pesticide application rates and report them as part of the USDA National Agricultural Statistics Service (NASS). Information on pesticide application can also be obtained from Cooperative Extension offices located within each state university system. In Maryland, the Department of Agriculture conducts surveys of pesticide users throughout the state on a triennial basis and publishes statistical summary reports on county level pesticide use. Because these sources typically vary in terms of the level of information that can be obtained, three major sources were consulted to summarize information of pesticide application rates and trends for the Potomac River Basin. The sources used were the Chesapeake Bay Program, the United States Geological Survey (USGS), and the National Center for Food and Agricultural Policy (NCFAP).

Tables 6.4.2 through 6.4.5 show statewide (PA, WV, MD, and VA) pesticide use information for atrazine, metolachlor, and 2,4-D organized by type of crop. This information is summarized from the NCFAP Pesticide Use Database (NCFAP, 2001), which is a national database for pesticide use on cropland. The database was compiled using surveys of farmers and expert opinions from cooperative extension service specialists. The USDA, EPA, and USGS have used the database extensively to conduct analytical studies concerning trends in pesticide use and regulation. For some states, this database represents the only available statewide information on pesticide use.

Table 6.4.2: 1997 pesticide use in crop production in Pennsylvania

Pesticide	Crop	Acres Planted	% Acres Treated	Application Rate (lbs/acre AI*)	Acres Treated	Amount Applied (lbs AI*)
Atrazine	Corn	1,455,846	91	1.14	1,324,820	1,510,295
	Sweet Corn	18,318	20	1.00	3,664	3,664
Metolachlor	Cabbage	1,577	40	1.50	631	946
	Corn	1,455,846	57	1.57	829,832	1,302,837
	Grn. Beans	7,458	60	1.50	4,475	6,712
	Potatoes	12,597	80	2.16	10,078	21,768
	Soybeans	347,981	50	2.43	173,990	422,797
	Sweet Corn	18,318	80	1.50	14,654	21,982
	Sw. Peppers	953	40	1.50	381	572
	Tomatoes	4,328	25	1.50	1,082	1,623
2,4-D	Apples	32,903	45	1.40	14,806	20,729
	Barley	63,782	15	0.30	9,567	2,870
	Cherries	1,587	25	1.49	397	591
	Corn	1,455,846	11	0.40	160,143	64,057
	Oats	144,456	30	0.43	43,337	18,635
	Pasture	1,259,965	8	0.50	100,797	50,399
	Peaches	5,851	16	1.54	936	1,442
	Pears	946	6	2.01	57	114
	Rye	7,308	5	0.50	365	183
	Seed Crops	3,813	10	0.50	381	191
	Soybeans	347,981	7	0.50	24,359	12,179
	Strawberries	1,409	50	1.20	704	845
	Wheat	167,488	20	0.25	33,498	8,374

*AI = Active Ingredient

Table 6.4.3: 1997 pesticide use in crop production in West Virginia

Pesticide	Crop	Acres Planted	% Acres Treated	Application Rate (lbs/acre AI*)	Acres Treated	Amount Applied (lbs AI*)
Atrazine	Corn	63,141	85	1.25	53,670	67,087
	Sweet Corn	874	50	1.10	437	481
Metolachlor	Corn	63,141	65	2.00	41,042	82,083
	Soybeans	13,132	31	1.75	4,071	7,124
	Sweet Corn	874	70	1.40	612	857
2,4-D	Apples	10,362	42	1.50	4,352	6,528
	Barley	1,577	15	0.30	237	71
	Corn	63,141	10	0.30	6,314	1,894
	Oats	2,720	5	0.46	136	63
	Other Hay	470,644	7	0.62	32,945	20,426
	Pasture	1,666,124	2	0.62	33,322	20,660
	Peaches	1,516	20	1.50	303	455
	Wheat	7,620	40	0.25	3,048	762

*AI = Active Ingredient

Table 6.4.4: 1997 pesticide use in crop production in Maryland

Pesticide	Crop	Acres Planted	% Acres Treated	Application Rate (lbs/acre AI*)	Acres Treated	Amount Applied (lbs AI*)
Atrazine	Corn	498,568	85	1.25	423,783	529,728
	Sweet Corn	11,332	50	1.10	5,666	6,233
Metolachlor	Corn	498,568	65	2.00	324,069	648,138
	Grn. Beans	6,350	70	1.25	4,445	5,556
	Green Peas	3,130	29	1.19	908	1,080
	Potatoes	2,219	80	2.20	1,775	3,905
	Soybeans	509,683	45	1.75	229,357	401,375
	Spinach	966	10	0.75	97	72
	Sweet Corn	11,332	70	1.40	7,932	11,105
	Tomatoes	1,969	25	1.50	492	738
2,4-D	Apples	3,221	50	1.20	1,610	1,933
	Barley	47,405	10	0.25	4,740	1,185
	Corn	498,568	10	0.25	49,857	12,464
	Oats	5,611	10	0.25	561	140
	Other Hay	168,877	10	1.00	16,888	16,888
	Pasture	287,215	20	1.00	57,443	57,443
	Peaches	1,328	34	1.06	452	479
	Sod	4,048	100	0.88	4,048	3,562
	Strawberries	369	50	1.20	184	221
	Sweet Corn	11,332	1	0.60	113	68
	Wheat	199,351	10	0.25	19,935	4,984

*AI = Active Ingredient

Table 6.4.5: 1997 pesticide use in crop production in Virginia

Pesticide	Crop	Acres Planted	% Acres Treated	Application Rate (lbs/acre AI*)	Acres Treated	Amount Applied (lbs AI*)
Atrazine	Corn	461,424	95	1.40	438,353	613,694
	Sweet Corn	2,790	50	1.10	1,395	1,535
Metolachlor	Corn	461,424	40	1.00	184,570	184,570
	Cotton	98,244	1	0.75	982	737
	Green Beans	5,441	87	1.25	4,734	5,917
	Peanuts	74,687	65	2.50	48,547	121,366
	Potatoes	5,925	36	1.50	2,133	3,200
	Soybeans	487,001	31	1.75	150,970	264,198
	Sweet Corn	2,790	70	1.40	1,953	2,734
	Tomatoes	3,822	6	0.94	229	216
	Watermelons	1,839	10	0.94	184	173
2,4-D	Apples	22,886	20	1.50	4,577	6,866
	Barley	51,096	20	0.50	10,219	5,110
	Corn	461,424	20	0.40	92,285	36,914
	Oats	5,216	5	0.46	261	120
	Other Hay	1,077,455	7	0.62	75,422	46,762
	Pasture	3,186,225	15	0.50	477,934	238,967
	Peaches	2,223	20	1.50	445	667
	Soybeans	487,001	5	0.30	24,350	7,305
	Strawberries	503	14	1.20	70	85
	Wheat	257,063	40	0.25	102,825	25,706

*AI = Active Ingredient

From the information presented in the tables, it is clear that for all states in the Potomac River Basin, atrazine is used exclusively on corn and sweet corn. Metolachlor is used primarily for soybeans and corn and then is also used on a variety of vegetable crops in smaller amounts. 2,4-D is applied to primarily to pasture and hay lands as well as to wheat and small grain crops. 2,4-D is also applied to various fruit crops, especially to apples. Maryland's county-level survey of pesticide applications confirms the prevalence of the metolachlor and atrazine use in the counties in the Potomac River Basin (MD Dept of Agriculture, 1999). 2,4-D was the most heavily applied pesticide in Montgomery County, where D. C. 's water supply intakes are located.

While the statewide information was useful in determining the types of crops that received the most pesticides, a summary of pesticide use for the Potomac drainage basin was also helpful. A study by the USGS used information from the NCFAP database to summarize pesticide usage for its National Water Quality Assessment (NAWQA) program. The Potomac River Basin was one of the study units in NAWQA and the information is presented below for summary purposes (Table 6.4.6).

Table 6.4.6: Pesticide usage information for the Potomac River Basin

Pesticide	Rank in Herbicide Usage	Amount Applied (lbs AI*)	Area Treated (Acres)	Application Rate (lbs/acre AI*)	% of Reported Use in Basin
Metolachlor	1	417,324	220,804	1.89	9.68
Atrazine	2	377,874	279,091	1.35	8.77
2,4-D	4	161,023	274,636	0.59	3.74

*AI = Active Ingredient
Source: Thelin and Gianessi, 2000

The prevalence of atrazine, metolachlor, and 2,4-D application is supported by a study of pesticide usage conducted by the Chesapeake Bay Basin Toxics Loading and Release Inventory (CBP, 1999). Metolachlor and atrazine were ranked first and second in their estimate of 1996 pesticide usage in the Chesapake Bay Basin. 2,4-D was less widely applied, but was the most heavily applied pesticide to small grains. In addition to summarizing application rates for atrazine, metolachlor, and 2,4-D, historical trends in pesticide use from 1990 to 1996 were reviewed to determine the factors that control their use and application. Pesticide usage was variable from year to year and showed no detectable trends. The primary controlling factors in pesticide use were weather, the amount of pest pressure, product availability, price, and regulatory concerns (Maurer, 1999).

6.4.2 Pesticides and Drinking Water Quality in the Potomac River Basin

The application of atrazine, metolachlor, and 2,4-D on agricultural lands in the Potomac River Basin is important to control weeds and to improve supply of agricultural goods. However, when these chemicals are applied to the ground, they can meet a variety of fates, one of which is transport into streams and rivers that may be used for drinking water supply. This section presents an overview of the fate and transport of atrazine, metolachlor, and 2,4-D in surface and groundwater. Upon understanding how these chemicals can be transported to streams and rivers in the Potomac River Basin, a summary of water quality monitoring data is then presented to characterize where, how much (e.g. concentrations and loads), and how often these pesticides are detected throughout the Potomac River Basin.

6.4.2.1 Fate and Transport of Atrazine, Metolachlor, and 2,4-D

A suite of factors controls the fate and transport of atrazine, metolachlor, and 2,4-D. The factors are affected by the individual properties of each pesticide as well as the site characteristics (soil type, climate, management practices, etc.) into which the pesticide was introduced. Pesticide properties are the most important for the determination of risk to surface and groundwater supplies and are listed below (Trautmann and Porter, 1998):

1. Solubility in water
2. Volatilization to the atmosphere

3. Adsorption to soils
4. Degradation into chemical daughter products

Solubility in water is important because pesticides that are highly soluble are more likely to be transported by surface runoff or infiltration. Volatilization measures the tendency of a compound to become a gas. At higher vapor pressures, pesticides are lost to the atmosphere, meaning that less pesticide remains available for leaching and transport by runoff, though volatilized pesticides can be transported to surfacewater.

Soil adsorption determines a how strongly a pesticide will adhere to soil particles. It is characterized using two different parameters. The first is called the adsorption partition coefficient (K_d), which is the ratio of the pesticide concentration in the adsorbed phase to that in solution. Partition coefficients for soils are a function of the percent organic matter in the soil by weight. The second parameter, the organic carbon partition coefficient (K_{oc}), gives the partition coefficient between the pesticide and organic carbon. Generally, the K_d of a soil for a pesticide is the product of K_{oc} and the fraction of organic matter in the soil. The organic carbon partition coefficient thus gives a soil-independent method for characterizing a pesticide's sorption to soil.

The degradation of a pesticide determines the rate of chemical breakdown. The longer it takes a pesticide to breakdown, the longer it can remain available for leaching and transport by runoff. Pesticides are broken down via photolysis (exposure to sunlight), hydrolysis (reaction with water), and oxidation (chemical and biological reactions in soil). The most common measure of pesticide degradation is field dissipation half-life, which determines empirically the amount of time it takes for half of the pesticide to disappear. The value for half-life takes into account physical, chemical, and biological degradation, but it can vary greatly due to soil conditions, climatic factors, and the types of organisms present in the soil (Trautmann and Porter, 1998). Typical ranges for solubility, vapor pressure, adsorption, and degradation are presented in Table 6.4.7. An indication of the relative persistence of each pesticide is also given. The longer the half-life of a pesticide, the more persistent it is (Rao and Hornsby, 1989).

Table 6.4.7: Chemical properties and relative persistence of atrazine, metolachlor, and 2,4-D

Pesticide	Water Solubility (mg/L at 20°C)	Vapor Pressure (mm Hg at 20°C)	K_{oc} (mL/g)	Field Half-Life (days)	Persistence
Atrazine	33[A]	2.89 x 10-7[A]	100[A]	60[A]	Mod. Persistent[C]
Metolachlor	530[B]		200[B]	120[C]	Persistent[C]
2,4-D	890[A]	8.00 x 10-6[A]	20[A]	10[A]	Nonpersistent[C]

[A]Source: Agricultural Research Service, 1995
[B]Source: EXTOXNET, 2002
[C]Source: National Research Council, 1993

From the table, it is evident that atrazine, metolachlor, and 2,4-D behave very differently once exposed to the environment. Metolachlor is the most persistent of the three pesticides, has the longest half-life, and also sorbs the most strongly to soil particles. 2,4-D is the least persistent, has the shortest half-life, and does not adsorb very strongly to soils. The method of application must also be taken into account because 2,4-D is

frequently applied in an emulsification, which increases binding to the soil and reduces the risk of transport in runoff.
The transport of pesticides in surfacewater is the primary potential pathway for pesticide contamination at the intakes on the Potomac River. Transport of herbicides into surfacewater typically occurs within a critical period of about 2 to 6 weeks after application and is maximized during storm events that follow application (Ng and Clegg, 1996). Herbicides are transported to surfacewater in runoff or overland flow and in interflow or soil-water flow (Ng and Clegg, 1996; Hyer et al., 2001). Pesticide properties play an important role in determining the type of transport that occurs. Ng and Clegg (1996) found that atrazine was much more likely to be transported in surface runoff as compared to metolachlor, due to the fact that atrazine had a lower adsorption coefficient. Conversely, the loss of metolachlor was found to be dominated by soil-water transport and thus resulted in higher stream baseflow concentrations. This was also due to the differences in adsorption coefficient for metolachlor and atrazine. 2,4-D, which was not addressed in either study, has the lowest adsorption coefficient and therefore would be most likely dominated by surface transport mechanisms.

6.4.2.2 EPA Drinking Water Standards for Atrazine, Metolachlor, and 2,4-D

The use of pesticides and their subsequent transport into the Potomac River Basin presents a contamination risk to drinking water supplies. The EPA has set maximum contaminant levels (MCLs) and health action levels (HALs) for atrazine, metolachlor, and 2,4-D for a variety of health risks that are possible when exposed to elevated concentrations of these pesticides over a period of time. Table 6.4.8 presents the EPA MCLs and HALs as well as potential human health effects due to pesticide exposure. The values in the table will be important reference points throughout the remainder of the chapter when comparing historical water quality monitoring data as well as model output for the risk analysis.

Table 6.4.8: EPA MCLs and HALs for atrazine, metolachlor, and 2,4-D

Pesticide	MCL (µg/L)	HAL (µg/L)	Potential Health Effects
Atrazine	3[A]	3[B]	Cardiovascular system or reproductive problems, Suspected carcinogen[A]
Metolachlor	None	100[B]	Kidney or liver problems, Suspected carcinogen[C]
2,4-D	70[A]	70[B]	Kidney, liver, or adrenal gland problems[A]

[A]Source: EPA, 2001
[B]Source: van Es and Trautmann, 1990
[C]Source: EPA, 1995

If concentrations of pesticides exceed the established MCL values for finished drinking water for a period of 4 consecutive days, then the Safe Drinking Water Act mandates that water utilities must either actively treat the water to reduce the concentrations or find an alternate water supply (Sutton, 1997). If pesticide contamination is detected at a water treatment plant and the episode lasts for a series of days, several treatment options are available. Removal of pesticides at water treatment plants is typically

accomplished through the use of granular activated carbon (GAC), powdered activated carbon (PAC), or reverse osmosis (Knappe et al., 1999).
The treatment plants operated by WSSC and WAD use PAC to remove pesticides when concentrations become elevated (O'Melia, 2002). The current operating rule is to begin treating the water with PAC upon notification that pesticide concentrations are above the drinking water standards in raw water (Brown, 2002).

6.4.2.3 Water Quality Monitoring for Atrazine, Metolachlor, and 2,4-D

Monitoring for pesticides in surfacewater and groundwater has been conducted throughout the Potomac River Basin to determine the extent of pesticide occurrence in surfacewater and groundwater resources. The USGS conducted the most extensive monitoring as part of its NAWQA program. Four studies were published by the USGS using data from NAWQA to characterize the occurrence of pesticides in the Potomac River Basin. The results from the studies stated that atrazine and metolachlor were the two most detected pesticides in surfacewater and groundwater samples (Fisher, 1995; Ator and Ferrari, 1997; Ferrari et al., 1997; Donnelly and Ferrari, 1998). Atrazine was detected in 88 percent of the samples analyzed and metolachlor was detected in 85 percent of the samples. The maximum reported concentration of atrazine was 25 µg/l; the 90th percentile concentration was 0.730 µg/l. For metolachlor, the maximum and 90th percentile concentrations were 23 and 0.990 µg/l, respectively. 2,4-D was detected less frequently. Only 20 percent of the samples analyzed had detectable concentrations. The maximum observed concentration was 2.8 µg/l and the 90th percentile concentration was 0.34 µg/l.

Table 6.4.9 shows the minimum, median, and maximum concentrations of atrazine, metolachlor, and 2,4-D observed at key monitoring stations in the Potomac River Basin during the USGS NAWQA study from 1993-1996. The highest concentrations occurred in the heavily agricultural upper Monocacy watershed, where concentrations of atrazine and metolachlor above 1 ug/l were not uncommon. Values of both these pesticides above 20 ug/l were observed. Three atrazine observations on Conococheague Creek were above the 3 ug/l MCL. Two of those occurred during the same storm in June 1996. Of 11 atrazine samples collected by the USGS at Chain Bridge between 1994 and 1996, two samples, both in June 1996, had concentrations above 3 µg/L. The maximum observed concentration was 4.1 µg/l and the median value was 0.039 µg/l.

Table 6.4.10 summarizes the data from a NAWQA study, which attempted to characterize geographically the prevalence of pesticides in surface waters in the Potomac River Basin. Twenty-three streams were sampled for pesticides during June 5 through 16, 1994. The table shows that atrazine and metolachlor were detected throughout the Potomac River Basin, though at concentrations that were typically less than the MCLs and/or HALs for both pesticides.

Table 6.4.9 Summary of Observed Pesticide Concentrations from the USGS NAQWA Study, 1993-1996 (concentrations in µg/l)

Pesticide		**South Branch**	***Conococheague***	**Shenandoah**	**Monocacy at Bridgeport**	**Chain Bridge**
Atrazine	Minimum	.007	.27	.014	.001	.032
	Median	.0085	.66	.064	.21	.28
	Maximum	.012	7.5	1.0	25.0	4.1
Metolochlor	Minimum	.001	.022	.014	.002	.031
	Median	.005	.515	.059	.31	.28
	Maximum	.006	4.1	.4	23.0	2.7
2,4-D	Minimum	No Data	.035	.035	.035	.035
	Median			.035	.035	
	Maximum			.11	2.8	

Table 6.4.10: Summary of surfacewater atrazine and metolachlor concentrations in the Potomac River Basin, June 5-16 1994

USGS Station Name	Drainage Area	Land Use (percent)			Flow (cfs)	Concentration (µg/L)	
		Forest	Agriculture	Urban		Atrazine	Metolachlor
N.Br. Potomac River at Pinto, MD	596	83	12	2	435	< 0.017	< 0.009
N.Br. Potomac River near Cumberland, MD	875	82	13	3	590	< 0.017	< 0.009
S.Br. Potomac River near Petersburg, WV	642	79	21	0	226	< 0.017	< 0.009
S.Fk. S.Br. Potomac River near Moorefield, WV	283	85	14	<1	52	< 0.017	< 0.009
S.Br. Potomac River near Springfield, WV	1,480	78	22	<1	435	< 0.017	< 0.009
Cacapon River near Great Cacapon, WV	677	82	18	<1	219	< 0.017	< 0.009
Conococheague Creek at Fairview, MD	494	36	60	4	342	0.730	0.600
Opequon Creek near Martinsburg, WV	272	24	70	6	165	0.190	0.078
Antietam Creek near Sharpsburg, MD	281	24	69	7	302	0.300	0.088
North River at Burketown, VA	379	59	34	7	154	0.094	0.028
Middle River near Grottoes, VA	375	31	60	8	163	0.049	0.015
South River at Harriston, VA	212	59	30	11	104	0.028	< 0.009
S.Fk. Shenandoah River near Luray, VA	1,377	50	42	8	640	0.069	0.023
S.Fk. Shenandoah River at Front Royal, VA	1,642	51	40	8	776	0.078	0.033
N.Fk. Shenandoah River at Mt. Jackson, VA	506	55	40	5	170	0.140	0.290
N.Fk. Shenandoah River near Strasburg, VA	768	54	40	6	297	0.065	0.086
Shenandoah River at Millville, WV	3,040	51	41	7	1,350	0.150	0.300
Catoctin Creek at Olive, MD	112	26	71	2	38	0.230	0.060
Catoctin Creek at Taylorstown, VA	90	18	81	1	24	0.120	0.150
Monocacy River at Bridgeport, MD	173	20	78	2	31	0.570	0.700
Monocacy River near Frederick, MD	817	23	73	3	312	0.510	< 0.009

Source: Fisher, 1995

6.4.3 Development and Validation of the Atrazine Pesticide Model

To help determine the susceptibility of the District of Columbia's source water supply to pesticide contamination, the Watershed Model was modified to represent the fate and transport of atrazine. The primary purpose of this model, hereafter referred to as the Pesticide Model, was to help quantify the risk posed by atrazine applications if they are applied under adverse hydrological conditions. Because atrazine is primarily transported to surface water in runoff, the risk of atrazine transport is increased if there is a storm following an application with surface runoff. The best time to apply atrazine is before a gentle rain with little runoff, so that the atrazine infiltrates into the soil.

The Base Case Scenario of the model represents the recommended timing of atrazine applications. It assumes that on a basin-wide scale, applicators apply atrazine under favorable conditions. The model was parameterized and, to a certain extent, calibrated so that the results of the base case scenario matched the observed data, the underlying assumption being that for the most part, applicators apply atrazine at the proper time. The observed data does not always support this assumption. Subsequent scenarios were used to determine the risk posed by applying atrazine under adverse conditions, when a significant amount of the applied atrazine is transported in runoff.

6.4.3.1 Model Development

HSPF has a special module, PEST, for representing the fate and transport of pesticides on pervious surfaces like cropland. PEST simulates the partitioning of the pesticide between soil and pore water, the decay of a pesticide in the soil, and its transport in runoff, infiltration, interflow, and ground water discharge. Only the transport of atrazine in runoff was simulated in the Pesticide Model. The GQUAL module, which can represent the fate and transport of almost any constituent, was used to simulate the fate and transport of atrazine in river reaches. The only in-stream processes represented in the Pesticide Model are first-order decay and partitioning between sediment and the water column.

The model was parameterized using values from documentation of the modeling performed by the U.S. EPA's Office of Pesticides for the proposed reregistration of atrazine (U.S. EPA, 2001b). Table 6.4.11 gives the parameter values.

Table 6.4.11 Important parameter descriptions and values used in the pesticide model

Parameter	Description	Units	Value
CMAX	Maximum dissolved concentration	μg/L	33.0
K1	First order partition coefficient	L/mg	1.3
SDGCON	Aerobic soil decay rate	Day^{-1}	4.75 E-3
UDGCON	Aerobic soil decay rate	Day^{-1}	4.75 E-3
LDGCON	Anaerobic soil decay rate	Day^{-1}	4.36 E-3
ADGCON	Anaerobic soil decay rate	Day^{-1}	4.36 E-3
FSTDEC	First order instream decay rate	Day^{-1}	2.44 E-3
ADPM(1,1)	Partition coefficient for suspended sand	L/mg	7.82 E-6
ADPM(2,1)	Partition coefficient for suspended silt	L/mg	1.756 E-6
ADPM(3,1)	Partition coefficient for suspended clay	L/mg	4.389 E-6
ADPM(4,1)	Partition coefficient for bed sand	L/mg	7.82 E-6
ADPM(5,1)	Partition coefficient for bed silt	L/mg	1.756 E-6
ADPM(6,1)	Partition coefficient for bed clay	L/mg	4.389 E-6

6.4.3.2 Input Loads

An atrazine loading rate of 1.1 pounds per acre was applied on 90 percent of all corn acreage in the basin. This application rate falls within the range of application rates cited in Tables 6.4.2 through 6.4.6 and was also approved by Randy Shenk (2002) of Virginia Department of Agriculture and Rob Hofstader (2002) of the Maryland Department of Agriculture. Table 6.4.12 shows the number of corn acres by modeling segment for the Potomac portion of the Watershed Model. Soybean and grain (sorghum, wheat, oats, and barley) acres are also presented for reference purposes because they receive applications of metolachlor and 2,4-D.

Table 6.4.12: Cropland, corn, soybeans, and grain acres in the Potomac River model segments

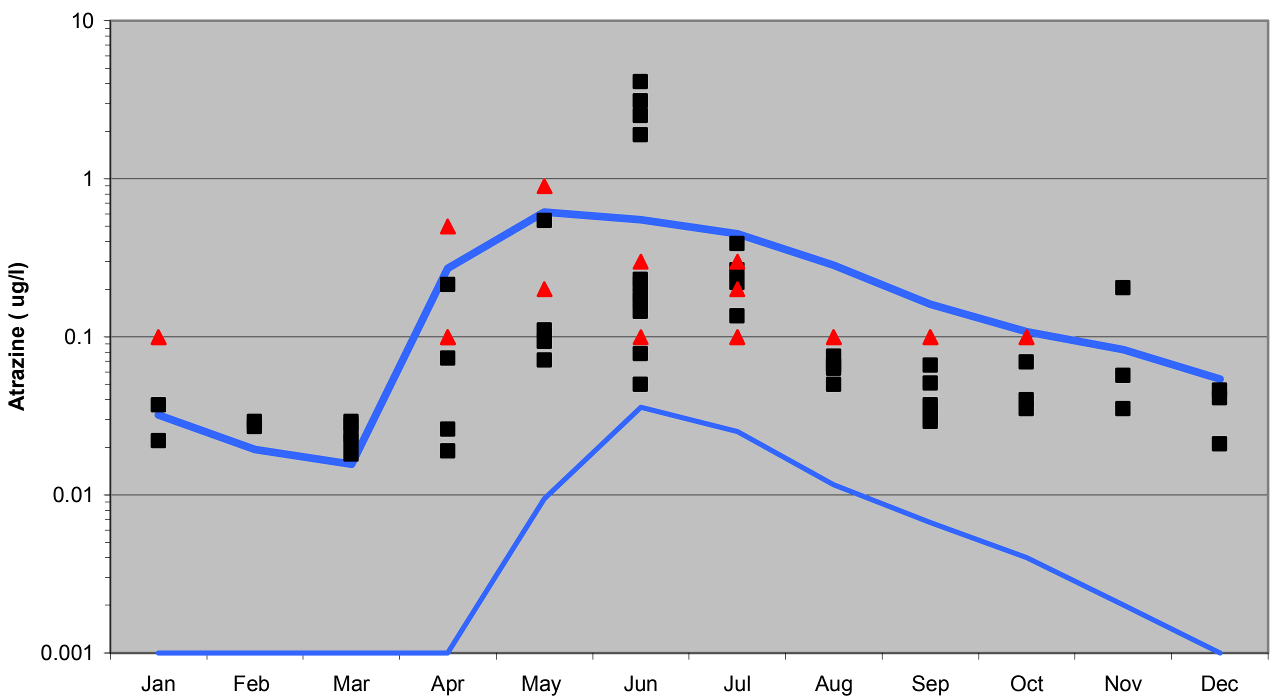
River Reach	Segment	Cropland (acres)	Corn (Acres)	Soybeans (Acres)	Grain (Acres)
Upper Potomac River	160	21,807	8,105	0	1,912
	170	14,719	7,557	0	510
	175	20,702	9,726	153	1,959
Shenandoah River	190	65,912	22,895	2,397	3,729
	200	61,176	20,902	3,798	5,214
Middle Potomac River	180	86,724	32,653	10,275	15,420
	730	77,810	46,145	67	8,428
	740	78,296	31,118	3,299	12,584
Lower Potomac River	210	121,654	40,607	26,246	24,572
	220	72,305	18,977	14,329	10,589
	750	26,970	10,803	1,037	5,204

The base run of the Pesticide Model is supposed to represent the suggested application procedures recommended by agricultural extension experts. Atrazine was applied just prior to the growing season during the months of April and May. Three application dates per model segment were chosen on days with a low ratio of runoff to rainfall and the application rate was divided evenly among them. Thus, atrazine was applied during “good” days when losses due to surface runoff would be minimized.

6.4.3.3 Model Calibration

Simulated atrazine concentrations from the Lower Potomac (220) were compared with the range of concentrations observed by the USGS at Chain Bridge and by WAD in their finished water. The HSPF model parameter representing the depth of the surface layer was adjusted until there was reasonable agreement with the range of observed concentrations on a monthly basis. Figure 6.4.1 shows the observed concentrations and the monthly maximum and minimum simulated concentrations. Overall, the base case model captures the seasonal range of values quite well. About 85% of the observed values lie between the maximum and minimum simulated values. The base case model tends to underpredict the range of observed winter values, when concentrations are low.

Figure 6.4.1 Monthly Range of Simulated Base Case Atrazine Concentrations vs. Observed Concentrations at Chain Bridge and Delcarlia Reservior



Black Squares: Atrazine Concentrations observed by USGS at Chain Bridge 1993-2000.
Red Triangles: Atrazine Concentrations observed by WAD in Delcarlia Reservoir 1995-2001.
Blue Lines: Monthly minimum and maximum simulated atrazine concentrations for Pesticide Model Base Case Scenario.

It is important to recognize that the Base Case Scenario does not represent actual conditions: to simulate actual conditions, the actual application dates for atrazine would have to be known basin-wide. Several observed values lie above the maximum range of the base case model. In particular, there are four observations above 1 µg/l in June, two of which are above the MLC of 3 µg/l. These observations all occurred in 1996 over a period of four days during a large storm event. They indicate that a significant amount of atrazine can be washed into the Potomac by runoff and probably represent the impact of atrazine applied under hydrologically unfavorable conditions.

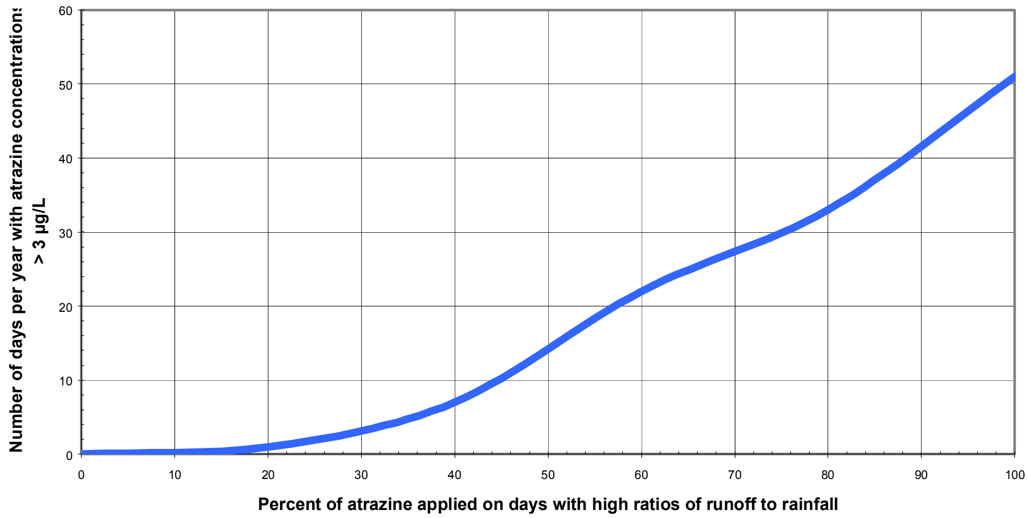
6.4.3.4 Risk Assessment Scenarios

To estimate the risk of atrazine contamination at the intakes, five scenarios were run, each increasing the amount of atrazine applied under hydrologically unfavorable conditions. For each model segment, dates with high runoff to rainfall ratios were chosen. Atrazine application rates on those dates were increased by the following amounts:

1. 20 percent applied on a date with high runoff
2. 40 percent applied on a date with high runoff
3. 60 percent applied on a date with high runoff
4. 80 percent applied on a date with high runoff
5. 100 percent applied on a date with high runoff

Thus, a determination could be made about the risk of atrazine contamination at the intakes given poor pesticide application and the influence of hydrological events in the Potomac River Basin. The results of the risk assessment scenarios are summarized in Figure 6.4.2. The figure illustrates both the hydrological and the management implications of poor pesticide application and what impact that would have at the surfacewater intakes near [REDACTED]. If 20 percent of the pesticide users in the Potomac River Basin applied atrazine on days with runoff, there would be only about one or two days per year with atrazine concentrations greater than the MCL of 3 µg/L at Chain Bridge. If 50 percent of pesticide users applied on days with high runoff, then anywhere from 10 to 15 days may have atrazine concentrations higher than 3 µg/L. In the unlikely event that 100 percent of pesticide users in the basin applied atrazine on days with high runoff, then about 50 days of atrazine concentrations greater than 3 µg/L could be expected. This represents the “worst case” scenario.

Figure 6.4.2: Number of days per year with atrazine concentrations greater than 3 µg/L versus the percent of atrazine applied on days with high ratios of runoff to rainfall.



The results of this analysis indicate that the risk of atrazine contamination at the surfacewater intakes is moderately low. The risk is not zero, but it is not likely that a long period of elevated atrazine concentrations would occur at the intakes.

6.4.4 Susceptibility Analysis for Pesticides

The results of the Pesticide Model simulations suggest that the risk of sustained periods when the concentration of atrazine is above its MCL, while not negligible, are moderately low. The results of the simulation can be extrapolated to metolachlor by comparing the characteristics of the two pesticides. Metolachlor partitions more strongly on the soil and decays more slowly in the soil than atrazine. For equal application rates, concentrations of metolachlor should be initially lower, but more persistent, than atrazine concentrations. Metolachlor application rates tend to be higher than that of atrazine, but its HAL is over 30 times larger than that of atrazine. Therefore the chances of observing sustained concentrations of metolachlor over its HAL are low.

Similar arguments can be used to show that the risk of sustained concentrations of 2,4-D are low. 2,4-D partitions less strongly to the soil than atrazine. The concentration of 2,4-D in runoff after application is typically higher than atrazine. 2,4-D is usually applied in an emulsion, which lowers runoff losses (North Carolina Cooperative Extension Office, 1984). Because it decays quickly in the soil, initially high concentrations in runoff would not be expected to persist. 2,4-D is applied at a lower rate than atrazine, and currently, it is applied on fewer acres than atrazine. Moreover, its HAL is more than twenty time higher than atrazine's. The chances of seeing sustained concentrations of 2,4-D over its HAL are also low.

The relatively low susceptibility of the District of Columbia's source water to pesticide contamination is due to dilution. The primary health risk from herbicides comes from chronic exposure. Sustained concentrations at the MCL or HAL are necessary before herbicides pose a health risk. The amount of herbicide applied is relatively small compared to the volume of flow in the Potomac. Table 6.4.13 shows the average monthly flow volumes in the Potomac, and the herbicide load necessary to sustain concentration at the HAL. To sustain an atrazine concentration over the MCL in the month of June, when the highest concentrations of atrazine are observed, approximately 20 to 25 percent of the atrazine applied in the basin, according to Table 6.4.6, would have to be lost from the field. By comparison, the amount of atrazine lost in the June 1996 storm, which has the highest observed atrazine concentrations, was approximately 1.5%. Sustained concentrations of metolachlor or 2,4-D above their HALs are even less likely. According to the application rates in Table 6.4.6, the amount of metolachlor or 2,4-D necessary to sustain concentrations at the HAL are larger than the amount applied annually in the basin.

A study by Capel and Larson (2001) helps put the size of the losses necessary to sustain atrazine concentrations above the MCL in perspective. They calculated the annual atrazine load as a percent of use (LAPU) for 408 watersheds. The watersheds varied in size from experimental plots to the Mississippi Basin. LAPU was relatively invariant with watershed size, although it was slightly larger for large watersheds. The mean LAPU for large watersheds is 1.82%. The median value is 1.30%. The Shenandoah River, which was one of the watersheds they studied, had a LAPU of 0.92%.

The use of atrazine and metolachlor has been on the decline since the mid-1980s and can be expected to decrease in the future (Betty Marose, 2002). As Section 6.2.2 demonstrated, CBP land use projections predict a decrease in the amount of cropland in the next decade. The application rate of these pesticides has been steadily decreasing, as farmers try to limit their pesticide use to economically efficient application rates. The use of 2,4-D has also been declining since the mid-1980s, although the next decade will see an increase in suburbanization and the cultivation of hay, trends that tend to potentially increase the opportunities for its use in weed control.

Table 6.4.13: Pesticide loading rates necessary to sustain HAL concentrations at intakes

Month	Avg. Monthly Flow (cfs)	Mass of Herbicide (lb) needed to Average HAL		
		Atrazine **(HAL = 3µg/L)**	**Metolachor (HAL = 100 µg/L)**	**2,4-D (HAL = 70 µg/L)**
January	682,997	342,606	11,420,191	7,994,134
February	560,754	255,880	8,529,319	5,970,524
March	989,198	496,203	16,540,088	11,578,062
April	638,267	309,840	10,328,007	7,229,605
May	434,464	217,936	7,264,544	5,085,181
June	247,514	120,153	4,005,110	2,803,577
July	151,869	76,181	2,539,358	1,777,551
August	158,911	79,713	2,657,109	1,859,976
September	204,777	99,407	3,313,565	2,319,496
October	187,852	94,231	3,141,023	2,198,716
November	255,636	124,096	4,136,533	2,895,573
December	419,964	210,663	7,022,089	4,915,462

6.4.5 Additional Pesticide Monitoring to Lower Risk

The risk of pesticide contamination at the surfacewater intakes near [REDACTED] was evaluated for atrazine, metolachlor, and 2,4-D. Pesticide contamination risk was determined to be moderately low for all three pesticides. This assumes that pesticides continue to be applied on dates with low runoff and that application rates remain constant and/or decrease into the future. The fact that past monitoring data has suggested that concentrations of pesticides, especially atrazine, can occur and that the pesticide model did not indicate a zero risk of elevated atrazine concentrations points to a need for pesticide monitoring, especially during the critical period from May through July when elevated concentrations would be most likely. Thus, a general recommendation would be to increase the frequency of water quality monitoring efforts for pesticides of concern during that time each year to assure that raw water and finished water at the District of Columbia’s water intakes maintains concentrations of pesticides below the EPA MCLs.

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Appendix A: Phase IV Chesapeake Bay Watershed Model Hydrology Calibration Results. EPA 903-R-98-004. CBP/TRS 196/98.

Appendix B: Phase IV Chesapeake Bay Watershed Model Water Quality Calibration Results. EPA 903-R-98-003. CBP/TRS 196/98.

Appendix D: Phase IV Chesapeake Bay Watershed Model Precipitation and Meteorological Data Development and Atmospheric Nutrient Deposition. EPA 903-R-97-022. CBP/TRS 181/97.

Appendix E: Phase IV Watershed Land Use and Model Linkages to the Airshed and Estuarine Models. EPA 903-R-97-019. CBP/TRS 180/9.

Appendix F: Point Source Loadings. EPA 903-R-98-014. CBP/TRS 207/98.

Appendix H: Tracking Best Management Practices in the Chesapeake Bay Program. EPA 903-R-98-009. CBP/TRS 201/98.

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