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CHANGES IN IMPERVIOUS SURFACE AREA, FLOOD FREQUENCY, AND WATER CHEMISTRY WITHIN THE DELAWARE RIVER BASIN DURING THE PAST 50 YEARS: INITIAL RESULTS

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ABSTRACT

Housing development and total road mileage expansion, which result from the growing population and economic activity in the region, increased the total impervious surface area (ISA) within the Delaware River Basin (DRB) from either 3.19% or 3.69% of the total basin area in 1950 to either 5.41% or 6.44% of the total basin area in 2000, depending on which of two plausible scenarios are used for interpreting the available housing and road mileage data. Assuming an average area of 0.3 acre and 35% ISA for a single-unit detached house and 0.1 acre and 60% ISA for all other housing units, the projected ISA for the DRB is 5.66% in 2006. This result is comparable with the existing GIS data from the LandSat Thematic Mapper Imager for part of the DRB. Associated with the increasing ISA in the DRB, there also is an increase in flood events for recent years. Increased peak flows in July and August, which are the two months with the highest precipitation, also are noticeable. Concentrations of sodium and chloride in the Delaware River water increased between 2-4.6 times over the last 50 years at both upstream and downstream locations. Increased application of sodium chloride, in the form of deicing salt that is tied to the expansion of total road mileage in the basin, may be one of the main reasons for the increase of these ions in the waters of the Delaware River.

Key words: Impervious surface area, flood, Delaware River.

1. INTRODUCTION

Because of continuing pressure from population growth and robust economic activities within the Mid-Atlantic and Northeast regions of the United States, new housing and associated infrastructure are constantly being added within the Delaware River Basin

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(DRB; Figure 1). In addition, the continuing migration of population from cities to suburbs also is accelerating this land development trend. In response, state and federal governments are creating new roads and sidewalks, along with expanding existing ones, to catch up with the increased traffic demand. The result is a continuous expansion of the impervious surface area (ISA) in the DRB (Hasse and Lathrop, 2001 and RFA-Dismal Sciences, 2001). The expansion of the ISA within a drainage basin can result in more frequent flooding, decreased water quality, lower fish populations, reduced groundwater reserves, and increased habitat fragmentation (Mackenzie, 1989; Kauffman and Brant, 2000, 2002; and Delaware River Basin Commission (DRBC), 2002). Therefore, examining the ISA in the DRB and understanding its hydrologic and water quality impacts is critical for protecting both the economic and ecologic health of the communities and environments within the basin.

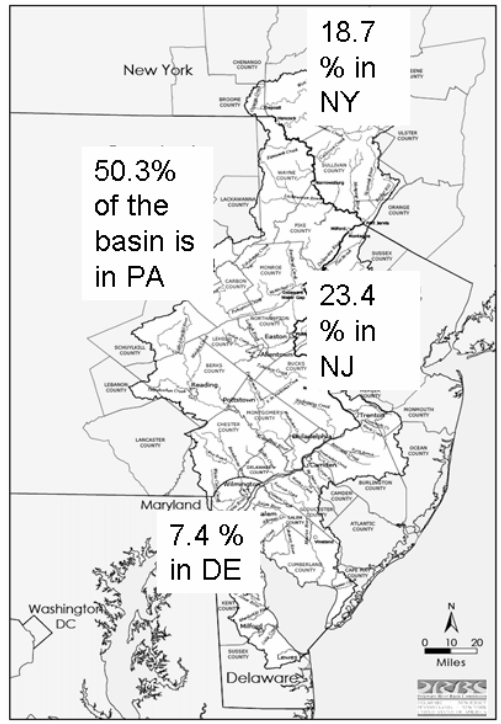

Figure 1. Map of the Delaware River Basin showing the % of areas located in each of the four states.

Due to the difficulties in organizing a multi-state effort, there have not been any prior basin-wide studies on the ISA and its impact in the DRB, although there have been a number of recent, but separate, ISA studies for the states of New Jersey (NJ), Pennsylvania (PA), and Delaware (DE) (Hasse and Lathrop, 2000, 2001 and RFA-Dismal Sciences, 2000). The ISA data published for NJ and PA studies of 2000 and 2002 (Hasse et al., 2001; PA Governor's Center, 2001, 2002, 2003; and RFA-Dismal Sciences, 2000) were derived mainly from the interpretation of LandSat Thematic Mapper color images (LSTM) and do not provide many of the needed ISA details.

The ISA resulting from housing and roads needs to be identified and characterized into the database. The regional trend of the recent ISA expansion needs to be understood as well. This is particularly important given the three most recent major flooding events in a two-year period (around 9/19/04, 4/4/05 and 6/29/06) in the middle and lower Delaware River at numerous locations, including Lambertville and Trenton, NJ, and New Hope, Easton, Yardley, and Philadelphia, PA. It is clear that all government entities in the DRB urgently need to examine their development practices, which create the increase in ISA, and understand the impacts associated with these increases.

In response to these needs, this paper provides initial results in the following three areas: 1) an examination of the factors contributing to the increase in total ISA; 2) an analysis of the trend of the ISA from 1950 to 2006; and 3) an evaluation of hydrologic and water quality changes and farmland loss within the DRB associated with the increase in ISA since 1950.

Factors that contribute directly to the ISA are total road mileage and number and types of housing units. The hydrologic impact is the changed peak flood frequency and peak flow amount. Changes in the concentration of sodium, chloride, calcium, magnesium, and sulfate, along with pH and hardness levels, from the upper, middle, and lower Delaware River are the water quality parameters that will be examined. The reasons associated with these changes will be discussed as well.

2. POPULATION INCREASE

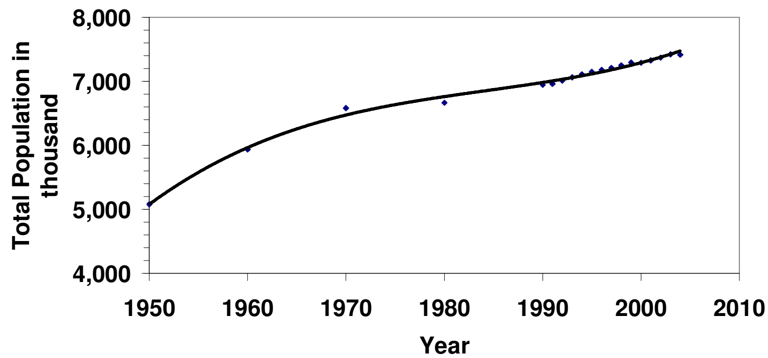

Figure 2. Total population of the DRB from the 29 counties.

Population data for all 29 counties in the DRB were collected from the US Census Bureau (USCB database, 2006). The percentages of population, road mileage, housing units, and farmland area for each of the 29 counties used in all calculations presented in this paper are weighted by the percentage of the land area of each county in the basin. Counties with less than 5% of their area located within the basin are excluded. Census data are available for every tenth year and the data for more recent years, which were interpolated by the Census Bureau, also are available on its database (USCB database, 2006). The overall population trend for the DRB shows that there is a 46% increase from 1950 to 2004 (Figure 2). By the end of 2004, there were approximately 7.4 million people residing in the DRB, compared to 5.1 million in 1950.

3. IMPERVIOUS SURFACE AREA INCREASE FROM ROADS

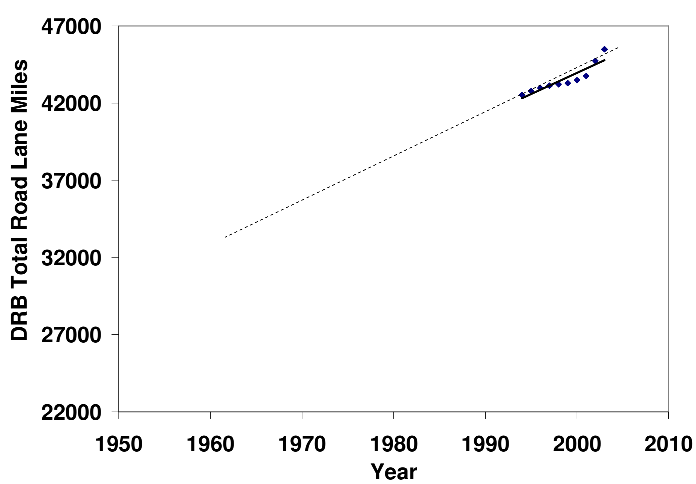

Figure 3. Total public road lane mileage of the DRB from 1993 to 2003 and the linear regression projection of the data for the period prior to 1993.

Over the past 50 years, in addition to the continued extension of concrete/asphalt paved major arterial roads and highways in the basin, some of the secondary and tertiary roads also have been upgraded from gravel to asphalt surfaces. Though those changes may benefit traffic flow, they do contribute to an increase of the ISA in the DRB.

Public road mileage in the DRB increased by 6.94% between 1994 to 2003, based on the available data from all the 29 counties located in the basin (Figure 3). This rate is substantially higher than the basin's population growth rate (4.4%), although lower than the growth rate for housing units in the DRB (~11.8%; see below), for the same period. For years prior to 1994, road data for individual counties are not available except for two counties in NY. All municipal roads are counted as "local" and all roads owned by other governmental units (both federal and state) are counted as "non-local" for this analysis. The percentages of "non-local" and "local" total lane miles are 37% and 63%, respectively, based on the 2002 and 2004 road jurisdiction mileage of the PA Department of Transportation (PENNDOT). For NY, the percentages are 36% and 64%, respectively, based on the 2003 road jurisdiction mileage of the NYDOT. Because PA contains the largest portion of the DRB area, its percentages of non-local (37%) and local (63%) were applied to the whole basin.

The road lane width was calculated as 10.25 feet per lane, based on the average width of federal aid roads in NY, PA, NJ and DE. This width also is used for the local lane width, since the average local lane width data are not widely available. The average "non-local" road lanes are 2.3 lanes per center line and average "local" lanes are 2 lanes per center line, based on the road lane data from the GIS database of the DRBC. Unfortunately, there are no reliable statistical data for the shoulder width of all these roads. Ranges of 10.0 to 12.5 feet for shoulder width per lane for "non-local" road and 3 to 6 feet for shoulder width per lane for local roads are used in calculating the total road ISA. Based on a shoulder width of 10 feet per lane for "non-local" roads and 3 feet per lane for "local" roads, and 10.25 feet width per lane for all roads as a conservative estimation, the total road ISA is calculated as 191,191 acres in 2003, which is about 2.5% of the total basin.

The total road ISA data prior to 1993 were calculated using the same assumptions, but based on the trend between 1993 and 2003. The backward projection of the road mileage for the years 1992-1950 is a rough estimate at this point and the road data prior to 1993 is not available for most parts of the basin. However, by using the relationship model of the total public road and federal-aid road mileage, one may improve the accuracy of this projection based on the federal-aid road mileage data that has a relatively longer period of availability.

4. IMPERVIOUS SURFACE AREA INCREASE FROM HOUSING UNITS

Annual housing data for the 29 counties in the DRB are available between 1950 and 2004 from the US Census Bureau (USCB database, 2006). Analysis of the total housing data reveals that the total number of housing units in the DRB has increased by 102.4% from 1950 to 2000 (Figure 4). This rate of increasing is 115% from 1950 to 2004, in comparison to the 46% population increase during the same period (see Section 2 for population data).

For the analysis of the ISA undertaken in this study, housing units are subdivided into two broad categories: 1) single-unit detached houses, which usually are located in suburban areas; and 2) all other types of housing unit, which include single-unit attached, all multi-unit buildings, mobile homes, boats, and RVs. These two categories of housing type are summarized separately for all 29 counties in the DRB.

Unfortunately, the Census Bureau's data do not include average lot sizes for these housing unit types. Therefore, the lot-sizes are assumed to have a range of values. The average lot size for a single detached housing unit is assumed to range from 0.4 (Scenario 1) to 0.3 acres (Scenario 2), whereas all other housing units are assumed an average of 0.1 acres per unit. Furthermore, a single detached housing unit is given an ISA of 35% of lot size, with all other housing types given an ISA of 60% of lot size. For example, for a single unit detached house with a 0.3 acres lot size, the ISA will be 0.105 acres; all other units, which have a lot size of 0.1 acres per unit, will have an ISA of 0.06 acres per unit. The average ISA percentages of 35% and 60% for the two housing unit types, respectively, are taken directly from the literature (McBridge et al., 1991; NJ Water Authority, 2000; and Shuster et al., 2005) and indirectly from runoff coefficients (Pilgrim and Cordery, 1992). In general, runoff coefficients are closely correlated with the ISA percentage of an area. Using the above values, the total housing ISA percentage in the DRB went from 1.56 to 3.06%, a 96.4% increase, from 1950 to 2004 in scenario #2. The more recent housing ISA data for 1990 and 2000 (the census years) are listed in Table 1.

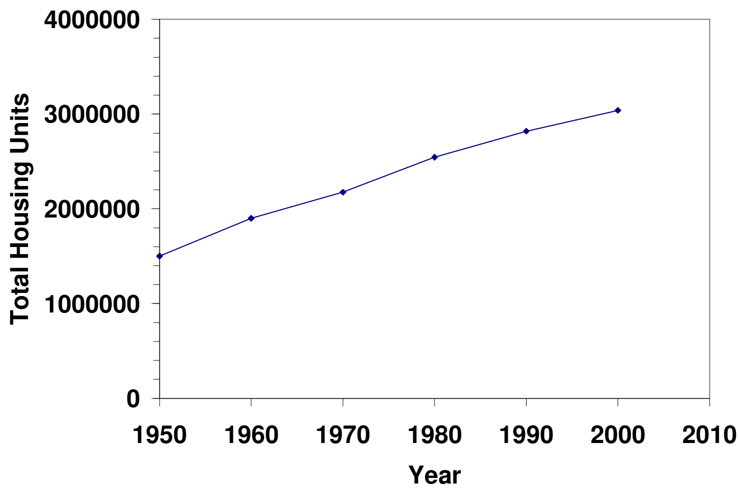

Figure 4. Total housing units of the DRB from 1950 to 2000.

Table 1. ISA of Housing Units of 2000 and 1990 in theDRB.

Total Acres In DRB: 8640000 Acres			Scenario #1	Scenario #2
2000	Housing Units	% of toal housing units	ISA Acres (0.4)	ISA Acres (0.3)
SingleDetached	1516371	48.62%	212292	159219
All others	1602158	51.38%	96129	96129
Total Housing	3118529		308421	255348
Impervious Area %			3.57%	2.96%
1990	Housing Units	% of toal housing	ISA Acres (0.4)	ISA Acres (0.3)
SingleDetached	1298793	45.13%	181831	136373
All others	1579266	54.87%	94756	94756
Total Housing	2878059		276587	231129
Total Impervious %			3.20%	2.68%

(0.4) or (0.3) implies that a single detached house was given an average lot size of 0.4 or 0.3 acre and 35% impervious. The non-detached houses were given an average lot-size of 0.1 acre and 60% impervious per housing unit.

5. TOTAL IMPERVIOUS AREA IN THE BASIN

The total ISA is the summation of the ISA due to housing, sidewalks and paved public roads and is presented in Table 2. The housing ISA for the census years from 1950 to 2000 is the summation of the ISA of the single detached and all other housing units of the years listed given the assumed lot sizes and impervious percentage discussed in the previous section. All data between the census years given in this study (such as 2004's housing data) are projected from the regression trend line of the census years from 1950 to 2000. For the road ISA, the actual calculated data were from 1993 to 2003 and the data from 1950 to 1992 were projected from the 1993 to 2003 regression trend. For years after 2003, the total ISA of the basin was determined by forward projecting regression model of the 1950-2000 ISA trend line. Either 20% (Scenario 1) or 10% (Scenario 2) of the housing ISA is used for assigning the ISA contribution from sidewalks. Based on these assumptions and values, the total estimated ISA in the DRB is between 5.66% (Scenario 2) and 6.73% (Scenario 1) for 2006 (Table 2).

Table 2. Estimated Housing, Road and Total ISA Percentage from 1950 to 2000.

Scenario #1	2000	1990	1980	1970	1960	1950
Housing Impervious %	3.57%	3.22%	2.85%	2.51%	2.28%	1.84%
Road Impervious %	2.16%	2.02%	1.89%	1.75%	1.62%	1.48%
Sidewalk Impervious % (20%of the total housing)	0.71%	0.64%	0.57%	0.50%	0.46%	0.37%
	2000	**1990**	**1980**	**1970**	**1960**	**1950**
Total Impervious %	6.44%	5.88%	5.31%	4.76%	4.35%	3.69%
	2100	**2050**	**2030**	**2020**	**2010**	**2006**
Projected total Impervious %	11.80%	9.10%	8.02%	7.48%	6.94%	6.73%

Scenario #2	2000	1990	1980	1970	1960	1950
Housing Impervious %	2.96%	2.67%	2.38%	2.09%	1.90%	1.56%
Road Impervious %	2.16%	2.02%	1.89%	1.75%	1.62%	1.48%
Sidewalk Impervious %(10% of the total housing)	0.30%	0.27%	0.24%	0.21%	0.19%	0.16%
	2000	**1990**	**1980**	**1970**	**1960**	**1950**
Total Impervious %	5.41%	4.96%	4.50%	4.05%	3.70%	3.19%
	2100	**2050**	**2030**	**2020**	**2010**	**2006**
Projected total Impervious %	9.77%	7.58%	6.71%	6.27%	5.83%	5.66%

Average lot sizes of 0.4 and 0.3 acre were used for a single detached housing unit for the upper and low scenarios, respectively. An average lot size of 0.1 acre is used for the other housing units. 35% of the single detached housing area is assigned impermeable and 60% of the area of the other housing units is assigned impermeable. 10 and 3 feet shoulder widths per lane are used for the "non-local" and "local" roads respectively. The road widths are all 10.25 feet.

6. COMPARISON WITH EXISTING GIS DATA

Although a direct calculation of the ISA for the entire DRB is not available from existing GIS maps, ISA percentages for NJ and PA are available from existing LSTM-based GIS maps for recent years. GIS data for the DRB section in PA from 1999 to 2002 were clipped from Pennsylvania State University's PASDA database. This data gives an ISA of 4.5%, whereas the total ISA for the year 2000 determined in the present study is 6.37% for the PA section of the basin using Scenario 2 of Table 2. GIS data for the DRB section in NJ were extracted from Hasse and Laptop (2001). For 1995, their data give an ISA of approximately 6.8%, whereas this paper gives an estimation of 5.20% using Scenario 2 of Table 2 for the NJ portion of the basin. Another point of comparison was the study by Exum et al. (2005) that gives an average of 2-5% ISA in 2000 for the northern part of southeastern states (Table 2). One should notice that the ISA percentage for each of the four states in this study corresponds to the population density of that state (Table 3), that is, the higher the population density, the higher the ISA.

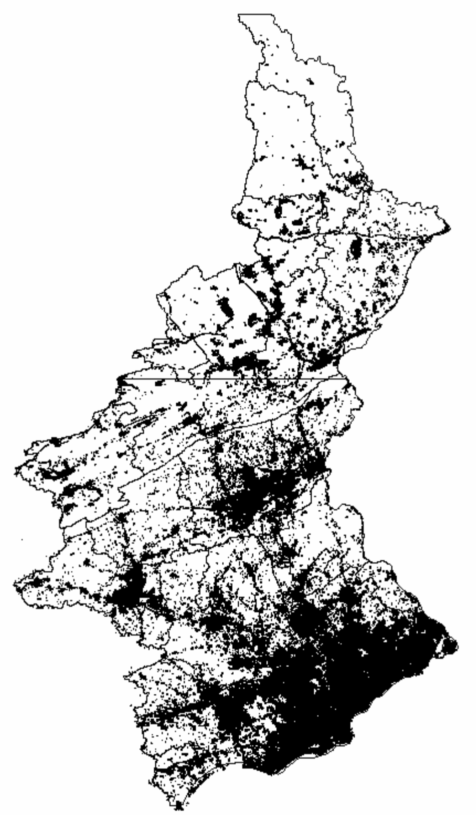

Figure 5. The ISA (black area) map of Pennsylvania's section of the DRB extracted from PASDA's ArcView GIS Image.

Table 3. Estimated ISA Percentage for the Four States in the DRB Using Scenario 2 of Table 2 and Their Population Density.

ISA Percentage				
	2000	1995	1990	1980
DE	4.92%	4.67%	4.41%	3.84%
NJ	5.47%	5.20%	4.57%	3.93%
NY	1.18%	1.13%	1.13%	1.06%
PA	6.37%	6.18%	6.00%	5.56%
Population Density (Person/Acre)				
	2000	1995	1990	1980
DE	0.82	0.76	0.78	0.75
NJ	0.77	0.73	0.70	0.64
NY	0.06	0.07	0.07	0.06
PA	1.18	1.15	1.12	1.09

7. HYDROLOGIC CHANGES

The discharge hydrograph for the Delaware River at Trenton, NJ (located just above the river's entrance into the Delaware Bay) can be divided into two periods over the past 100 years (Figure 6; all flow data are from US Geological Survey). The first period spans the years prior to 1961, before the establishment of the multi-state regulatory agency, the Delaware River Basin Commission. During this period, there were larger ranges between low and high flows. That is, there were more severe droughts and floods when water flow

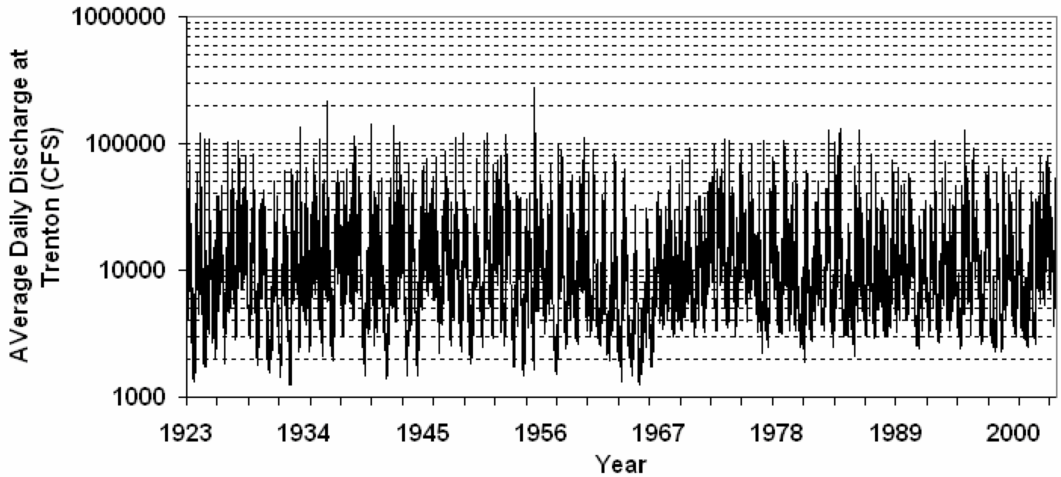

Figure 6. Average daily discharge hydrograph of Delaware River at Trenton from 1923 to 2004.

through the river was not regulated. The second period is for the years after 1961, when river flow was regulated by the controlled storage and release of water from upstream reservoirs by the DRBC. During this period, the typical range between high (flood) and low (in particular) flow levels was reduced (Figure 6). The reduced fluctuations in river flow may not be beneficial to the overall long-term health of the ecosystem in the basin.

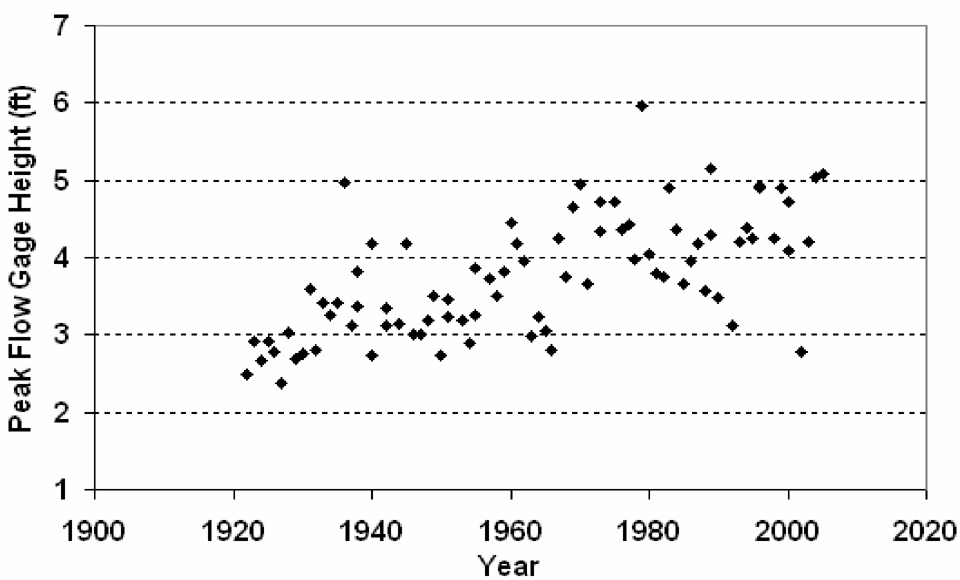

Figure 7. Peak flow gage heights of Pequest River of DRB at New Jersey showing the increasing trend from 1920 to 2004.

However, they obviously are beneficial to public water use.

Some tributary watersheds of the DRB do not show this pre- and post-1961 change in behavior. For example, the Pequest River at Pequest, NJ, exhibits a continuous increase in peak flow height over the past 85 years (Figure 7), as does the Neshaminy Creek at Neshaminy, PA.

The peak flow change in the post-1961 period, upon which this study is focused, is obvious. During this period, there is a significant increase in the number of peak flows, particularly since 1980 (Figure 8). At the Trenton Station, there were 7 peak flows/flood events with a gage height above 20 feet between 1981 and 2006, whereas there were no such events between 1961 and 1980. In addition, peak increases in river discharge and surface runoff in July and August, which are the two months with the highest average precipitations, also are apparent in the hydrograph data. Surface runoff can be calculated based on the modified recess displacement method developed by Rutledge (2000) and Sun (2004).

The explanation for the increase in peak discharge from 1981 to 2006, including the three major flood events of the last two years (9/19/04, 4/4/05, and 6/29/06) at Trenton, NJ, and Yardley, PA, can be complicated. However, it is likely that the increase in ISA in the basin over the years played a significant role. Even though an increase in the capacity of the reservoir storage or the number of reservoirs might alleviate the problem temporarily, unless a long-term, regional, and sustainable development plan is agreed to by all the relevant government entities, the problem of severe flooding for downstream communities will likely worsen in the future, given the increasing trend of population and resulting ISA projected for the DRB in this study.

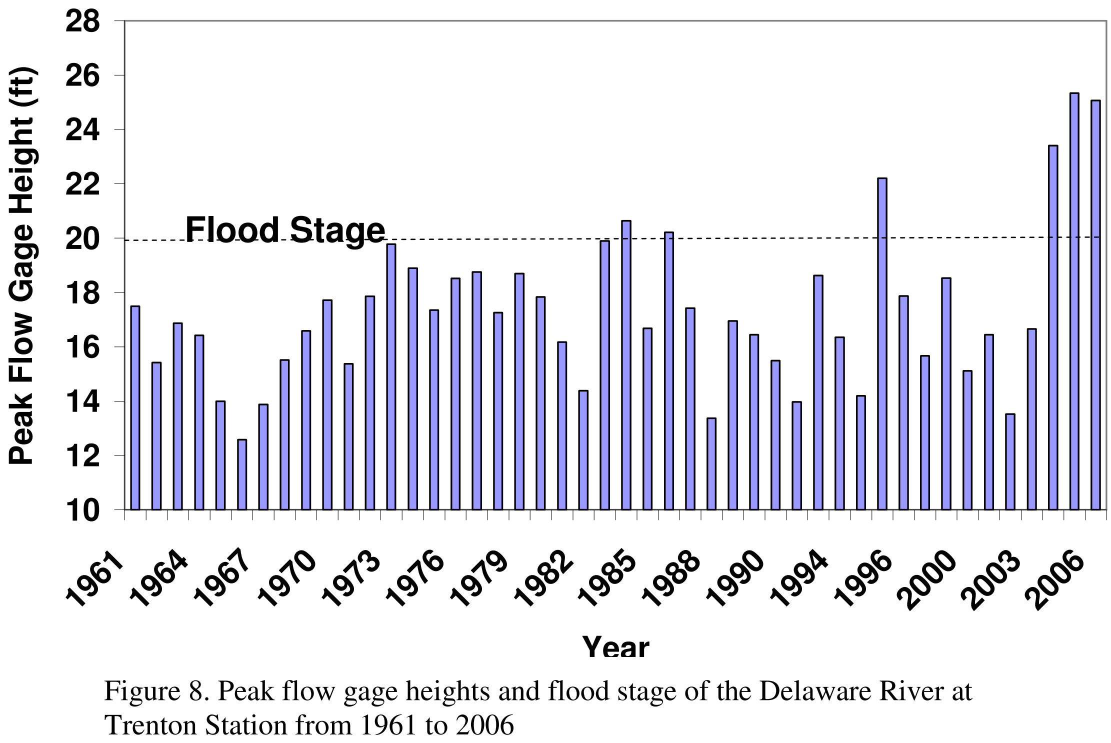

Figure 8. Peak flow gage heights and flood stage of the Delaware River at Trenton Station from 1961 to 2006

8. CHANGE OF THE WATER QUALITY IN THE BASIN

The documented expansion of housing and roads within the DRB over the past 50 years also may have brought about changes in the water quality of the Delaware River due to increased surface runoff. Although the average levels of many common parameters, such as pH, hardness, calcium, and magnesium have not changed significantly during that time period from our analysis of USGS data, average concentration increases for sodium and chloride in the river water are observed in the available data (USGS water data,2006) (Figure 9).

Based on linear regression trend lines determined for the data shown in Figure 9, average chloride concentrations changed from approximately 3.5 mg/liter in 1944 to 16 mg/liter in 2004 at the Trenton Station, from 8.5 mg/liter in 1963 to 17.5 mg/liter in 2004 at the Riegelsville Station, and from 2.8 mg/liter in 1961 to 11.6 mg/liter in 2004 at the Montague Station. The sodium/chloride ratio also stabilized at around 0.6 in 2004 at the Trenton Station, down from about 1.0 typical in the 1940s. Both the sodium and chloride concentrations are at their highest from the end of January to March when snow and ice removal from roads is a concern within the DRB.

Conventionally, sodium chloride is regarded as a cyclic salt, and the average concentrations of both ions are proportional to their concentrations in rainwater (OUCT, 1997). However, the average concentrations of chloride measured at three different National Atmospheric Deposition Program precipitation stations within the DRB were 0.365, 0.197, and 0.61 mg/liter, respectively, and show no meaningful long-term trend for the period of 1981 to 2004 (Figure 10). Therefore, the main source of sodium and chloride in the waters of the Delaware River is unlikely to be precipitation at the current time. Though a saline soil can form as the result of excessive irrigation in agricultural areas, and runoff from a saline surface can increase the salt supply to the river over time, the significant increase in the sodium and chloride concentrations (~ 4.6x for chloride from 1944 to 2004 at the Trenton Station, and ~ 4.3x from 1961 to 2004 at the Montague station) in the waters of the Delaware River can not be explained simply as the result of saline runoff from irrigation. This is because the total acreage for farmland in the DRB has decreased by about 49.1% from 1950 to 2004 (see following Section 9) and the usage of water for irrigation has shown a decreasing trend over the last 20 years, according to USGS water usage data. This leaves the application of road salt, which in the DRB is most commonly sodium chloride, during the winter months as the likely source of the increasing sodium and chloride content in the Delaware River.

Furthermore, because the measured total paved road mileage within the DRB increased by 6.94% from 1994 to 2003, and the linear regression trend indicates the total paved road mileage increased by about 36% from 1960 to 2003, it is likely that the amount of road salt being applied during the winter months has increased at a similar, if not higher, rate. This is consistent with the findings of the Transportation Research Board, National Research Council for the entire nation (TRBNRC, 1991). Compared to the conservative chloride ion, sodium is more readily adsorbed by sediments and biota in the region (OUCT, 1997). This selective adsorption could explain the less dramatic increase for sodium, as compared to chloride over the same time period.

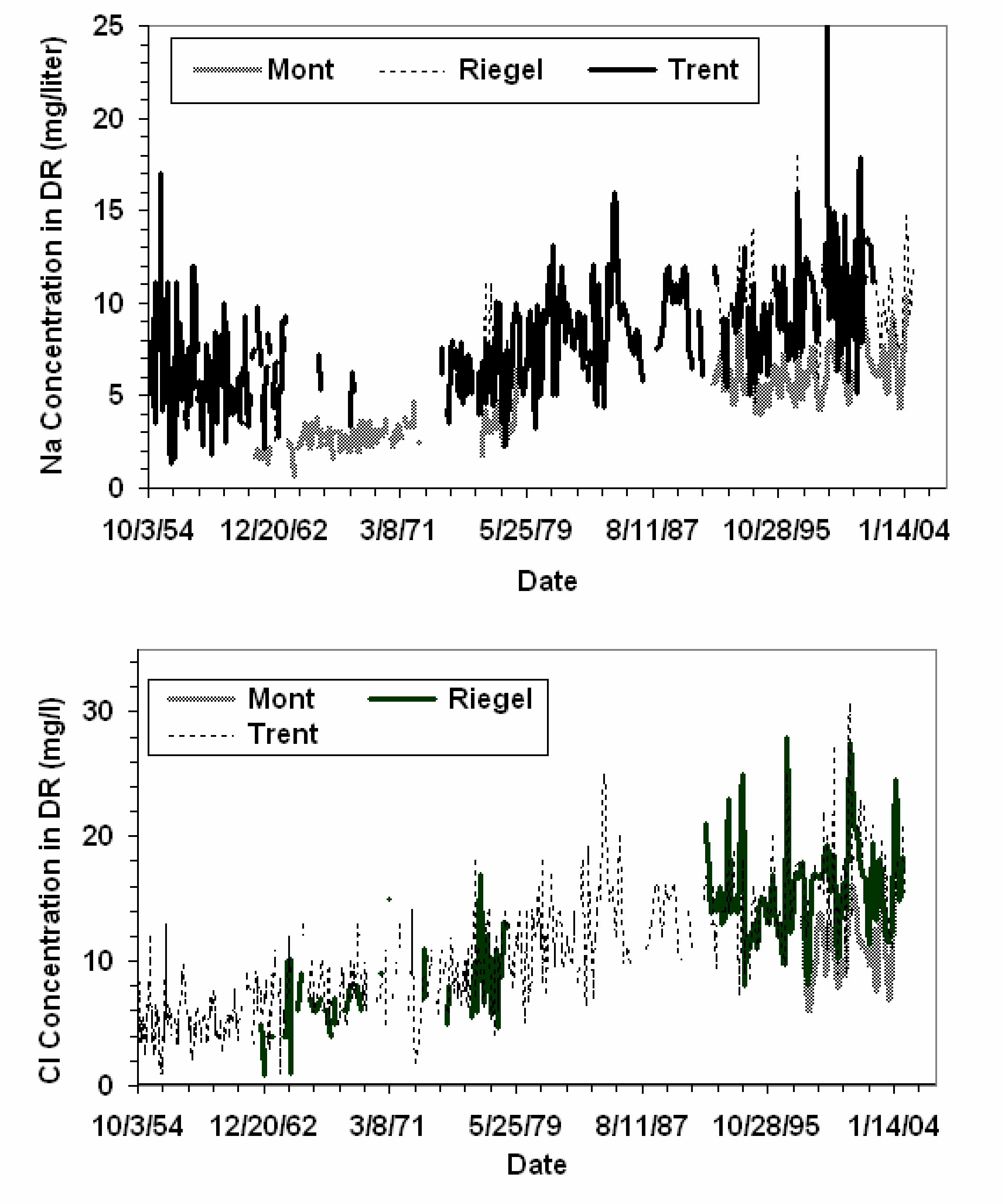

Figure 9. Chloride and sodium concentrations of Delaware River from three gage stations: Mont, Montague, NJ; Riegel, Riegelsville, NJ; Trent, Trenton, NJ.

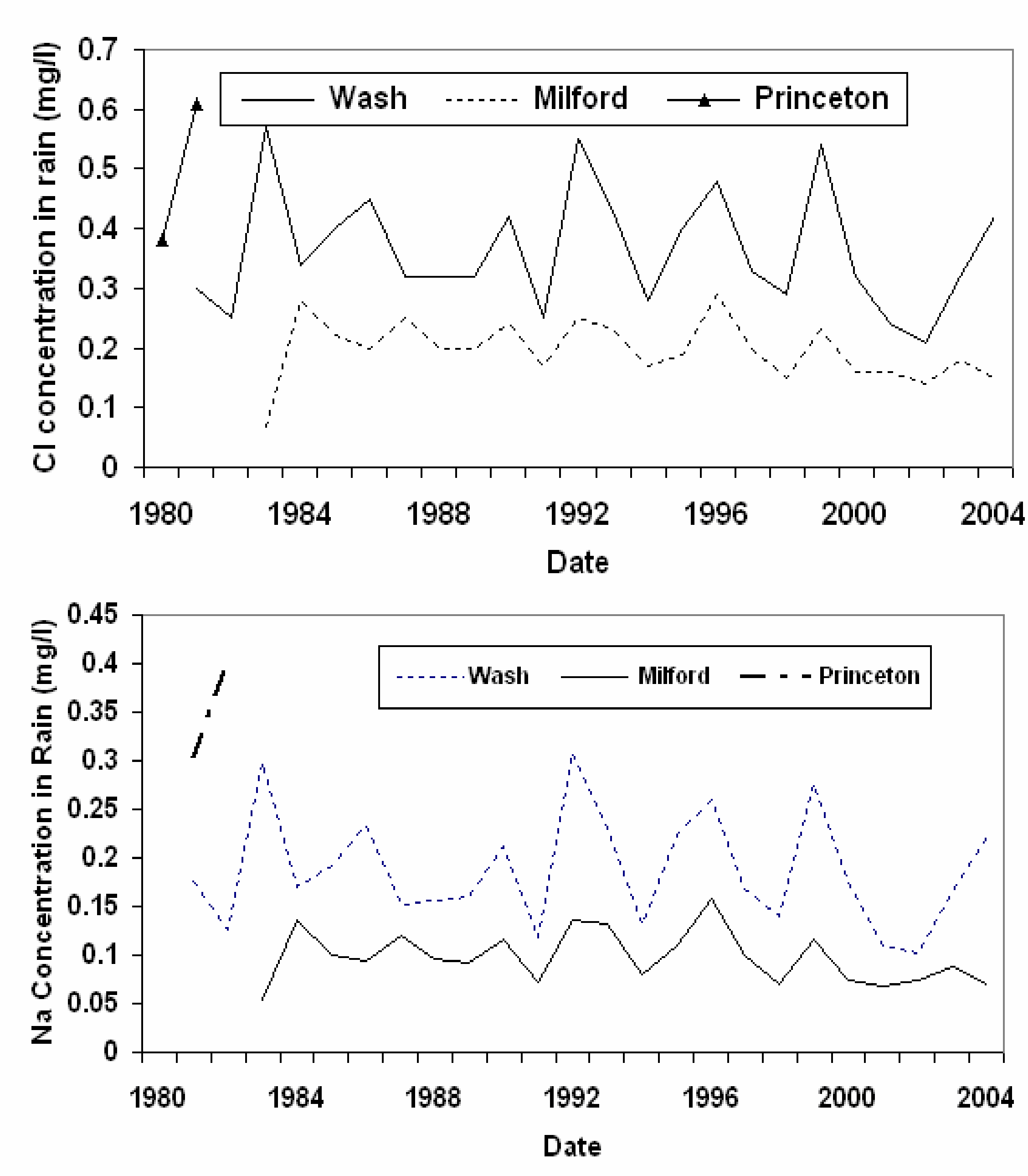

Figure 10. Chloride and sodium concentrations in the rain water from three precipitation stations: Washshinton Crossing (Wash),NJ; Milford, PA; and Princeton, NJ from 1980 to 2004.

9. LOSS OF FARMLAND

Another significant change associated with increasing development within the DRB is the reduction of farmland. According to data from the National Agriculture Statistics Service (NASS) from all 29 counties within the DRB, the total acreage of farmland has decreased from 3,409,000 acres, or approximately 39.5% of the basin's land area, in 1950 to

1,706,000 acres, or approximately 19.8% of the basin's land area, in 2006 (Figure 11; NASS, 2006). This represents a farmland loss rate of approximately 50% for the DRB, as compared to a national loss rate of 22.5% during the same time period (NASS, 2006).

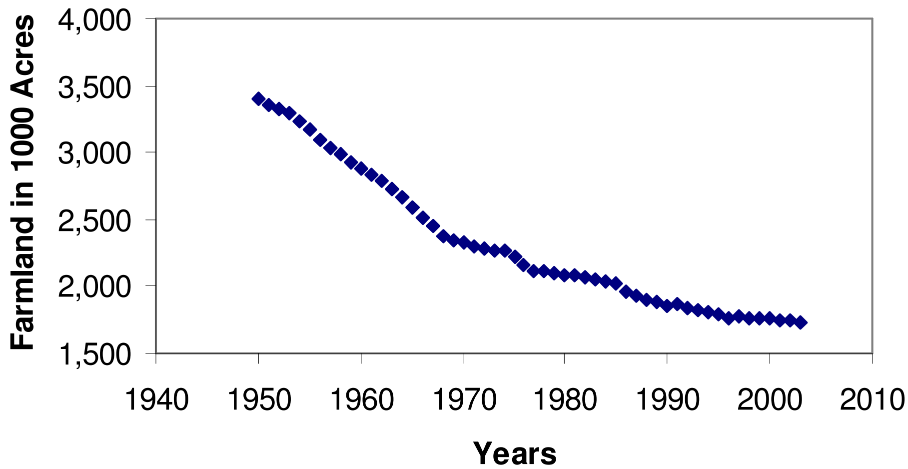

Figure 11. Estimated farmland acreage change of the DRB from 1950 to 2004.

SUMMARY AND CONCLUSIONS

Recent population expansion and economic growth within the DRB have increased the demand for housing and roads. As a result, the total impervious surface area (ISA) within the basin also has increased. From 1950 to 2004, the population within the basin increased by 46%, from 5.1 to 7.4 million. During the same period, the estimated road ISA increased by as much as 49%, from 1.48% to 2.21% of the basin's land area, and the housing ISA increased by as much as 96.4%, from 1.56 to 3.06% of the basin's land area (Scenario 2, Table 2). The total ISA from all roads, houses, and sidewalks increased by as much as 74.4%, from 3.19% of the basin's land area in 1950 to 5.57% in 2004 (Scenario 2, Table 2). Based on the projection of the ISA regression line for the two scenarios discussed, the ISA percentage for 2006 is between 6.73% and 5.66% of the total basin area. Even though low river flow periods after 1961 were less frequent than those prior to 1961, thanks to the regulatory efforts of the DRBC, there were significantly more floods in the downstream portion of the river during the last 25 years than during the preceding 25 years. In addition, an increase of 2-5 times for sodium and chloride concentrations in the river water is found compared to pre-1950 levels. A possible reason for this increase is the runoff from deicing salt used during the winter months in ever larger amounts because of the increase in total road mileage within the DRB.

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