IMPERVIOUS SURFACES AND THE QUALITY OF NATURAL AND BUILT ENVIRONMENTS

by

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About the Cover Photograph

The cover photograph is an oblique aerial view of the Towson, Maryland area looking southeastward from the vicinity of York Road and Fairmount Avenue toward the intersection of Fairmount Avenue and Dulaney Valley Road. In our opinion, the photograph clearly documents the various components of imperviousness. We thank Dale Johnson, a former employee of the Baltimore County Department of Environmental Protection and Resource Management, for permission to use this photograph in our research report.

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Abstract

The growth and spread of impervious surfaces within urbanizing watersheds pose significant threats to the quality of natural and built environments. These threats include increased stormwater runoff, reduced water quality, higher maximum summer temperatures, degraded and destroyed aquatic and terrestrial habitats, and the diminished aesthetic appeal of streams and landscapes. This paper provides a basic introduction to impervious surfaces and an overview of the environmental effects of increased watershed imperviousness, with particular consideration given to the watershed of the Chesapeake Bay.

Introduction to Impervious Surfaces

Impervious surfaces are mainly constructed surfaces--rooftops, sidewalks, roads, and parking lots--covered by impenetrable materials such as asphalt, concrete, and stone (Figure 1). These materials effectively seal surfaces, repel water and prevent precipitation and meltwater from infiltrating soils. Surfaces covered by such materials are hydrologically active, meaning they generate surface runoff. According to Novotny and Chesters (1981), impervious surfaces are nearly 100 percent hydrologically active, and high percentages of such surfaces occur within urbanized areas containing commercial, industrial, transportation, and medium to high density residential land uses. Other impervious, hydrologically active surfaces include compacted soils, high clay content soils, frozen soils, saturated soils, and soils with high groundwater tables (Novotny and Chesters, 1981). With the last three, imperviousness and hydrological activity is usually seasonal or temporary, in marked contrast to urbanized areas, which are permanently impervious and hydrologically active.

Paving watershed areas with asphalt and concrete makes these surfaces “desertlike” in terms of hydrology and climate. Storm water washes over paved, sparsely vegetated urban surfaces in much the same manner as it does over a desert landscape. Intense storms over urban and desert areas can quickly generate large volumes of runoff, even flash floods, followed by relatively dry conditions a short time later (Christopherson, 2001). Rapid runoff and the paucity of vegetation over these surfaces also reduce the amount of water available for evapotranspiration. Therefore, much of the incoming solar energy that could have been utilized to evaporate water is instead transformed into sensible heat. This effectively raises the temperatures of these surfaces and of the overlying atmosphere. Moreover, impervious urban surfaces behave like rocky desert surfaces in that they tend to have high thermal conductivities and heat storage capacities in comparison to vegetated, pervious surfaces (Douglas, 1983; Christopherson, 2001). The differences in the thermal characteristics of surface materials that overlie urban areas versus those that overlie natural pervious areas have profound implications not only for microclimates, but also for stream and watershed health.

Many types of pollutants, originating from a variety of sources, accumulate over impervious urban surfaces. These pollutants are subsequently washed into water bodies during, and immediately following, storm events, severely degrading water quality and harming aquatic life. Furthermore, the temperatures of stormwater runoff during summer months can be dramatically increased via heat conduction from impervious surfaces. These forms of water pollution, which arise over broad land areas, are known as nonpoint or diffused source pollution, with pollutants being conveyed to water bodies via overland flow rather than by pipes, ditches, or conduits issuing from factories or sewage treatment plants. This type of pollution is linked to land-use activities, and its severity is a function of land-use type and intensity, including the amounts of impervious surface and the frequency and magnitude of storm events.

From a hydrological perspective, the impervious areas of a watershed can be differentiated between total impervious area (TIA) and effective impervious area (EIA). The former refers to all areas within a watershed that are “covered by constructed, non-infiltrating surfaces,” whereas the latter is “impervious surfaces with direct hydraulic connection to the downstream drainage (or stream) system”(Booth and Jackson, 1997). Impervious areas, which drain onto pervious surfaces such as lawns, gardens, and grassy fields, would be included in calculations of TIA, but excluded from EIA calculations; if, however, those areas contribute runoff directly into streams and other surface water bodies, they would be included in calculations of EIA. It must also be noted that most impervious surfaces are not 100 percent impervious, even in effective impervious areas, since cracks and gaps in concrete and other surface materials allows some water to infiltrate underlying soils.

Most of the impervious surfaces within the watersheds of the Chesapeake Bay and the coastal bays of Maryland are the result of urbanization. The majority of these surfaces are associated with transportation, specifically roads and parking areas. Transportation land-uses account for between 63 percent and 70 percent of the impervious covers measured for urban sites in Olympia, Washington (Schueler, 1994). As residents, businesses, and industries relocate to suburban and rural locations within the bay’s watershed, the amount of land covered by roads, parking lots, driveways, sidewalks, and structures will also increase. Impervious surfaces are diffusing from the Bay’s urban centers into surrounding areas, subsequently altering the land’s physical characteristics and functions.

Why Consider Impervious Surfaces in Land Use Decisions?

The increasing imperviousness of the bay’s landscapes has five broad, interrelated impacts: 1) alteration of local and regional hydrological cycles (changes in water quantity); 2) changes in water quality; 3) changes to local energy balances and microclimates; 4) habitat degradation, loss, and fragmentation; and 5) changes to stream and landscape aesthetics. Imperviousness directly affects stormwater runoff and water quality. Moreover, the temperature response and reflective properties of impervious surfaces are linked to the “urban heat island” effect, which affects human comfort and health because of changes in sensible heat fluxes and the concentration of atmospheric pollutants.

The measurement of imperviousness provides a succinct, straightforward indicator of stream degradation and terrestrial habitat loss and degradation (Arnold and Gibbons, 1996; Schueler, 1994). Increasing imperviousness can also result in dramatic changes to the aesthetic character of streams and landscapes within the bay's watershed, indicating a shift from forested and rural landscapes to more suburban and urban settings, and is a measure of both directed and undirected (sprawl) urban development. These changes profoundly affect the quality of life for millions of residents within the Chesapeake Bay watershed.

A recent report on climate change issued by the Mid-Atlantic Regional Assessment Team, MARA (2000), predicts continued population growth in the Mid-Atlantic region, especially in coastal areas and the Piedmont. This will lead to more land conversion and development, with increases in impervious surfaces throughout many of the Chesapeake Bay's sub-watersheds, particularly those within or adjacent to metropolitan areas. Unless actions to control development are undertaken now, the environmental impacts of imperviousness will increase along with population growth.

Following sections in this paper provide an overview of the five impacts listed above. It is important to consider these impacts in light of projected population growth and recent efforts to control sprawl development such as Smart Growth, rural land preservation, and similar initiatives. Dealing with the problems of imperviousness should be an integral part of land use planning and land management activities within the Chesapeake Bay Watershed and Maryland's Coastal Bays.

Water Quantity Impacts

As watershed areas are developed for residential, commercial, industrial, and transportation land uses, local hydrological cycles are substantially altered. Dramatic changes in the timing and volumes of storm waters delivered to nearby streams follows the paving of previously vegetated areas. Changes in stream levels between storms, in the heights of groundwater tables, and in the rates and volumes of stream erosion are also likely outcomes of increasing watershed imperviousness. In addition, replacement of vegetation by impervious surfaces significantly reduces average annual evapotranspiration over watersheds. For example, it is estimated that by replacing forests in the northeastern United States with 25 percent, 50 percent, and 75 percent impervious cover will respectively reduce annual potential evapotranspiration by 19 percent, 38 percent, and 59 percent (Douglas, 1983).

A notable characteristic of impervious surfaces is the production of runoff during even relatively small storms since these surfaces are: 1) impermeable; and 2) have limited depression storage, which is the ability of surfaces to store and retain water. Water held in depression storage, that is, in cracks, grooves, and pits on the surface, is unavailable for runoff. A study reported by Novotny and Chesters (1981) estimates that in urban Chicago, the amount of water held in depression storage is four times greater on pervious surfaces than on impervious surfaces. Also, within more natural pervious areas, much of the water held in depression storage eventually infiltrates the surface.

The limited amounts of water held in puddles and surface irregularities on urban surfaces generally cannot infiltrate underlying soils and quickly evaporates as skies clear and surfaces heat up. Relatively small storms can quickly wet impervious surfaces, but this moisture is not retained. On vegetated surfaces, evaporation rates are lower and a higher portion of moisture is retained, regardless of the amounts of rainfall involved (Douglas, 1983).

Reduced infiltration due to imperviousness leads to greater volumes of stormwater runoff and more rapid peak stream discharges. An average increase in peak storm flows of 2.5 times occurs as impervious coverage increases from 0 percent to 100 percent within areas not serviced by storm sewers. The change for peak stream discharges in sewered areas is even greater, with up to an eightfold increase at 100 percent imperviousness (Leopold, 1968; Berry and Horton, 1974). Impervious surfaces and storm sewers dramatically increase peak discharges associated with storm and snowmelt events, increasing the likelihood of downstream flooding as storm waters exceed stream channel capacities. Storms that would not have caused flooding prior to development may now do so because of increased runoff from impervious surfaces. In general, floods become more frequent with the expansion of impermeable surfaces. Impervious surfaces and storm sewers also reduce the amount of time it takes stormwater runoff to reach receiving streams. This time, known as lag time, is the period between peak rainfall and peak stream discharge (Goudie, 1994). Smooth, paved surfaces provide less frictional resistance to overland flow than do vegetated surfaces. What’s more, storm sewers convey urban stormwater directly into streams, thereby increasing the speed of stormwater delivery.

In some watersheds, lower groundwater tables and declining stream discharges may accompany increases in impervious surfaces between storm events, especially during the summer. This is due to diminished groundwater (interflow and baseflow) contribution to streams. A decline in summertime stream discharges is not a universal consequence of watershed urbanization, however, and many urbanized areas do not exhibit drops in low flow discharges (Schueler, 1994). The failure to definitively confirm this impact may stem from the fact that not all impervious surfaces contribute runoff to streams. This is especially so in residential areas were runoff from rooftops may simply soak into front lawns and backyards rather than discharge into storm sewers. Moreover, excessive watering of pervious surfaces (parks and lawns) within urban areas can significantly recharge groundwater, maintaining or even raising local groundwater tables (Douglas, 1983).

Water Quality Impacts

The urbanization of watersheds poses threats to water quality from both point and nonpoint sources of pollution. Point sources are locations where specific pollutants are discharged directly into lakes, streams, estuaries, and coastal waters via pipes and other conduits. Point sources include factories, power plants, and sewage treatment plants. Nonpoint source pollution is generated from broad land areas, and pollutants are delivered to water bodies via stormwater and snowmelt runoff. It generally takes several runoff events to transport nonpoint pollutants from their source areas to receiving lakes and streams. Nonpoint pollutants can also contaminate groundwater since infiltrating water interacts with contaminants on the surface and within the soil. These pollutants are then transported in solution or suspension into the groundwater system. Nonpoint source pollution is the primary cause of water pollution within the United States, and its contribution to poor water quality becomes more apparent as point source discharges are reduced or eliminated.

The types and amounts of nonpoint source pollutants entering water bodies depend upon land use and land cover, population density, season, topography, geology, and storm characteristics and frequencies (Bolstad and Swank, 1997; Novotny and Chesters, 1981). Sources of nonpoint pollution include agriculture, silvacultural activities, atmospheric deposition of pollutants, and urban runoff. Agriculture is the leading source and cause of nonpoint pollution. However, urban runoff is the cause of significant local and regional nonpoint pollution problems. The following discussion is limited to water pollution from impervious urban surfaces and from the construction of impervious surfaces.

The types and sources of pollutants present in urban runoff are quite varied as indicated in Table 1. Many are harmful to aquatic animals and plants. The construction of impervious surfaces, such as streets, buildings, and parking lots, generates large quantities of sediments per unit area of land, but fortunately the sizes of affected areas are typically small. Sediments transported by runoff from construction sites muddy urban and suburban streams and may cover stream channel bottoms. Once construction is finished and the surface stabilized, soil erosion drops dramatically.

As impervious surfaces are established, pollutants collect on top of them. A number of factors, as highlighted in Table 2, affect the presence of pollutants and their accumulation upon these surfaces. For example, street curbs trap rubbish and urban sediments, which are moved to the sides of roads by traffic. Much of the pollutants that accumulate on impervious urban surfaces, especially the fine materials, are readily removed by stormwaters. Subsequently, the pollutants degrade the biological, chemical, and physical characteristics of lakes, streams, and estuaries receiving urban runoff. This runoff contains conventional pollutants (nutrients, bacteria, organic matter) as well as heavy metals and other toxic substances such as petroleum (Clark, 1985; Whipple, 1977). The quality of urban runoff “often approaches that of treated sewage or may even be worse” (Novotny and Chesters, 1981). The most polluted waters are associated with the “first flush” of pollutants from impervious surfaces during storm events. The longer the time interval between storms and snowmelts, especially in the absence of frequent street cleaning, the greater the build-up of pollutants on urban surfaces and the higher the loadings of pollutants into nearby waters.

Runoff from impervious surfaces may contain large quantities of organic matter such as pet, bird, and animal wastes, leaf litter, grass clippings, and rubbish. Such wastes are known as oxygen-demanding wastes. Organic wastes in water are decomposed by aerobic bacteria, which utilize free oxygen (O2). When excessive organic materials are present in water, the respiratory demands for oxygen by aerobic bacteria may dangerously lower or deplete dissolved oxygen levels, subsequently killing or driving away fish and other organisms. When this occurs, decomposition is completed by anaerobic bacteria, which break down organic matter in the absence of free oxygen. An outcome of anaerobic decomposition is the production and release of noxious gases and compounds that impart foul odors to water (Berry and Horton, 1974; Dzurik, 1990; Vesilind, Peirce, and Weiner, 1990).

Oxygen depletion is particularly problematic during the summer and early autumn when bacterial activity is high, organic matter is largely available, and water temperatures are warm. Warmer water heightens bacterial action and lowers dissolved oxygen levels since oxygen is less soluble in warm water than it is in cold water. Also, stormwaters that are heated through contact with impervious surfaces may cause thermal shock to organisms inhabiting the water bodies that receive these waters. Higher water temperatures raise the metabolisms of aquatic and marine organisms and decrease the efficiency of their oxygen use. For temperature sensitive organisms such as trout, the input of thermally polluted runoff can be lethal. Temperature increases may also adversely effect the reproductive behaviors and successes of aquatic and marine organisms, reduce the tolerance of fish to other environmental stressors and pollutants, and encourage the growth of less desirable types of algae and pathogens (Black, 1977; Dunne and Leopold 1978).

Land areas devoted to transportation make up the greatest percentage of impervious surfaces in urban areas, and therefore the types of pollutants specific to transportation merit a closer examination. These pollutants and their sources are summarized in Table 3. It is important to note that impervious surfaces devoted to transportation uses are principally effective impervious surfaces. Reducing the amount of land area devoted to transportation uses will therefore significantly reduce stormwater runoff and prevent a mass of pollutants from accumulating upon them and then flushing into the Chesapeake Bay Watershed’s lakes, streams, and rivers. Maintaining or improving the quality of the bay’s water resources requires curtailing the spread of impervious surfaces and reducing their adverse impacts.

Energy Balances and Microclimatic Impacts

As development changes land from pervious forests, grasslands, and croplands to impervious surfaces, balances between solar energy intercepted at the surface (insolation) and outgoing terrestrial energy are also changed. Solar radiation that reaches the Earth’s surface is reflected, absorbed and transformed into sensible heat, or utilized in evapotranspiration. In addition, a very small percentage of solar radiation is used in photosynthesis. It is important to note that the atmosphere is heated mainly by energy radiating off the earth’s surface and not by direct solar heating. Surface materials therefore affect the amount of solar radiation which is either reflected or absorbed, and also affects the flow of heat from the surface to the atmosphere. This, in turn, influences the temperature and humidity of the overlying air. The conversion of pervious surfaces to impervious surfaces alters local energy balances through changes in:

1. the albedos of surfaces;
2. the specific heat capacities and thermal conductivities of surfaces; and
3. the ratio of sensible heat to latent heat flowing from the surface into the atmosphere (Oliver, 1973).

According to Strahler: “The thermal effect is that of converting the city into a hot desert. The summer temperature cycle close to the pavement of a city may be almost as extreme as that of a desert floor” (1975). These changes, coupled with a handful of other factors, contribute to a phenomenon know as the “urban heat island,” which affects human health and comfort and increases energy demands for cooling.

Albedo

Albedo is the percent of incoming solar radiation reflected by a surface. It determines relative rates of surface heating and evaporation since radiant energy rejected by surfaces returns to space and is not transformed into either sensible heat or latent heat. Less energy reflected by surfaces means that more energy is absorbed and transformed into heat energy. The various types of surfaces commonly found within watersheds have different reflective properties, and a high degree of impervious surfaces profoundly alters the proportions of incoming solar energy reflected or absorbed. The albedos of surfaces typically found within the watersheds of the Chesapeake Bay are presented in Table 4. The overall albedo of impervious urban surfaces is about 10 percent lower than that for rural surfaces (Oliver, 1973), leading to higher percentages of absorbed radiation. The lower albedo for urban areas is likely due to the prevalence of impervious surfaces associated with transportation.

Specific Heat Capacity and Thermal Conductivity

Surface materials differ as to: 1) the amount of heat energy they can store; 2) their ability to conduct heat; and 3) their changes in sensible temperature when exposed to solar radiation. Some substances, such as water, can absorb and store a considerable amount of energy before increasing in temperature; likewise these substances can lose a good deal of energy before declining in temperature. On the other hand, some substances experience a rapid rise or decline in temperatures with the gain or loss of a relatively small amount of energy. This relationship between heat energy and temperature is referred to as a substance’s specific heat capacity, which is the ratio of the gain or loss of energy to a corresponding rise or fall in temperature. This is also expressed as: the change in heat / the change in temperature.

The specific heat of some representative substances, in calories/gram/^{o}C, is presented in Table 5. By comparing the specific heat of water (1) with that of concrete (0.2), it can be seen that five times more energy is needed to raise the temperature of water 1^o C than that which is required to raise the temperature of a corresponding mass of concrete (Danielson, et al., 1998).

Conduction, which is the flow of energy from molecule to molecule, is an important heat transfer process at the earth's surface. Once radiant energy is absorbed and transformed into sensible heat, it is transferred by conduction towards areas of lower temperatures in the surrounding air and soil. The thermal conductivity of a substance is "the amount of heat transmitted per unit time per unit perpendicular area per unit temperature gradient" (Bueche, 1979). This can be expressed as:

$$W / mk$$

for the heat flux through a column 1 m^2, where W is watts, m is meters, and K is a temperature gradient of 1 Kelvin per meter (Marsh, 1998).

Surface heat is conducted into the ground where it is stored and later released. Rapid conduction enables heat to penetrate to greater depths. This allows more heat to be absorbed and delays its introduction to the atmosphere through conduction and convection. Solids are generally better conductors of heat than liquids, and liquids more so than gases; hence dense impervious urban surfaces of concrete, stone, and asphalt conduct heat more efficiently and absorb more heat than do the pervious surfaces they replaced (Strahler, 1975; Douglas, 1983). In fact, the thermal effects of impervious urban surfaces are "more intense than ... a sandy desert floor" (Strahler, 1975). Loose, dry soils are comparatively poor thermal conductors because of the air contained in porous spaces within the soil. The thermal conductivity of soils increases, however, with the addition of water (Ellis and Mellor, 1995). Table 6 presents the conductivities of some common materials.

As noted, the materials that typically comprise impervious surfaces are thermally conductive. In addition, these materials have low specific heat capacities and thus heat rapidly when exposed to solar radiation. This is demonstrated by comparing a dry asphalt parking lot with an adjacent lawn. The parking lot has a low albedo; the lawn has a higher albedo. Radiant energy is transformed into sensible heat over the parking lot, whereas the lawn utilizes a significant amount of radiant energy in evapotranspiration. Also, the water contained in the grass and soil has a high specific heat capacity compared to asphalt, and hence the lawn's temperature does not increase as rapidly as that of the parking lot. Lastly, the parking lot is more thermally conductive than the lawn; thus these two surfaces experience a striking difference in daytime surface temperatures. The daytime temperatures of impervious urban surfaces during the summer can be very hot, with temperatures at the surfaces of parking lots often exceeding 600 C (1400F). Fortunately, air is a poor thermal conductor, since otherwise air temperatures over these surfaces would be even more uncomfortable and dangerous to human health.

Ratios of Sensible Heat to Latent Heat

Terrestrial heat energy enters the atmosphere as either sensible heat or as latent heat. Sensible heat is infrared energy that can be sensed and measured with a thermometer, and the other is energy that is used to evaporate water. Latent heat cannot be felt, for it is essentially “locked-up” or stored in water vapor, keeping the molecules in a gas state. Evaporation of moisture serves to lower surface temperatures since the energy used in evaporation is not available for sensible heating. Therefore, evaporation is a cooling process. Only after water vapor condenses is this energy felt. This is because condensation releases latent heat to the atmosphere as sensible heat. Since impervious surfaces retain little rainfall and are drier than vegetated surfaces, most of the solar radiation reaching the surface is transformed into sensible heat rather than used in evapotranspiration (Douglas, 1983; Christopherson, 2001). Evapotranspiration is limited to lawns, patches of bare soil, and street trees (Strahler and Strahler, 1999). The results are higher daytime temperatures and lower relative humidity levels over urban areas.

Unfortunately, heat indices, which reflect felt temperatures based on the human body’s reactions to temperature and humidity, remain higher for cities than for surrounding suburbs and rural areas. Any reductions in humidity over urban areas, providing hope for increased comfort, are essentially negated by temperature increases. This, coupled with restricted street level air circulation due to buildings, effectively raises summer heat indices and human discomfort levels in urban areas, especially during heat waves. This does not bode well for cities within the Chesapeake Bay watershed given projected increases in the frequency of summer heat waves due to global warming (EPA, 2000; MARA, 2000). However, the adverse impacts of heat waves and urban island effects in general can be partially offset by revegetating urban areas and by curtailing, or even reversing, the conversion of pervious surfaces to asphalt and concrete within and around cities.

The ratio of energy available for sensible heating (SH) to energy available for latent heating (LH) is known as the Bowen Ratio (Moran and Morgan, 1986) and is expressed conceptually as:

$$B = SH / LH$$

The Bowen Ratio, in turn, is used to calculate the Sensible Heating Index (SHI), which is the ratio of sensible heating to total heating (sensible + latent). It represents the proportion of total heat energy used to raise the temperature of air and is formulated as:

$$SHI = B / (B + 1)$$

Multiplying the index by 100 converts the value to a percentage. The higher the index value, the greater the percentage of available energy that is used for sensible heating. Conversely, lower index values indicate higher latent heat fluxes to the atmosphere, which means greater evaporative cooling at the surface over the summer months. A comparison of Bowen Ratios and Sensible Heat Indices for different surfaces is presented in Table 7. Comparing warm season values for both measures reveals interesting similarities between deserts and urban areas, and striking contrasts between these two surfaces and more pervious surfaces. Although the Bowen Ratio for desert is much higher than that for urban, the magnitude of difference between the two values is less than that between the values for urban and grasslands. Moreover, the sensible heat indices for desert and urban surfaces are much closer in value to each another than is the sensible heat index for urban surfaces and those for grasslands and forests. It is not surprising that temperatures in urbanized areas are thus higher than in adjacent rural areas.

Habitat Degradation, Loss, and Fragmentation

Aquatic and terrestrial habitats are degraded and destroyed as watershed lands are made impervious, and are adversely impacted by water pollutants and by the greater volume of stormwater runoff issuing from sealed urban surfaces. Measures of streams' biological integrity and habitat quality exhibit inverse relationships with the amounts of impervious surfaces adjacent to them (Klein, 1979; Schueler, 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997; Kennen 1999). Although no set threshold exists, significant declines in biological integrity and habitat quality are observable in watersheds with impervious cover ranging between10 percent to 20 percent. These observations include:

1. Shifts in populations of environmentally sensitive organisms to organisms more tolerant of degraded conditions;
2. Less riparian vegetation, and therefore reduced shading and entry of leaf litter;
3. Reduced macroinvertebrate, fish, and amphibian diversity;
4. Lower plant and amphibian density; -increased rates of water and sediment delivery;
5. Less wood (snags) in channels to dissipate stream energy; and
6. Channel instability (Booth and Jackson 1997; Kennen 1999; Schueler 1994).

As the imperviousness of watersheds increases, so does stream degradation and habitat loss. It is also important to note that some species show signs of stress and population decline before the 10 percent impervious cover threshold is reached.

Physical Degradation of Streams

As previously noted, urbanization increases the amount of sealed surfaces and increases the speed of water transmission in channels, leading to:

1. Increases in sediment yields, especially during construction;
2. Decreases in the numbers of stream channels to carry increased sediment loads;
3. Eradication of first-order stream channels;
4. Simplification of drainage networks and replacement of channels with storm sewers;
5. Faster flow velocities;
6. Increases in stream discharges that equal or exceed bank capacity; and
7. Increases in the cross-sectional areas of channels at bank capacity levels for drainage basins under 26 square kilometers (10 mi^2) (Dunne and Leopold 1978).

The removal of first-order, and in some cases, second-order channels is problematic since runoff and sediments formerly distributed among many small channels are now delivered to fewer channels. The outcomes of this are more rapid flow velocities and flood peaks, reduced channel storage, and the delivery of runoff to larger channels (Dunne and Leopold, 1978).

Channel and bank instability, which leads to the physical degradation of streams, stems from the increased flooding that follows development. The signs of instability, however, may not become evident for several years following urbanization. Signs of instability include channel widening by bank erosion or a deepening of the channel through down cutting. With the former, channel beds may become covered in sediment; with the latter, beds are subject to frequent scours. Table 8 demonstrates the degree of enlargement of channel area following development in a basin of 2.5 to 13 square kilometers (1 to 5 mi2). Note the time lag between development and channel enlargement as it is reflected by the ratio values: the longer the disturbance, the higher the ratio value.

Two final effects of increasing imperviousness are increased flood and erosion hazard following urban development. When development occurs on floodplains not previously developed, natural flooding will inevitably threaten the people and property inhabiting those floodplains, which can lead to environmental harm. What’s more, areas that did not commonly flood before urbanization may suffer more frequent inundations due to the greater volumes of runoff and increased flood heights associated with imperviousness. Properties and structures may be threatened by bank erosion from streams’ whose channels have been destabilized by upstream development. Finally, stream habitats may be degraded or destroyed should communities choose to cope with these hazards by straightening and/or dredging stream channels to promote rapid drainage from flood-prone areas and by paving stream channels to curtail bank erosion. This alteration of stream channels is called channelization. In addition to habitat loss, additional potential losses from channelization include:

1. Channel instability or the negative effects of channel readjustment to the newly imposed conditions;
2. Increases in downstream bank erosion, bed degradation or aggradation; and
3. Aesthetic degradation, especially changes in stream biota, and the visual alteration of stream banks, channel pattern or form, and riparian vegetation (Dunne and Leopold, 1978).

Biological Degradation of Streams

Biological degradation is generally manifested more rapidly than physical degradation. Aquatic and marine organisms respond immediately to widely fluctuating water temperatures, reduced inputs of organic matter, decreased food supplies, more frequent high flows, faster stream velocities, and higher loadings of sediments and other harmful pollutants during storms. These stressors may prove fatal to some organisms, impair the physiological functions and energy efficiencies of others, or encourage mobile organisms to migrate to more hospitable sections of streams, lakes, and estuaries. In urban and suburban settings, storm sewers and artificial channels have replaced many natural stream channels. This alters the types and amounts of habitats for aquatic organisms, and severely decreases streams' abilities to support sustainable, healthy biotic communities.

Sediments pose perhaps the most significant hazard to aquatic organisms within urbanizing watersheds. The sources of sediments include construction sites and the bank erosion that occurs as stream channels adjust to new flow regimes following increased imperviousness (Dunne and Leopold, 1978; Novotny and Chesters, 1981; Troeh, Hobbs, and Donahue, 1999). Increases in the suspended sediment loads of streams adversely affect stream and bay biota in fours ways:

1. Scouring of plant materials from rocks deprives grazers of food and disrupts aquatic food webs;
2. Sediments deposited on channel bottoms destroy benthic life, and kill the eggs and larval and juvenile forms of other organisms;
3. Sediment loads increase the turbidity of receiving waters, blocking sunlight and curtailing photosynthesis, especially photosynthesis by submerged aquatic vegetation; and

4. Water pollutants, especially nutrients and pesticides, enter streams and the bay attached to the sediments.

Effects of Urbanization on Terrestrial Habitats

Development, particularly spatially dispersed forms such as large-lot single family housing, results not only in greater amounts of impervious surfaces throughout watersheds, but in the destruction and fragmentation of terrestrial habitats. Of course, the outright destruction of habitat immediately and dramatically stresses plants and wildlife. The loss of biodiversity in such instances is swift and catastrophic. The adverse impacts of habitat fragmentation, however, are manifested more slowly and are often cumulative. Habitat fragmentation is the piecemeal disassembly of terrestrial habitats into discontinuous and oftentimes isolated patches of habitat. These patches are typically surrounded by or adjacent to roads, residential areas, commercial sites, or croplands that are hostile to many of the plants and animals that remain within. What is more, fragmentation changes the biological character of an area, favoring “edge” species and those tolerant of humans (Brewer, 1994).

As patches of remaining habitats become smaller and more isolated, the ability of those patches to support large and diverse populations of flora and fauna decreases. This is particularly so for birds and animals that are sensitive to human intrusion or whose ecological requirements include large tracts of continuous habitat. Moreover, forest fragmentation through road building and expansion and through increased residential development increases: 1) light penetration of the upper canopy; and 2) the amount of area exposed to direct sunlight. Hence, fragmentation favors light-tolerant (shadeintolerant) plants at the expense of those shade-tolerant plants that occupy the floors and lower tiers of interior forests. Habitat fragmentation reduces biodiversity--the pace may be slow, but the losses are certain. As Soule observes, “by the time the disappearance of wildlife is noticed by the human residents in a new subdivision, it is too late to do anything about it” (1991).

There are several major effects associated with habitat fragmentation: area, edge, distance, and age effects, which are summarized as follows:

1. Area effect. This effect concerns the harm done to wildlife by decreasing fragment size. Local open spaces and other conservation areas are usually too small to provide the habitat required by many species.

2. Edge effect. Edges, also known as ecotones, are boundaries between habitats. These boundaries can be transitional or, as in the case of human-modified landscapes, very sharp. Edges include boundaries at the margins of lawns, cropland, and wooded areas, and roads, utility rights-of-ways, and forests. The ratio of habitat edge to interior habitat increases as patches become smaller, or as patches become elongated in shape. Some species benefit from edges, such as white-tailed deer and turkeys; however, increases in edges are generally detrimental to overall

biodiversity. The edge effect includes: - increased plant desiccation and wind-throw hazard; - more frequent and more severe wildfires; - increased poaching and hunting; - higher predation rates; - heavier browsing and more disturbances that favor opportunistic species, and - increased cowbird parasitism of songbird nests.

3. Distance effect. In order to move from one habitat patch to another, animals and birds must pass through inhospitable and increasingly dangerous spaces, where injuries and deaths from accidents, predation, or adverse environmental conditions are more likely to occur. Increasing distances between residual habitats makes it more difficult for animals to move between fragments for purposes of foraging, hunting, or mating. Greater separation distance means fewer movements by animals between patches, and, consequently, less interaction between populations.

4. Age effect. Habitat fragmentation and the accompanying losses in the types and numbers of species are gradual and cumulative. Older isolated patches should therefore be more disturbed and contain fewer species than comparably sized patches more recently isolated (Adams, 1994; Bolen and Robinson, 1999; Brewer, 1994; Soule, 1991).

Stream and Landscape Aesthetics

The trend toward more impervious cover within a watershed alters the visual character of its streams and landscapes. Whether such changes are deemed blighting or appealing depends upon the visual preferences of individuals and groups. The old adage “beauty is in the eye of the beholder”- applies to streams and watersheds as well as to individuals and works of art. Since no general rule exists as to what constitutes a beautiful or attractive landscape, it must be acknowledged, in the words of geographer Peirce Lewis, that “Aesthetic judgment is inherently perilous” (1973). A landscape that pleases one may offend the eye of another. To some individuals, urban sprawl, with its impervious surfaces, is preferable to the agricultural and rural landscapes it consumes. Others lament the lost of rural landscapes and find the visual character of sprawl unappealing and offensive. Loss of rural scenery is not the only concern though; also lost are the ways of life nurtured by rural landscapes.

Regardless of how the visual impacts of development are judged, it is undeniable that the natural values of streams and their watersheds are compromised or destroyed by urbanization and that their visual characteristics are profoundly changed. For example, the banks of urban streams are often stripped of vegetation and heavily eroded. Stream channels may be littered with debris such as bricks, tires, shopping carts, and other thoughtlessly disposed rubbish. Clearly, the aesthetic appeal and recreational values of such streams are diminished or destroyed.

As streams channels in urbanizing areas are gradually enlarged due to more frequent flooding, channel beds become either scoured or muddy, diminishing their visual appeal. In order to combat urban flooding or channel instability, some communities may replace natural stream channels and banks with artificial or severely altered channels and banks. This is an extreme measure, for it destroys aquatic habitats and alters the appearance of streams. Gone is the interplay of light and shadow, the varying water depths and bottom characteristics, the presence and interaction of vegetation and aquatic organisms, all of which produce dynamic and diverse visual scenes. In their stead are the homogenous and monotonous scenes of imperviousness--devoid of vegetation and inimical to life.

Summary

The uncontrolled conversion of land covers from permeable to impervious is a serious threat to the integrity of both natural and built environments within the Chesapeake Bay watershed, and to the comfort and overall quality of life for its residents. The increase in watershed imperviousness and the outward diffusion of impervious surfaces from established urban and suburban core areas into rural lands are dramatically increasing the volumes of stormwater with which communities must contend. This increased runoff creates flood hazards and contaminates surface water with pollutants that accumulate on the streets, highways, parking lots, and even the lawns of urbanized areas, all the while degrading the physical quality of streams. Due to the contributions of impervious surfaces to the urban heat island effect, human comfort is reduced during the summer. Aquatic and terrestrial habitats are degraded or lost as commercial, industrial, and residential land uses consume more and more space. Finally, the destruction and alteration of stream channels and the transformation of forests and croplands to residential subdivisions, malls, and parking lots are degrading the aesthetic quality of many of the bay's streams and landscapes.

Although urban and suburban growth within the bay's watershed is inevitable, many of the environmental impacts of impervious surfaces are avoidable or controllable. Working together, local governments and citizens can reduce the amount of land rendered impervious, and can reduce its adverse impacts, promoting a healthier environment through sound land use planning and improved land management. If there is a will to save the bay's watersheds, there are ways to do it.

Table 1. Urban Nonpoint Pollutants: Categories, Parameters, and Sources

Category	*Parameters*	*Potential Sources*
Bacteria	Total and fecal coliforms, fecal streptococci, other pathogens	Animals, birds, soil bacteria, humans
Nutrients	Nitrogen and phosphorus	Pets, birds, and animals; lawn fertilizers; decomposing organic matter (leaves and grass clippings); urban street refuse; atmospheric deposition
Biodegradable chemicals	Biological oxygen demanding wastes, chemical oxygen demanding wastes, total organic carbon	Leaves, grass clippings, animals, street litter, oil and grease
Organic chemicals	Pesticides, PCBs	Pest and weed control, packaging, leaking transformers, hydraulic and lubricating fluids
Inorganic chemicals	Suspended solids, dissolved solids, toxic metals, chloride	Erosion (lawns, stream banks and channels, construction sites), dust and dirt on streets, atmospheric deposition, industrial pollution, illegal dumping during storms, traffic, deicing salts
Physical and aesthetic	Thermal, discoloration, odors	Heated streets, parking lots, sidewalks, and rooftops (summer only) Runoff from industrial sites Animal wastes and organic matter, hydrocarbons

Sources: Novotny and Chesters, 1981; Hansen, et al., 1988; Whipple, 1977

Table 2. Factors Strongly Affecting Urban Nonpoint Source Pollution

Factors Which Are Closely Correlated with Urban Land Use and Land Cover	*Factors Which Are Poorly Correlated with Urban Land Use and Land Cover*	*Factors Unrelated to Urban Land Use and Land Cover*
Amount of impervious area (usually correlated with population density)	Street surface conditions	Meteorological and climatic factors
Curb length density and height	Amount of impervious area hydraulically connected to stream channels	Soil texture, structure, and composition
Vegetation cover and pervious surfaces	Net amount of nonpoint pollutants delivered to streams compared to gross amounts of pollutants available (Delivery Ratio)	Permeability
Traffic density	Surface storage	Soil cation exchange capacity
Atmospheric fallout	Organic content of soils	Slope
Street litter accumulation rates	Nutrient content of soils	
Street cleaning practices		
Pollutant conveyance systems (storm sewers, combined sewers, unsewered)		

Source: Novotny and Chesters, 1981

Table 3. Nonpoint Pollutants Associated With Transportation

Pollutant	*Source*
Asbestos	Clutch plates, brake linings
Copper	Thrust bearing, bushing, and brake linings
Chromium	Metal plating, rocker arms, crankshafts, rings, brake linings, and pavement materials
Lead	Leaded gasoline (banned in US), motor oil, transmission babbitt metal bearings
Nickel	Brake lining and pavement materials
Phosphorus	Motor oil additive
Zinc	Motor oil and tires
Grease and hydrocarbons	Spills and leaks of oil and n-paraffins lubricants, antifreeze, hydraulic fluids
Rubber	Tire wear

Source: Novotny and Chesters, 1981

Table 4. Albedos of Various Watershed Surface Covers

Surface Cover	*Albedo (%)*
Brick and Stone	20% - 40%
Blacktop Surfaces (asphalt)	5% - 10%
Dry Concrete	17% - 20%
Dark Roof	8% - 18%
Light Roof	35% - 50%
Crops	15% - 25%
Deciduous Forest	10% - 20%
Coniferous Forest	5% - 15%
Grass	25% - 30%

Sources: Conway, 1997; Christopherson, 2001.

Table 5. Specific Heat of Some Common Substances

Substance	Specific Heat (calories per gram per ^{o}C)
Water	1.0000
Wet Mud	0.6000
Wood	0.4200
Brick	0.2140
Concrete	0.2000
Dry Sand	0.1900
Asphalt	0.1785*

Source: Danielson, et al 1998; Forsythe,1959; Moran and Morgan, 1986; Marsh, 1998; and author's calculations.

Table 6. Thermal Conductivities of Common Earth Materials

Substance	Thermal Conductivity in W/mK
Air	
Still (at 10^{o}C)	0.025
Turbulent	3500-35,000
Water	
Still (at 4^{o}C)	0.6
Stirred	350.00
Sandy soil (40% pore space)	
Dry	0.30
Saturated	2.20
Clay soil (40% pore space)	
Dry	0.25
Saturated	1.58
Organic soil (80% pore space)	
Dry	0.06
Saturated	0.50
Asphalt	0.8 - 1.17
Brick (dry)	0.8 - 1.2
Concrete	0.9 - 1.3

Source: Ellis and Mellor, 1995; Kaye and Laby, 1995; Marsh, 1998.

Table 7. Warm Season Bowen Ratios and Heat Indices for Selected Surfaces

Surface Type or Cover	Bowen Ratio	Sensible Heat Index (%)
Desert Surface	20.0	95%
Impervious Urban Surface	4.00	80%
Grassland and Cropland	0.67	40%
Coniferous Forest	0.50	33%
Deciduous Forest	0.33	25%

Source: Oliver 1973

Table 8. Ratio of Enlarged Channel Area to Natural Channel Area

Land Use / Land Cover	Ratio (Enlarged Channel Area/Natural Channel Area)
Wooded land	0.75
Previous developed land	1.08
Impervious area less than 4 years old; unsewered streets and houses	1.08
Cultivated land	1.29
Houses more than 4 years old fronting on sewered streets	2.19
Sewered streets more than 4 year old	5.95
Impervious areas more than 4 years old	6.79

Source: Dunne and Leopold 1978.

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