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Fragmentation, Impervious Surfaces and Water Quality: Quantifying the effects of density and spatial arrangement

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FRAGMENTATION, IMPERVIOUS SURFACES AND WATER QUALITY: QUANTIFYING THE EFFECTS OF DENSITY AND SPATIAL ARRANGEMENT

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Impervious surfaces have for many years been recognized as an indicator of the intensity of the urban environment and, with the advent of urban sprawl, they have become a key issue in habitat health. In addition to the direct impacts to water quality, impervious surfaces fragment open space and habitat and are therefore a primary land use indicator of both water quality and ecological degradation. This paper develops an understanding of the land use planning implications of the interaction of impervious surfaces, water quality and the spatial form those surfaces take in a watershed. In order to clarify these relationships, the analysis relies on two levels of information: 1) a review of the literature to determine the extent to which the density and placement of impervious surfaces has been found to affect water quality; and 2) modeling three types of residential developments to determine their effects on impervious surface ratios as well as their effect on both habitat fragmentation and water quality.

1 INTRODUCTION

Impervious surfaces have for many years been used as an indicator of the intensity of the urban environment (Stankowski, 1972). With the advent of sprawl, impervious surfaces have also become a key factor in habitat quality. Increasing urbanization within watersheds has resulted in increased amounts of impervious surfaces - roads, parking lots, roof tops, etc. - and a decrease in the amount of forested lands, wetlands and other forms of open space which absorb and clean stormwater in the natural system (Leopold, 1968). This change in the balance of impervious and pervious surface area within watersheds has caused significant changes to both the quality and quantity of runoff. These changes can be measured in terms of increased quantity of stormwater for stream systems to absorb (termed flashier hydrographs), sedimentation, and an increased pollutant load carried by the stormwater. Although more highly concentrated per acre in urban areas, the amount of impervious surface per capita rises exponentially in suburban and exurban areas.

In addition to the direct impacts to water quality, developing areas containing impervious surfaces can fragment open space and habitat and are therefore a primary land use indicator of both water quality and ecological degradation. All of these environmental changes to stormwater quality and quantity are significantly influenced by shifts in population centers and urban growth patterns, the associated conversion of forested land and agricultural land to roads, commercial areas, housing developments and parking lots, and the increase in overall impervious surfaces as the ratio of persons per acre in urban and

suburban areas decreases. Although considerable study has been given to understanding the sources and fluxes of nutrients from individual watersheds (Schueler, 1994), comparatively little work has been undertaken to see how watersheds have changed in land cover over time and what effect that this change has had on water quality. Previous research has attempted to quantify the water quality impacts of impervious surfaces (Graham et al., 1974), however the spatial forms and relational impacts that imperviousness has in various land uses have been largely ignored, yet these are a critical issue in the puzzle of land use planning.

This paper develops an understanding of the land use planning implications of the interaction of impervious surfaces, water quality and the spatial form those surfaces take in a watershed. In order to clarify these complex relationships, the analysis relies on two levels of information: 1) a review of the literature to determine the extent to which the density and placement of impervious surfaces has been found to affect water quality; and 2) modeling three types of residential developments to determine their effects on impervious surface ratios as well as their effect on both habitat fragmentation and water quality.

2 ANALYSIS OF EXISTING LITERATURE

Although scientifically, the ratio of total imperviousness in a watershed has been shown to be the key parameter in stormwater runoff models (Graham, Costello and Mallon, 1974), that fact has not been rationalized into the planning and development process. An increase in runoff volume due to impervious surface can range from 0.09%-0.04% per 1% impervious cover depending on the level of rainfall (Corbett et al., 1997). Various studies have quantified this number in a variety of situations: 1) in an urban watershed with 23% impervious cover, runoff was 5.5 times higher than in a forested area in a model; 2) in a 75mm rainfall, runoff doubled between 0-10% impervious cover (Corbett et al., 1997); and 3) increases in runoff were measured between 220-1820% based on development types in Akron, Ohio (Harbor, 1994). To date, land use planning and zoning is commonly carried out based on use and density categories which can provide specific indicators - through allowable lot coverage, road standards and parking lot requirements - of the total impervious surface that will result. However, local planning departments do not typically engage these potential projections, nor existing land use analyzes, to plan on a watershed basis for water quality protection.

2.1 Measures of the Effects of Impervious Surface on Stream Quality

From a planning perspective, the most important numerical quantification of the impact of imperviousness on stream quality is the threshold level at which water quality impacts occur. Threshold, as defined in this paper, means a point at which measurable stream quality degradation first occurs. The level of impervious surface at which degradation is first measurable is generally the level at which the greatest change in stream quality occurs. However, May et al. (1997) state that "...physical, chemical and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion." Yet, after a certain level of degradation there may not be much aquatic life that remains to be harmed, even if the increments of measurable destruction become larger in relation to the amount of additional impervious surface (Wang et al., in press). However, before a threshold can be determined, the concept of impact must be defined.

Since stream quality is a combination of the physical, chemical and biological health of a stream, it stands to reason that there are a variety of measures for stream quality. These generally fall into two categories: biotic and abiotic measures. Many of the studies reviewed for this paper define a percent of impervious surface at which a factor of stream quality is

measurably degraded, however these differ in their criteria for the designation of a healthy versus an impacted stream.

In the studies reviewed, the threshold of biotic degradation is defined most commonly by Index of Biotic Integrity (IBI) (Steedman, 1988) which measures aquatic species richness and composition, local indicator species, trophic composition, fish abundance and fish diversity (Miltner, 1997; Wang et al., in press; Horner et al., 1997; Shaver et al., 1995; Wyzdga, 1997).

The threshold for many physical parameters was defined in terms of their effect on biota. They are classified as abiotic measurements because they do not measure overall biotic health but rather the response to one variable such as increased water volumes; sedimentation and solids (Wyzdga, 1997; Griffin et al., 1980; May et al., 1997; Horner et al., 1997), channelization and streambank erosion (Booth and Jackson, 1997; May et al., 1997), habitat (Horner et al., 1997; Booth and Reinelt, 1993), temperature (Galli, 1990), volume of baseflow (Tennant, 1975), dissolved oxygen (May et al., 1996), nutrients (Griffin et al., 1980; May et al., 1997) and heavy metals (Horner et al., 1997).

Abiotic measures have a variety of thresholds:

1. **Flooding:** High peak flows can also increase the frequency and size of floods. A study of 15 small catchments showed that floods with a 1 year recurrence level are affected after 5% TIA while floods with a 100 year return period may double in size after 30% impervious cover (Hollis, 1975). Similarly, Booth (1991) found that floods in streams of the U.S. Pacific Northwest might increase by up to 2 orders of magnitude under urbanized conditions.
2. **Sedimentation:** Eroded soil from degraded streambanks creates sediment as it is deposited in streams. Sedimentation can be as great as 5.5 times higher in an urban watershed than in undisturbed areas (Corbett et al., 1997).
3. **Channelization:** Channelization occurs when high peak flows erode stream banks and deepen the stream channel. Arnold et al. (1982) found that extensive bank erosion occurred when total impervious area increased from 0-15% in a Connecticut watershed. A similar trend was found in 78 small watersheds in Pennsylvania, exhibiting enlarged stream channels in areas of high development (Hammer, 1972).
4. **Habitat:** Large woody debris (LWD) in streams trap sediment, form pools and provide aquatic habitat. Impervious surfaces reduce the abundance of LWD because high flows wash out LWD and also because impervious surfaces often replace sources of LWD. A study of streams in the Pacific Northwest found that in basins with more than 9% impervious cover, LWD was always lower than 300 pieces/km (Horner, 1996). In another study of 22 Pacific Northwest streams, May et al. (1997) found that more than 350 LWD/km were found only in streams within basins with less than 5% impervious cover.
5. **Reduced or eliminated groundwater recharge:** Impervious surfaces block the absorption of water that would otherwise naturally filter into the ground to feed streams and aquifers. Streams in urbanized areas often run dry or have reduced base flow between storm events. Base flow in six Long Island, New York streams was compared between 1948-1970 and were shown to have decreased base flow of only 20% of original levels, while base flow in rural areas stayed relatively constant at 95% of total stream flow (Simmons and Reynolds, 1982). A model based on data from Akron, Ohio calculated the following changes in runoff and ground water recharge when a woodlot is converted to the following uses (Harbor, 1994):

Table 1: Runoff and groundwater recharge measurements for conversion of woodland to various types of development (adapted from Harbor, 1994)

| New land use | | Increase in runoff | Decrease in groundwater recharge |
|--------------------------------------|--|--------------------|----------------------------------|
| Agricultural/low density residential | | 220% | 11-30% |
| High density residential | | 1000% | 52-100% |
| Commercial | | 1820% | 94-100% |

6. **Nutrients and Heavy Metals:** Pollutants such as nutrients, heavy metals, petrochemicals, hydrocarbons and salt which are deposited on impervious surfaces combine with stormwater runoff and enter streams. Because of high runoff velocity, pollutants cannot decompose or infiltrate into the soil (Corbett et al., 1997). Pollutant levels show a higher tolerance to TIA than physical and biological changes, not registering as harmful or measurable until 30-60%. Results from a study of two Virginia watersheds showed an increase in phosphorus, nitrogen, dissolved oxygen and suspended solids related to urbanization but sharp increases were measured after impervious levels reached 40-50% (Griffin et al., 1980). May et al. (1997) similarly found that phosphorus, and suspended solids remained acceptable until impervious cover was greater than 45%. A similar study of Pacific Northwest streams and wetlands found no significant chemical changes until TIA reached 60% (Horner et al., 1996).

The most notable trend in the data of the studies reviewed is the difference in the thresholds for biotic and abiotic measurements (see Table 2). Biotic thresholds, including fish and macroinvertebrate diversity and abundance, ranged from 8 to 15% impervious surface with an average of 9.9%. Abiotic measurements, including water quality and habitat characteristics, ranged from 9 to 50% with an average of 32.29%.

The measurements were further divided into fish, macroinvertebrates, physical habitat and water quality. Fish and macroinvertebrates had similar thresholds. The threshold for fish population health ranged from 8-12% with an average of 10%. Macroinvertebrate health declined above a range of 8-15% with an average of 9.75%. Water quality was more variable, with thresholds ranging from 10-50% with an average of 39.36%. Physical measurements were much more variable ranging from 9-45% with no apparent consistency in findings.

The different thresholds for each group may be attributed to a number of factors. First, biota is effected by a combination of both physical and chemical habitat, reflecting the impact of a combination of abiotic changes. Therefore, degradation in biotic diversity and abundance may be a more accurate measure of overall stream health rather than chemical water quality and habitat. Second, biota reflect the long-term health of the stream and not chemical changes which may be shorter lived (Shaver et al., 1994). Third, biota appear to be more effected by habitat destruction than water quality. Therefore, aquatic communities change at a level of impervious surface much lower than that which impacts water quality measures.

Several studies have combined abiotic and biotic, measurements to arrive at an overall percent of impervious surface that a watershed can sustain. Using habitat characteristics, and biological integrity as stream health indicators, May et al. (1997) determined that at 5-10% TIA stream quality declined rapidly. After studying the channel morphology, mitigation barriers, base flow, temperature and water quality of 27 small watersheds in Maryland, Klien (1979) estimated that stream impairment could be avoided at TIA less than 15%.

Table 2: Water degradation thresholds for biotic and abiotic measurements.

| Impact Measurement | | % impervious threshold for degradation | Study |
|--------------------|----------------------------------|----------------------------------------|-------------------------|
| Measurement | Parameter | | |
| biotic | fish diversity & abundance | 3.6 | Booth and Jackson, 1994 |
| | fish diversity | 8 | Miltner, 1997 |
| | species diversity | 10 to 15% | Booth and Reinelt, 1993 |
| | fish diversity | 12 | Klien, 1979 |
| | benthic invertebrates | 8 | Horner et al., 1997 |
| | benthic invertebrate diversity | 15 | Klien, 1979 |
| | macroinvertebrates diversity | 8 | Miltner, 1997 |
| abiotic | peak flows | 4.6 | Booth and Jackson, 1994 |
| | large woody debris | 9 | Horner et al., 1997 |
| | stream bank erosion | 10 | Booth and Jackson, 1994 |
| | | 8 to 10% | Booth and Reinelt, 1993 |
| | | 30 | May et al., 1997 |
| | temperature for cold water biota | 12 | Galli, 1990 |
| | dissolved oxygen | 10 | May et al., 1997 |
| | oxygen | 43 | Griffin et al., 1980 |
| | stream flow | >21 | Horner et al., 1997 |
| | baseflow | 45 | Tennant, 1975 |
| | | 45 | Klien, 1979 |
| | chemical water quality | 45 | May et al., 1997 |
| | metals | 50 | Horner et al., 1997 |
| | zinc | 40 | Horner et al., 1997 |
| | nutrients | 42 | Griffin et al., 1980 |
| | phosphorus | 45 | May et al., 1997 |
| | solids | 43 | Griffin et al., 1980 |
| | | 45 | May et al., 1997 |
| | sediment | 20 | Wydzga, 1997 |
| | | 50 | Horner et al., 1997 |

2.2 Mitigation

Riparian buffers and best management practices (BMPs) are often used to mitigate the impact of impervious surfaces in a watershed. In studies of stream quality these measures have varying degrees of effectiveness, therefore there seems to be no conclusive answer to the question, "At what percent impervious surface can stream quality impacts not be mitigated?" However, after studying BMPs in Delaware, Maxted and Shaver (1998) found that BMPs could not mitigate the impacts of urbanization once the watershed reached 20% impervious cover. Galli (1990) found that none of the four BMPs he studied in Maryland prevented temperature standard violations in areas of impervious surface ranging from 12-30%.

The presence of riparian forests can mitigate the impacts of impervious surface in a watershed, however they also have effective limits. Steedman (1988) found that the amount of riparian cover that can be removed while sustaining biological integrity is inversely proportional to the amount of impervious surface. With 0% urbanization, 75% of the riparian forest could be removed. With 55% urbanization, 0% could be removed. However, even complete retention of streamside buffers could not prevent "measurable degradation" after approximately 7-10% impervious area (Booth and Reinelt, 1993), and after watershed

imperviousness reached 40% in Seattle area watersheds, riparian buffers ceased to effectively protect biological integrity (Horner, et al., 1994).

2.3 The Placement of Impervious Surface within a Watershed

The placement of impervious surface within the watershed appears to be of some importance to stream quality, although no quantitative relationships have been made between percent impervious surface, placement and stream quality. The placement of impervious surface determines a number of changes in stream functioning including speed with which flow enters stream and the level of absorption of rainfall by pervious surfaces.

The placement of impervious surface along the stream course may contribute most to stream health. In general, upstream impacts will create disturbances over more stream miles where as downstream disturbances will create more concentrated impacts (Maxted and Shaver, 1998). Increased sediment from streambank erosion occurs especially when the upper watershed is paved as compared with the lower reaches (Booth, 1991).

The distance of the impervious cover from the stream channel appears to be one the most important factors regarding placement. This is primarily true for areas in which runoff is not piped directly to the stream. Impervious cover located further away from the stream resulted in less channel enlargement in watersheds near Philadelphia (Hammer, 1972). Tufford et al. (1998), found that nutrient concentrations changed significantly in relation to land use within 150 meters of streams in South Carolina. Beyond this point, land use change did not significantly effect nutrient concentrations. In his assessment of Ontario area streams, Steedman (1988) also found that land uses 10-100km² above the site of interest are more important to biotic integrity than the land uses within the entire basin.

As discussed earlier, evidence shows the use of buffers to be somewhat effective in mitigating the effects of impervious areas. This same fact demonstrates that imperviousness placed further from the stream will have less impact if only by virtue of not destroying the buffer. For example, preserving streambank vegetation reduces evapotranspiration and increases groundwater absorption that can mitigate low flows (Ferguson and Suckling, 1990).

The organization of impervious surface is of some importance to stream quality although its significance may well change depending upon whether streets are sewered or not. For example, higher sediment yields were measured in areas with dispersed impervious surface as opposed to clustered development (Corbet et al., 1997). Conversely, Yoder and Rankin (1997) found that biological performance was good even with urbanization as high as 15% if the site was developed with large-lot, estate-type residences.

2.4 The Impacts of Pervious Surfaces

Although the data indicates that impervious surface is the dominant determinant of stream quality, pervious surfaces also impact stream quality. Several studies show how pervious surfaces variably effect peak flows, water quality and other stream characteristics.

In a study of 103 streams in Wisconsin, only 10-20% urban land use was needed to put IBI scores in the poor range, yet, over 50% agricultural land was required to reduce IBI scores. IBI scores increased steadily with increasing forest cover (Wang et al., 1997). In a study comparing three watersheds dominated by forest, agricultural land and urban land Crawford et al. (1989) found that streams in an agriculturally dominated watershed had the highest nutrient levels but the urban streams had the highest temperatures and concentrations of metals.

In a study of channel enlargement Hammer (1972) found that forested land contributed least to channel enlargement whereas sewared streets were the prime factor in stream channel enlargement. These results are corroborated by a finding that runoff volumes are highest in commercial areas and least in agricultural areas. Likewise, groundwater

absorption declines as urbanization rises, being greatest in agricultural setting and least in commercial (Harbor, 1994).

Ross and Dillaha (1993) compared runoff, nutrient and sediment concentrations from six different pervious surfaces in a simulated rainfall event (Table 3). The results showed a great difference in the runoff characteristics among different types of pervious surfaces. While a mulched landscape produced no runoff, a gravel driveway and bare soil acted very much like an impervious surface.

Table 3 Comparison of runoff characteristics for different pervious surfaces (Ross and Dillaha, 1993)

| Surface | RV (Runoff) | Nitrate | Soluble P | TSS |
|---------------------------|-------------|---------|-----------|------|
| Gravel Driveway | 0.51 | 0.03 | 0.06 | 692 |
| Bare Soil | 0.33 | 0.32 | 0.79 | 1935 |
| Cold-Season Grass, sodded | 0.05 | 0.31 | 1.12 | 29 |
| Warm Season Turf | 0.03 | 0.44 | 0.33 | 43 |
| Mulched Landscape | 0.00 | None | None | None |
| Meadow | 0.00 | None | None | None |

3 MODEL SITE PLANS AND POLLUTANT RUNOFF CALCULATIONS FOR THREE DIFFERENT SCENARIOS

While much of the foregoing analysis has been directed at the impacts of impervious surfaces on a watershed basis, the following model looks at the impacts of specific development patterns. As discussed above, the literature suggests that significant water quality improvement can be gained by directing the location of impervious surfaces in a watershed. The following series of design models analyze how the placement of new development on the land can affect the amount of impervious surface produced, however these models do not test the effects of the location of the development in the watershed. These design models indicate that a reduction in impervious surface gained through careful site design can also have the effect of protecting larger amounts of forested lands which can provide critical habitat as well as mitigating the impacts of urbanization on the watershed.

A 180 acre site in Frederick County, Maryland was chosen as a model of typical coastal piedmont development, in a region of various imperviousness impact studies (Galli, 1990 ; Schueler and Galli, 1992; Griffin, 1980; Klein, 1979). Three development scenarios were prepared: one using conventional, large-lot patterns, a second under a tightly clustered development scenario, and a third under a modified conventional pattern, which utilizes many of the same best management practices to mitigate the level of run off that were used in the cluster scenario.

The site contains Piedmont soils found through out the Chesapeake Bay watershed, and is representative of topography found in non-coastal states such as Pennsylvania. Digital computer mapping files for the model site were obtained from the Maryland Department of Natural Resources Chesapeake and Coastal Watershed Services GIS Services Division, including topography at two foot intervals, existing vegetative cover, soils, and wetland information.

3.1 Site Summary Data for the Model Development Scenarios

Frederick County's zoning ordinance and subdivision regulations were used to guide the design of the conventional site development plan. The County's regulations include a R-1 zoning category, exemplified by Scenario 1 (figure 1), which requires large lots (1 acre minimum), 25 foot set backs for building, streets that are a minimum of 36 feet wide, and

provides minimal forest and/or open space protection. Scenario 2 (figure 2), on the other hand, utilizes Frederick County's Planned Unit Development code to guide the design and a variety of design tools to create a clustered development that will reduce impacts to the surrounding natural environment. At the same time, Scenario 2 reduces the amount of roadway while maintaining a similar number of developable lots.

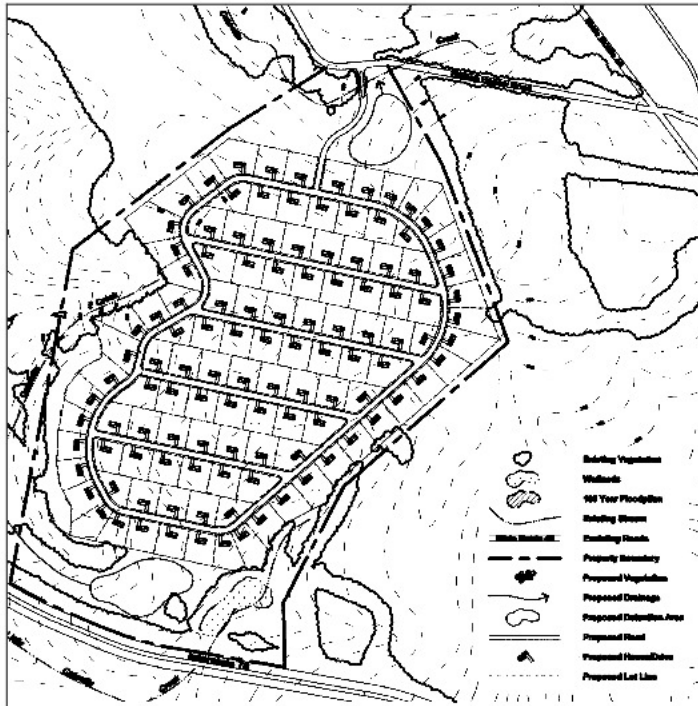


Figure 1: Scenario 1 showing conventional development pattern characteristic of suburban sprawl.

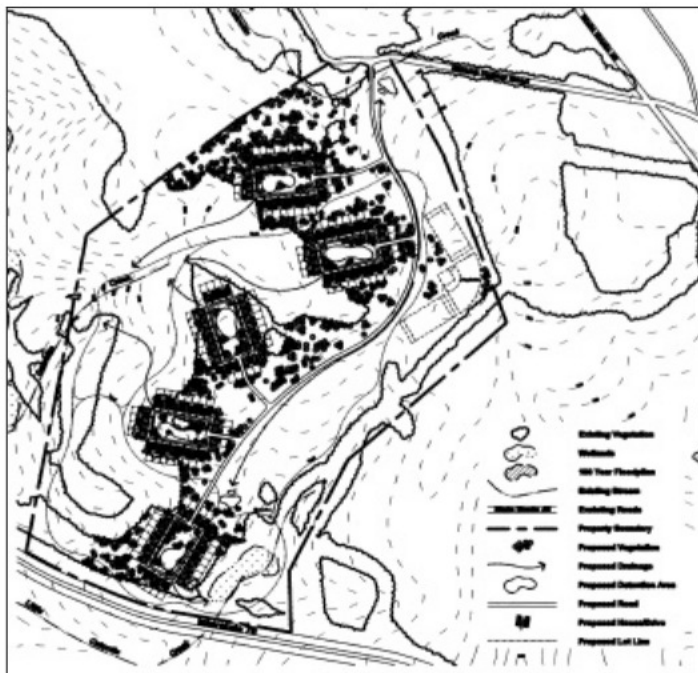


Figure 2: Scenario 2 showing cluster development option which conserves forest land and reduces impervious surface.

Scenario 3 (figure 3) presents a compromise between the two, applying a variety of design tools to a typical R-1 large lot layout. All three site plans are based on sanitary sewer access for each home.



Figure 3: Scenario 3 showing modified conventional development pattern using design tools to reduce impervious surface.

Each plan sites 116 homes, excluding steep slopes and wetlands in the buildable areas, except for the cluster development (scenario 2) which adds an additional 3 units as allowed by the County's code. With these units, the typical development (scenario 1) would result in the clearing of 102.46 acres, while the cluster development would only result in the clearing of 66.7 acres. This results retention of only 36% of the existing forest canopy under the conventional development pattern, and with the addition of reforested areas, results in the protection of 115% of the original forest canopy in the cluster design. Scenario 3 protects 83% of the original canopy through careful siting of the homes and the requirement to protect existing trees on site during the development process.

In addition to protecting a larger amount of forest cover, the cluster scenario also protects larger expanses of habitat than either of the two typical development plans. While Scenario 3 protects some additional forest areas when compared with scenario 1, the areas are fragmented with numerous road crossings and do not create any aggregate patches of forest.

The effect on impervious surface is seen most dramatically in the amount of roadway created, and to a lesser extent, the amount of driveway (see table 4). With the reduction in roadway length required to serve the clustered units in addition to the decreased roadway widths (from 36ft. to 18 ft.), the cluster development scenario has a total impervious ratio of 2.46%, compared to 10.95% for the conventional development plan. In the modified typical development of scenario 3, impervious savings are gained primarily through decreased roadway widths and a decrease in driveway area, leaving a total impervious ratio of 4.39%.

Compounding the water quality effect of the typical development plan is the fact that the streets are all of curb and gutter design, requiring piping of the stormwater runoff into a

storm sewer system. Both the cluster development and the modified typical development plans do not pipe the stormwater into a storm sewer system.

Table 4: Forest retention and total impervious cover resulting from the three model development scenarios.

| | Existing Conditions | Scenario 1: Typical Development | Scenario 2: Cluster Development with Tools | Scenario 3: Typical Development with Model Tools |
|---------------------------------------|----------------------------|----------------------------------------|---------------------------------------------------|---------------------------------------------------------|
| Total Site (Acres) | 180.80 | 180.80 | 180.80 | 180.80 |
| Number of Housing Units | 0 | 116 | 120 | 116 |
| Clearing and Grading (Acres) | | 102.46 | 62.66 | 75.66 |
| Existing Woodland (Acres) | 66.70 | 24.10 | 63.90 | 50.90 |
| Proposed Trees (Acres) | 0.00 | 0.00 | 12.75 | 4.65 |
| Total Canopy | 66.70 | 24.10 | 76.65 | 55.55 |
| % Original Canopy | 100.00% | 36.13% | 114.92% | 83.28% |
| Roads (Square feet) | 0.00 | 518,241.80 | 193,514.80 | 345,494.50 |
| Driveways (Square feet) | 0.00 | 125,280.00 | 89,442.00 | 94,338.00 |
| Roofs (Square feet) | 0.00 | 219,240.00 | 226,800.00 | 219,240.00 |
| Total Impervious Cover (Acres) | 0.00 | 19.81 | 4.44 | 7.93 |
| % Imperviousness | 0.00% | 10.95% | 2.46% | 4.39% |
| Proposed Trails (Linear feet) | 0.00 | 0.00 | 12,622.60 | 12,205.50 |
| Storm Water (Linear feet) | 0.00 | 14,255.50 | 0.00 | 0.00 |
| Other Utilities (Linear feet) | 0.00 | 14,255.50 | 11,078.90 | 14,255.50 |

4 CONCLUSIONS

Based on the three model site developments and on a review of the literature, there are a series of planning recommendations that can be made to reduce impervious surfaces and fragmentation of natural habitat.

Most critically, the clustering of land uses watershed wide results in lower per capita impervious surface rates. Although on an acre by acre basis, one house per acre may intuitively seem to result in lower impervious surface rates than 4 units on that acre, on a watershed wide basis, the savings in impervious surfaces per capita are significant. The primary source of impervious surfaces in a watershed is from roadways, not from buildings, therefore the most significant savings can be found here.

An additional benefit of the clustering of land uses lies in the undeveloped land that remains. Existing research indicates that in order to protect water quality and stream function, at least 30 to 50% of the watershed should be protected in mature forest stands. If this is accomplished on a parcel by parcel basis, the undeveloped portion of the site should be protected permanently as open space. The same result can be accomplished on a watershed scale through transfer of development rights, restrictive zoning or growth boundaries. The protected land, if left in undisturbed forest, can serve to mitigate the impacts of impervious surface elsewhere in the watershed. Forest stands infiltrate stormwater which runs off adjacent impervious surfaces, and in addition stabilize base flow conditions for the streams.

Priority should be given to retaining undeveloped open space found in existing forest stands along stream banks since they function as a riparian buffer. By serving as a source of large woody debris, mitigating temperature increases, and stabilizing stream banks, riparian buffers can mitigate some of the effects of watershed development.

Finally, the location of development within the watershed is key to mitigating its impacts. The location will depend on the particular goals for the watershed, however water quality goals are aided through the protection of headwater areas from development. Ten, prioritizing subwatersheds or feeder streams can help to determine whether to locate development in the upper reaches of the watershed and dilute the impacts of the development throughout the entire stream system, or to locate it closer to the mouth of the system, protecting high water quality in the upper reaches.

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