LITERATURE REVIEW:

Coastal Urbanization and Microbial Contamination of Shellfish Growing Areas

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INTRODUCTION

Many factors influence the condition and suitability of shoreline areas for growing and harvesting shellfish, and none is more vital than clean water. Human habitation of the nation's coastal regions has had a direct and dramatic effect on the condition of our coastal habitats and resources. A primary concern in shellfish growing areas is contamination from human and animal feces and the related public health risks associated with the consumption of contaminated shellfish. Sources of fecal pollution in the coastal environmental include discharges from municipal sewage treatment plants, on-site sewage systems, urban runoff (commonly called stormwater runoff), marinas and boaters, farm animals, pets, wildlife, and other assorted sewage sources.

While shoreline conditions vary from site to site, the contamination and classification of shellfish growing areas tend to correlate with population levels and land uses in the adjacent shorelines and uplands. In general, rural watersheds with limited development and intact native land cover are best suited to shellfish harvesting. However, rural watersheds are an increasingly rare commodity in coastal America because of population growth and development, which in turn is placing greater pressure on shellfish harvesting and other valued uses of the shoreline environment that depend so heavily on clean water. When left unchecked, the process of urbanization—defined as the transformation of natural landscapes to built environments—can render adjacent waters permanently unfit for the harvest and consumption of shellfish. In Puget Sound, Washington, for example, more than a century of development along the Sound's heavily populated eastern shore have essentially eliminated the opportunity to harvest shellfish in these areas because of the health risks associated with the urban land uses and poor shoreline water quality (Figure 1, next page).

Clearly there are different shoreline water quality conditions associated with different types, patterns and densities of coastal development, but our limited understanding of these relationships hampers efforts to manage land uses and effectively and permanently safeguard water quality for shellfish harvesting in Puget Sound and other parts of the country. To shed light on these important issues the Puget Sound Action Team organized a project to evaluate the relationship between coastal urbanization and microbial contamination of shellfish growing areas. This literature review is part of that project and is intended to provide an overview of the current state of knowledge on the subject. The findings have been combined with research conducted by the University of Washington and other available information to produce new guidelines for protecting shellfish growing areas in Puget Sound.

TRENDS IN COASTAL GROWTH

Coastal areas are uniquely productive, valuable, and fragile environments. They are also uniquely attractive and desirable places to live, work, and play. This leads to the complicated and daunting task of accommodating growth and development while, at the same time, trying to preserve healthy coastal ecosystems. As expressed by

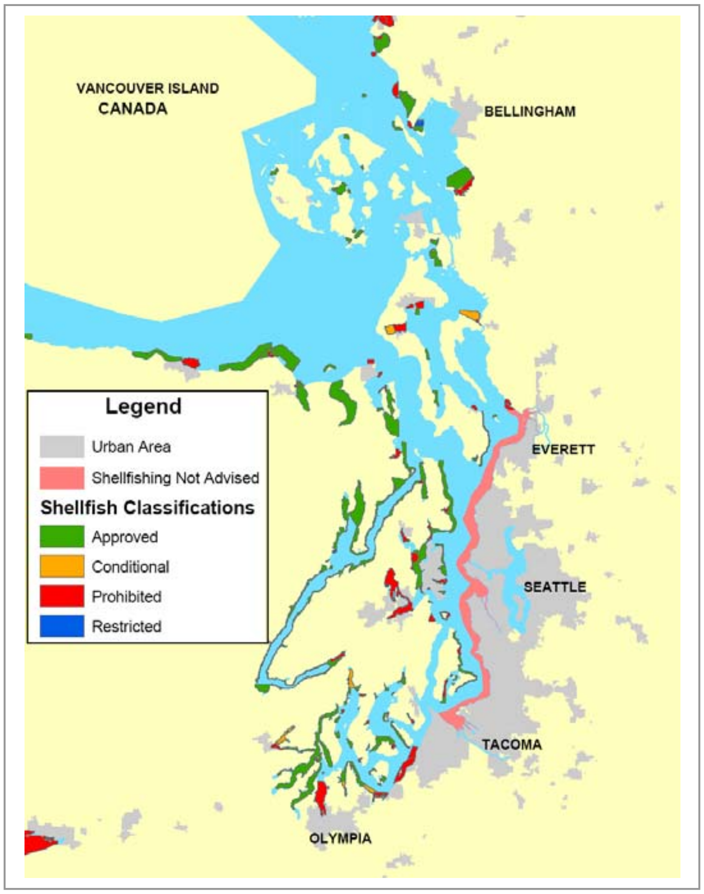

Figure 1: Puget Sound shellfish growing area classifications (WDOH 2002)

Lipp *et al*. (2001a), "a fragile balance exists between the needs of coastal cities and communities and the health of aquatic systems" (p. 286). Historical assessments indicate a relatively poor track record in this regard as researchers have documented significant degradation of estuarine habitats in all major coastal areas of the United States, including extensive contamination of shellfish growing areas and destruction of shellfish habitats (Dame *et al.* 2000; Emmett *et al.* 2000; NRC 1994; NSTC 1995; Roman *et al.* 2000; Paul 2001; Turner 2001; Walker *et al*. 2000).

Such assessments also reveal variations in patterns of human settlement in coastal areas over time. Coastal urbanization is a relatively recent, worldwide phenomenon that differs dramatically from past periods of resource *utilization* and, more recently, *industrialization* (Vernberg and Vernberg 2001; Vernberg 1997). Current development and population trends pose many unique and unprecedented environmental challenges, not the least of which is the fact that urbanization locks in an imprint on the landscape that is very difficult to reverse (Dale *et al*. 2000). The related environmental impacts are often equally intractable. Scott *et al*. (1998) contend that the contamination and closure of shellfish growing areas is "perhaps the most significant, quantifiable impact from urbanization" (p. 1313).

In the Pacific Northwest, growth and development pose significant threats to the Puget Sound-Georgia Basin estuarine ecosystem of Washington State and British Columbia as measured by a number of environmental indicators (GBEI 2002; PSAT 2002a). In Washington alone, two thirds of the state's 6 million people are concentrated around the shores of Puget Sound (Figure 2, next page). The region's population continues to grow steadily at about 20 percent each decade and much of the fastest growth is occurring in the Sound's rural, shellfish-rich counties (WOFM 2002a). The current population of the Puget Sound-Georgia Basin region is approximately 7 million people and is expected to reach 9 million by 2020 (BC Stats 2002; WOFM 2002b).

These population figures closely mirror national and global trends as human populations continue to increase and concentrate in low-elevation coastal areas (Small and Cohen 1999). In the contiguous United States, coastal counties cover only 17 percent of the total land area yet are home to more than 53 percent of the nation's population. Estimated at 139 million people in 1994, the nation's coastal population is projected to reach 165 million people and an average density of 327 people per square mile by 2015 (NOAA 1998a). Globally, approximately 37 percent of the world's population lives within 100 kilometers of the coastline and 50 percent within 200 kilometers (Cohen *et al*. 1997; Hinrichson 1999).

Population growth is only part of the story—land-cover change is the other. Development patterns have changed dramatically over the past century, even over the past couple of decades, as rural lands have been rapidly converted to urban and suburban uses (USEPA 2001). For example, analysis of land cover changes in the central Puget Sound lowlands between 1991 and 1999 estimated increases of 6.7 and 7.8 percent in "mixed urban" and "paved urban" areas respectively, coupled with an 8.2 percent decrease in forest cover (Alberti *et al*. 2002). Nationally, between 1982 and 1997, the amount of developed land in the contiguous U.S. increased by 34 percent, from 73.2 million acres to 98.3 million acres. Developed land now covers approximately 5.2 percent of the total land area in the contiguous U.S., but is unevenly concentrated in the eastern half and coastal areas of the county.

The recent national rate of development is more than double the underlying rate of population growth and the gap between the two measures continues to widen (Beach 2002; USDA 2001, 2000). Based on current trends, the percentage of developed land in the nation's coastal watersheds is expected to increase from 14 percent in 1997 to over 25 percent in 2025. Beach (2002) explains that "if developed land were expanding at the same rate as population, coastal zone management would be a formidable task," but with "development vastly outstripping even the relatively high rate of population growth, the challenge is considerably greater" (p. 5).

Despite these findings, the situation is not all bad for the nation's shellfish resources. The total area of coastal waters classified for shellfish harvesting more than doubled between 1966 and 1995, due largely to the classification of previously unclassified areas. The acreage approved for harvest also increased during the period, from 8.1 to 14.9 million acres, although the percentage of the total classified area approved for harvest declined by about 10 percent (NOAA 1998b, 1997a). Evaluation of the available data also reveals an interesting and important shift in pollution impacts. Nationally, harvest restrictions caused by industrial and municipal wastewater discharges (commonly called point source discharges) decreased while restrictions attributed to nonpoint source pollution increased, led by urban runoff (NOAA 1997a, 1997b). Nonpoint source pollution is also now the main cause of shellfish-harvest restrictions in Puget Sound, reducing the region's approved commercial acreage by approximately 25 percent since 1980. Key nonpoint sources in the region include failing on-site sewage systems, farm animal wastes and stormwater runoff (WDOH 2002; PSAT 2002b, 2000).

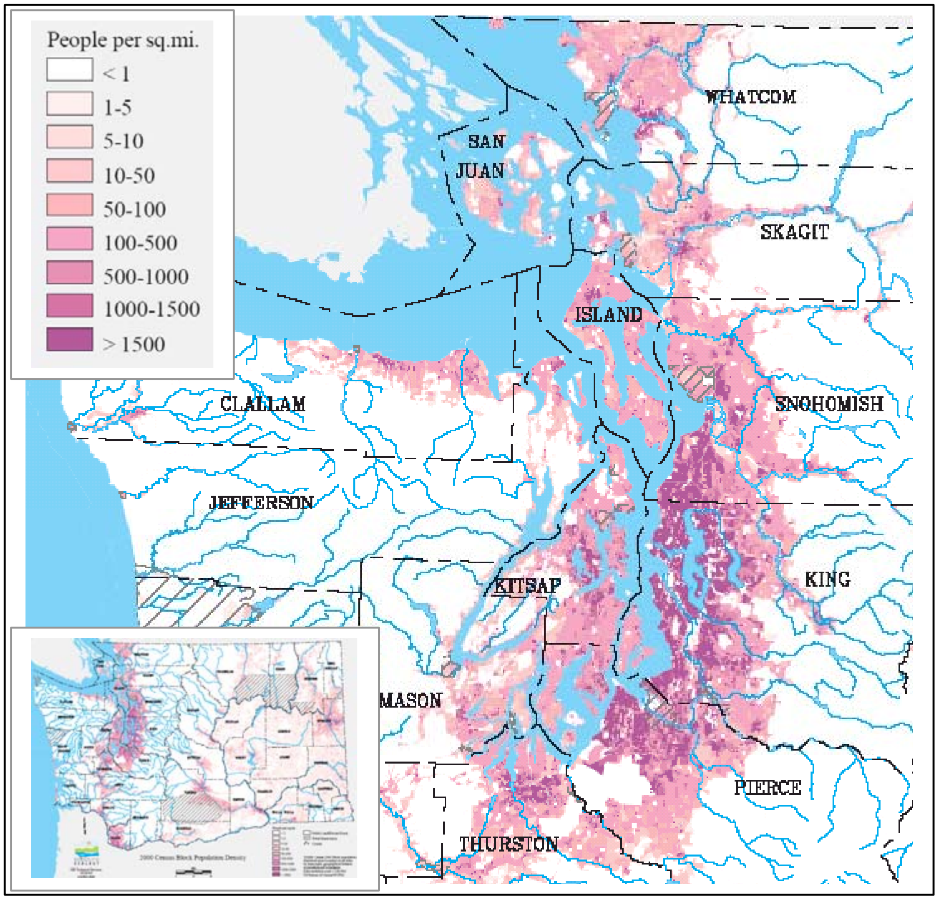

Figure 2: 2000 Puget Sound population density (WDOE 2003)

SHELLFISH SANITATION AND GROWING AREA CLASSIFICATIONS

Estuaries support many functions and uses, and no use is more dependent on clean water, more vulnerable to the effects of pollution and the transmission of diseases, than the harvest and consumption of shellfish. Oysters, clams and other bivalve molluscan shellfish feed by filtering plankton and other particles from the shoreline environment, and in the process can accumulate disease-causing microorganisms (pathogens) and other contaminants that may be present in the water or sediments. Most waterborne pathogens originate in human and animal feces (Rose *et al*. 1999). In the marine environment, all of the known pathogenic viruses that pose a significant public health threat are transmitted via the fecal-oral route, and are known collectively as enteric viruses (Griffin *et al*. 2003). The complete list of disease-causing organisms found in the marine environment is extensive (over 100 types of human enteric viruses alone), and viruses such as Hepatitis A and noroviruses are most commonly implicated in shellfish-associated disease outbreaks (Dadswell 1993; Geldreich 1978; Griffin *et al*. 2003; Lees 2000; Lipp and Rose 1997; NRC 1999, 1993; Richards 1987; Sair *et al*. 2002; Stelma and McCabe 1992; Vasconcelos 2001).

Most health risks associated with the consumption of shellfish and other seafood are attributed to the environment where the foods are grown and harvested (NRC 1991). However, Lees (2000) points out that, of the many seafoods, "only bivalve molluscan shellfish have consistently proven to be an effective vehicle for the transmission of viral disease" (p. 82). To address such health risks, all commercial shellfish growing areas are regularly monitored and classified under the National Shellfish Sanitation Program (NSSP). The main assessment tool of the NSSP is the comprehensive sanitary survey, which takes into account water quality conditions (principally measurements of fecal coliform bacteria[1]), pollution source investigations and meteorological and hydrographic evaluations (USFDA 2000). Shellfish areas not meeting the sanitary standards of the NSSP are closed to harvest.

Because of the difficulty and expense associated with the direct detection of pathogens, fecal coliform bacteria are used as indicator organisms to signal the possible presence of feces and pathogenic organisms. While bacterial indicators have generally provided a useful measure of sanitary conditions in shellfish growing areas, there's also growing recognition among researchers and regulators of the system's limits in accurately predicting the occurrence and survival of enteric viruses and other pathogens in the marine environment (Bosch 1998; Goyal *et al*. 1984; Jiang *et al*. 2001; Lees 2000; Lilja and Glasoe 1993; Lipp and Rose 1997; NRC 1993, 1999; Noble *et al*. 2003a*;* Noble and Furmen 2001; Schroeder *et al*. 2002; Wetz *et al*. in press; Vasconcelos 2001). A number of other factors further complicate the indicator system and the task of accurately gauging shoreline conditions and related health risks. These include variability in sampling procedures as well as unique geographic, hydrographic, and anthropogenic factors such as climate and weather patterns, circulation patterns, water properties, watershed hydrology and geology, land cover, land use patterns, population densities, and pollution sources and management practices (Bennett *et al*. 2000; Boehm *et al.* 2002; De Luca-Abbott *et al*. 2000; Henrickson *et al*. 2001; Leecaster and Weisberg 2001; Lipp *et al*. 2001b; Noble *et al.* 2003b, 2001; NRC 1993; Rose *et al*. 2001a, 2001b; Smith *et al*. 2001). These factors and uncertainties must be acknowledged and taken into account when discussing the relationship between coastal development and microbial contamination of shellfish growing areas.

EFFECTS OF URBANIZATION ON WATERSHED HYDROLOGY AND WATER QUALITY

Aquatic habitats are integral parts of the natural landscape, shaped and defined by many interacting physical, chemical and biological processes over time and space (Hynes 1975; Karr 1998; Naiman *et al.* 1992; Spence *et al*. 1996; Turner 1994). Numerous studies have shown that human modifications of the landscape have a direct and significant effect on the condition of aquatic systems. This includes research documenting the effects of development on river systems (Alberti *et al*. in press; Bolstad and Swank 1997; Booth 1991; Booth and Jackson 1997; Bunn and Arthington 2002; Hunsaker and Levine 1995; Klein 1979; May *et al.* 1997; Nelson and Booth 2002; Paul and Meyer 2001; Poff *et al*. 1997; Roth *et al.* 1996; Snyder *et al*. 2003; Wang *et al*. 2001; Wear *et al*. 1998) and marine and estuarine systems (Bay *et al*. 2003, 1999; Bowen and Valiela 2001; Breitburg *et al.* 2003; Holland *et al.* 2004, 1998; Lerberg *et al*. 2000; Mallin and Lewitus 2004; Mallin *et al*. 2001, 2000a, 2000b; Sanger *et al*. 1999a, 1999b; Valiela *et al*. 1992; Van Dolah *et al*. 2000; Vernberg *et al*. 1999, 1996, 1992; Vernberg and Vernberg 2001). Primary impacts include habitat fragmentation and loss (acreage and function) and degradation of water resources and water quality (USEPA 2001). For shellfish resources, both types of impacts are relevant and important and are best explained in a landscape context.

Microorganisms are discharged to waterways and shellfish growing areas from a variety of pollution sources via three main pathways: (1) direct discharges (e.g., marine sewage outfalls, boaters, marine mammals),

(2) subsurface flows from such sources as shoreline on-site sewage systems, and (3) overland flows, such as stormwater runoff from developed areas. These sources and pathways are determined by a variety of human activities and land uses that exert a progressively greater influence on the health of aquatic systems as development intensifies over time. Leopold (1968) contends that "of all the land use changes affecting the hydrology of an area, urbanization is by far the most forceful" (p. 1). In simplest terms, urbanization is hydromodification (MPCA 2001).

The term flow regime describes the seasonal flow of water in a particular stream or region and is considered to be a master variable in defining the character and integrity of aquatic systems (Karr 1998; Poff *et al*. 1997). Changes in flow regime[2] begin with the "first expression of human activity in a watershed" (Booth *et al*. 2001, p. 56) and then worsen as development increases in scope and scale (Booth 2000; Booth *et al*. 2001; CWP 2003; Poff *et al*. 1997; Schueler 2000a, 2000b). In the Pacific Northwest, "the fundamental hydrologic effect of urban development is the loss of water storage in the soil column" (Booth 2000, p. 3). As forests are cleared and soils are stripped, compacted and covered over with roads, buildings and other impervious surfaces, precipitation that was previously taken up by vegetation or moved slowly into and through the soil layer as subsurface flow is now converted to overland flow. Other features of the natural drainage system are ditched, drained, sewered and straightened to shed runoff as quickly and efficiently as possible, further reducing the watershed's natural capacity to absorb and attenuate flows and contaminants (Booth and Jackson 1997; CWP 2003; Mallin 2001, 2000a; Schueler 2000b, 2000c). This combination of reduced retention and enhanced conveyance results in greater runoff volumes, lower stream baseflows, more stormflow events and higher peak streamflows that rapidly rise and recede (Booth 1991; Corbett *et al*. 1997; CWP 2003; Konrad and Booth 2002, 2001; Leopold 1968; Poff *et al*. 1997; Schueler 2000a, 2000b) (Figure 3). Related impacts to property and water resources include increased flooding, degraded stream channels and other habitats, diminished groundwater recharge, degraded water quality and polluted shellfish beds and swimming beaches (Booth 2000; Booth *et al*. 2002; Booth and Jackson 1997; Burton and Pitt 2002; Dwight *et al*. 2002; Eisele et al. 2001; Griffin *et al*. 2003; Haile *et al*. 1999; Henrickson *et al*. 2001; Konrad and Booth 2002, 2001; May *et al*. 1997; Mallin *et al.* 2001, 2000a, 2000b; Noble *et al*. 2000a, 2000b; Pitt 2000a; Schueler 2000a, 2000c; Tourbier and Westmacott 1981; Weiskel *et al*. 1996). Mallin *et al*. (2001) contend that this close association between impervious surfaces and contaminated runoff is particularly critical in coastal areas "because shellfishing beds are often located within meters of developed land, and much of the stormwater runoff reaching these areas does not receive any pretreatment before entering the estuaries" (p. 189).

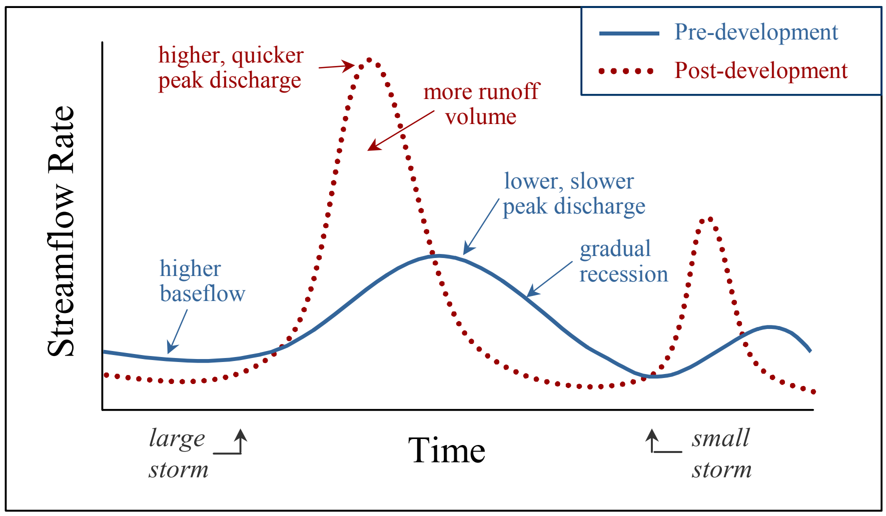

Figure 3: Changes in stream hydrograph following development (adapted from Schueler 2000a, 1987)

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[1] The two-part water quality standard for shellfish growing areas is based on 30 or more samples per sampling station and requires (1) a geometric mean ≤ 14 MPN/100 ml (applied in all areas) and (2) a 90th percentile value ≤ 43 MPN/100 ml (applied in areas where nonpoint sources of pollution are present) or no more than 10 percent of the results > 43 MPN/100 ml (applied in areas where point sources of pollution are present). MPN means *most probable number* and represents a single fecal coliform bacterium (PSAT 2002b; USFDA 2000).

[2] Flow regime is characterized by the magnitude, frequency, duration, timing and rate of change in water discharges (Poff *et al.* 1997). Flow regime is one of five main water resources features altered by the cumulative effects of human activity. The other four are physical habitat structure, water quality, energy sources (e.g., food sources), and biotic interactions (Booth *et al*. 2001; Karr 1998).

Microbial contamination presents a number of unique and perplexing challenges which Schueler (2000c) describes as follows:

> Microbes are problematic. They are small and include hundreds of groups, species, biotypes and strains. They are ubiquitous in the environment, found on nearly every surface of the earth. They exist within us, on us, on plants, soils and in surface waters. They grow rapidly, die-off, survive or multiply depending on a changing set of environmental conditions. Some microbes are beneficial to humans, while others exert no impact at all. Other microbes cause illness or disease, and a few can even kill you. The presence of some types of microbes indicates a potential risk for water contamination, while other microbes are pathogenic themselves. Microbes are nearly always present in high concentrations in stormwater, but are notoriously variable. They are produced from a variety of watershed sources, such as sewer lines, septic systems, livestock, wildlife, waterfowl, pets, soils and plants, and even the urban drainage system itself. It is little wonder that many watershed managers are thoroughly confused by the microbial world (p. 74).

Adding to the management dilemma is the fact that bacterial levels do not always correlate with development levels in adjacent shorelines and watersheds. For instance, shoreline areas with little or no development can be closed to shellfish harvesting due to fecal loadings from wildlife populations or a few, seemingly discrete raw sewage discharges. Such shellfish closures in Puget Sound have been attributed to elk and other wildlife in Lilliwaup Bay, to seals in the Dosewallips River delta, and to residential discharges in Similk Bay (Faigenblum *et* al. 1988; WDOH 2000, 1998; WPRC 1993).

Stormwater runoff is a defining characteristic of urbanizing landscapes—an almost unavoidable byproduct of concentrated human development. It represents a complicating, often confounding pollution problem that can readily offset gains achieved in controlling other pollution sources. A prime and widely repeated example involves the conversion from on-site sewage systems to centralized sewage treatment, which is generally undertaken to protect public health and water quality. While such conversions can achieve marked improvements in community sewage treatment, they also tend to facilitate added growth which, in turn, tends to generate more runoff and related stormwater impacts. Illustrating this point, Young and Thackston (1999) documented higher fecal bacteria concentrations in more densely developed, sewered watersheds than in unsewered watersheds with comparable land use/land cover characteristics. The North Carolina Coastal Federation (2002) goes so far as to say that with "sewers and shellfish you can't easily have both . . . unless those building the sewer go to great lengths to control the poisoned runoff that the sewer will inevitably bring" (p. 8).

Comprehensive evaluations of stormwater monitoring studies have reported mean fecal coliform concentrations ranging between 5,000 and 22,000 colonies per 100 ml in stormwater discharges, with concentrations varying as much as five orders of magnitude at individual sampling sites (CWP 2003; Schueler 2000c; Pitt *et al*. 2004). Studies have also documented very high of levels of selected pathogens in stormwater discharges (Burton and Pitt 2002). As with other types of contaminants, fecal coliform levels in stormwater are determined by such factors as rainfall and drainage area characteristics, including land uses, pollution sources, and washoff potential of different surfaces and landscapes (Burton and Pitt 2002; Pitt 2000b). Illustrating the variability of different source areas, Pitt *et al*. (2004) reported average bacterial concentrations of 7,750 for residential areas, 4,500 for commercial areas, and 2,500 for industrial areas. Potential sources of fecal contamination include cross connections with sewage lines; failing on-site sewage systems; feces from farm animals, pets and wildlife; and even bacterial growth in the drainage system itself. None of the potential sources is benign, and the cumulative loadings can be immense. Dog feces, for example, has been estimated to contain an estimated 23 million fecal coliform bacteria per gram (van der Wel, 1995; Schueler 2000c), and pet wastes have been called out as key pollution sources in many shellfish contamination studies (Kelsey *et al*. 2003, 2004; Mallin *et al.* 2001; Van Dolah *et al*. 2000; Weiskel *et al*. 1996; White *et al*. 2000). More broadly, numerous other studies have identified stormwater discharges as major sources of coastal microbial pollution (Ackerman and Weisberg, 2003; De Luca-Abbott *et al*. 2000; Dwight *et al.* 2002; Eisele *et al*. 2001; Lipp *et al*. 2001b; Marchman 2000; Macfarlane 1996; NRC 1999, 1993; Noble *et al*. 2000a, 2000b; Pitman 1995).

Many indicators and assessment techniques have been used to correlate watershed urbanization and impacts on aquatic systems, with the most extensive research focusing on stream systems. Stream-health indicators include water chemistry, stream biology, hydrology and physical habitat. Landscape measures that have been tested include such diverse indicators as population, land cover, development patterns, wetland cover, riparian buffer widths, road crossings, road densities, septic-system densities, housing densities and impervious cover (Arnold and Gibbons 1996; Bolstad and Swank 1997; Brown 2000; CWP 2003; Gergel *et al*. 2002; Johnson and Gage 1997; May *et al*. 1997; McBride 2001; Morse *et al*. 2003; Smith *et al*. 2001; Vølstad et al. 2003; Young and Thackston 1999). Studies correlating increased urbanization with higher stream bacterial levels include Bolstad and Swank (1997), Hydroqual (1996) and Young and Thackston (1999).

The relationship between stream health and impervious cover[3] has been studied most thoroughly, revealing many strong correlations and leading to the formulation of an “impervious cover model.” While the model has strong scientific underpinnings, it represents a relatively simple “threat index” or index of human activity in a watershed, and any application of the model should take into consideration a number of assumptions and cautions (CWP 2003; Booth *et al*. 2001) (Figure 4). The breakpoints in stream conditions at 10 and 25 percent imperviousness, for instance, do not represent *thresholds* as much as they reflect *transitions* based on a composite of different stream-health indicators (CWP 2003). Booth *et al*. (2002) underscore this point by explaining that certain stream indicators, particularly biological indicators, demonstrate a continuum of effects rather than threshold behavior and that a wide range of stream conditions can be associated with any given level of imperviousness, particularly at lower levels of development.

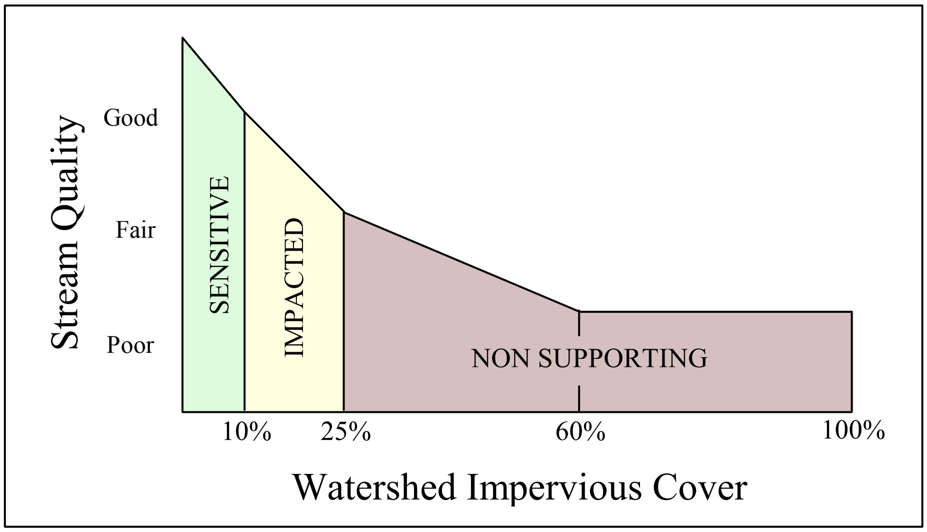

Figure 4: Impervious cover model (adapted from CWP 2003)

Contamination and degradation of marine shoreline environments is admittedly very different from stream systems, but parallel applications and comparable correlations are beginning to emerge. For example, studies of tidal creeks along the South Carolina coast by Lerberg *et al*. (2000) documented severe hypoxia, broad salinity fluctuations, potentially toxic levels of contaminated sediments, and low macrobenthic diversity and abundance in watersheds with greater than 50 percent impervious cover. In watersheds with 15 to 35 percent impervious cover, the effects were more muted but still showed signs of degradation associated with frequent hypoxia, salinity fluctuations and increased prevalence of stress-tolerant species. Related research by Holland and Sanger (2001) and Holland *et al*. (2004) characterize human population density and increases in impervious cover as the ultimate stressor on tidal creek ecosystems. The researchers documented adverse changes in physical-chemical processes (e.g., fecal coliform loadings, chemical contaminants, sediment characteristics) when impervious cover reached 10 to 20 percent in adjacent drainage basins and degraded biological resources (e.g., reduced abundance of stress-sensitive organisms and altered food webs) when impervious cover surpassed 20 to 30 percent. Mallin *et al*. (2000a) correlated impervious cover with

[3] Impervious cover is defined as any surface in the urban landscape that cannot effectively absorb or infiltrate rainfall (CWP 2003). “Total impervious area” is often defined as the sum of all roads, parking lots, sidewalks, rooftops, and other impermeable surfaces (USEPA 2000) and generally does not take into account other nominally pervious surfaces, such as lawns, or the hydraulic connection between the surfaces and the drainage system. “Effective impervious area” is defined as the impervious surface that is hydraulically connected to the downstream drainage system (Booth and Jackson 1997). Impervious area is not synonymous with “developed land” because impervious surfaces cover only a portion of developed area. The impervious cover of single-family residential development, for example, is estimated at about 40 percent of the developed area (Beach 2002).

bacterial levels in shellfish growing areas of coastal North Carolina, finding acceptable water quality for shellfish harvesting in watersheds with less than 10 percent impervious cover, impaired water quality in watersheds with 10 to 20 percent impervious cover, and highly degraded conditions above 20 percent. White *et al*. (2000), in contrast, documented bacterial contamination and shellfish closures in a watershed with less than 5 percent impervious cover. These findings suggest that bacterial levels and other indicators of estuarine health are closely linked with impervious cover as well as watershed hydrology, but more research is needed to better understand the relationships before, as Beach (2002) has suggested, championing the "ten-percent rule" as a central tenet of coastal protection programs.

FIELD STUDIES OF URBANIZATION AND SHELLFISH CONTAMINATION

Concentrated human activities can have a dramatic effect on the health of coastal ecosystems, and the impacts are largely attributable to marked changes in the natural landscape caused by urbanization and industrialization (Vernberg *et al*. 1996). The contamination and closure of shellfish growing areas is a measurable and, to some extent, predicatable outcome as coastal populations grow and land uses intensify. Vernberg and Vernberg (2001) contend that "the greatest concentrations of bacterial contamination lie at the interface of the land and sea and can be linked directly to upland population" (p. 102).

With the emergence of TMDL (total maximum daily load) assessments across the country, many watershed-based studies have now been completed or are being conducted to determine bacterial loadings and, where feasible, correlations with different land uses. While informative to the broader topic of bacterial contamination of water resources, this section focuses on a narrower set of studies correlating coastal development with shoreline bacterial contamination, and, to the extent possible, even more specifically on studies correlating coastal development with the contamination and closure of shellfish growing areas. These studies have been carried out in different parts of the country using a variety of research designs and techniques over the past two decades. A majority of the work has occurred along the east coast of the United States, and arguably the best and most extensive correlation studies have been conducted in the coastal areas of North and South Carolina as a result of several multidisciplinary research programs examining the effects of urbanization on coastal ecosystems, including the *Tidal Creeks Program*, *Urbanization and Southeastern Estuarine Systems* (USES) and *Land Use-Coastal Ecosystem Study* (LU-CES).

Early work by Maiolo and Tschetter (1981) evaluated the relationship between population growth, bacterial contamination and shellfish closures over a 27-year period in New Hanover and Carteret counties in North Carolina. The researchers correlated population increases in the two counties with degraded water quality, shellfish closures and reduced shellfish landings in the adjacent estuaries. They attributed the impacts mainly to growth that had outstripped the region's sewage management capacity and used the results to forecast shellfish closures and economic losses that could be expected with continued population increases.

Duda and Cromartie (1982) assessed coastal North Carolina watersheds during the same period and also documented sharp increases in residential development and corresponding shellfish closures. Their analysis strongly correlated bacterial levels with septic-system densities and identified stormwater runoff from impervious surfaces as a contributing factor in more urbanized watersheds. Most septic systems were installed in areas that were then ditched and drained to "overcome the limitations of these unsuitable soils" (p. 1273), but the modifications only exacerbated the pollution problem by increasing hydraulic connectivity and allowing the failing sewage systems to drain more efficiently to the adjacent tidal creeks. The researchers determined that average septic-system densities greater that one system per seven acres resulted in shellfish closures. Recommendations for remedying the situation focused on better sewage management as well as revegetation, restoration and protection of natural drainage features.

More recent research by Mallin *et al*. (2001, 2000a, 2000b) examined the effects of development on some of these same tidal creeks in North Carolina between the years 1984 and 1997. The period of research followed the completion of major sewage treatment projects in the early 1980s and allowed for broader evaluations of nonpoint pollution impacts. On a regional scale the researchers found significant correlations between population growth and shellfish closures. Watershed-scale analysis of five tidal creeks in Hanover County correlated bacterial levels with population, more strongly with percent developed land, and even more strongly with percent impervious area (Figure 5, next page). Watersheds with less than 10 percent impervious cover had generally good water quality and large areas open to shellfish harvesting; watersheds with 10 to 20 percent impervious cover had impaired water quality and shellfish closures in the upper portions of the creeks; and watersheds with greater than 20 percent impervious cover had severely polluted waters with all areas of the creeks closed to shellfish harvesting (Mallin et al. 2001, 2000a). The researchers also evaluated the effects of rainfall on water quality in 11 coastal plain streams, strongly correlating rainfall events with fecal coliform counts and turbidity except in watersheds with extensive wetland cover. The findings highlight the combined importance of reduced impervious cover and protected natural drainage features for mitigating microbial contamination of coastal waters.

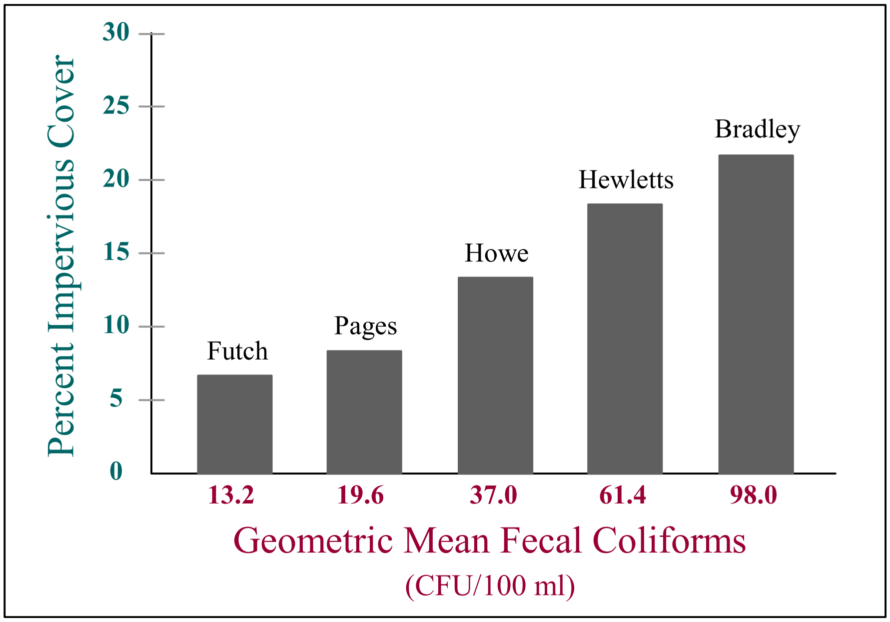

Figure 5: Percent watershed impervious cover and corresponding fecal coliform levels in five tidal creeks, New Hanover County, North Carolina (adapted from Mallin *et al.* 2001)

Research by White *et al.* (2000, 1998) in the Jumping Run Creek watershed in Carteret County, North Carolina, further underscores the influence of watershed hydrology on shoreline water quality. While population increases in this small, 800-acre coastal watershed coincided with shellfish closures in the adjacent waters, bacterial loadings did not correlate with other landscape indicators such as developed area or impervious surfaces (which covered less than five percent of the watershed). Instead, the researchers documented a strong relationship between the contamination levels and extensive ditching, bulkheading and channeling in the watershed. Because of the hydrologic modifications, runoff that once took days or even weeks to pass through the native pocosin wetlands now moved in greater volumes and reached the shellfish beds in hours, allowing little time for natural reduction and die-off of microorganisms. Evidence points to pet and wildlife wastes, and possible subsurface flows from septic drainfields, as the main pollution sources. Mitigation efforts are being targeted at riparian buffer restoration, wetland construction, stormwater treatment and public education.

In coastal South Carolina, scientists affiliated with the USES research program have employed a variety of techniques to monitor and compare land uses and ecosystem responses in highly urbanized Murrells Inlet and relatively undeveloped North Inlet (Kelsey *et al*. 2003, 2004; Scott *et. al*. 1996, 1998; Vernberg and Vernberg 2001; Vernberg *et al*. 1999, 1996, 1992). Among numerous other findings, 67 percent of the sampling stations in Murrells Inlet did not meet water quality standards for shellfish harvesting compared to 33 percent in North Inlet. Murrells Inlet also had a higher occurrence of *E. coli* bacteria, fewer coliform-negative stations, and fewer bacterial species comprising the coliform group—findings that the researchers attributed to urban influences and higher densities of septic systems in the Murrells Inlet watershed (Vernberg *et al*. 1996; Scott *et al*. 1998; Chestnutt *et al*. 2000). Subsequent analysis of Murrells Inlet by Kelsey *et al*. (2003, 2004) identified proximity to areas with septic systems, rainfall events, and runoff from urban areas as key predictors of fecal coliform levels. However, further evaluations using geographic-information-system techniques, regression analysis and multiple antibiotic resistance (MAR) analysis (a microbial source tracking technique) suggested that the majority of fecal contamination came from pets and other non-human sources. The researchers concluded that "the major source of pollution in Murrells Inlet appears to be stormwater runoff, particularly from urban areas" and the “study clearly shows the impacts of human activities on fecal pollution in Murrells Inlet” (Kelsey 2003, p. 345-346).

Management implications point to the need to reduce and intercept urban runoff, clean up pet wastes and eliminate boater waste discharges.

Analysis of land uses and estuarine conditions in the Okatee River and Broad Creek watersheds in nearby Beaufort County, South Carolina, has yielded similar findings (impervious cover in the two watersheds is 15 and 32 percent respectively). As part of a comprehensive environmental assessment, researchers used conventional monitoring techniques, MAR analysis and analytical profiling index (API) biotyping to document higher bacterial concentrations, fewer coliform-free sampling sites and a higher percentage of antibiotic-resistant *E. coli* strains (indicative of human sources) in the more urbanized Broad Creek watershed (Chestnut *et al*. 2000; Webster *et al*. 2004). High percentages of MAR-negative sampling stations in both waterbodies suggest that animal sources are major contributors in both areas. Recommendations for reducing bacterial loads in the two watersheds include better sewage management, comprehensive surface water management (including enhanced buffers and reduced impervious cover), increased public education on pet and other animal wastes, and better handling of marina and

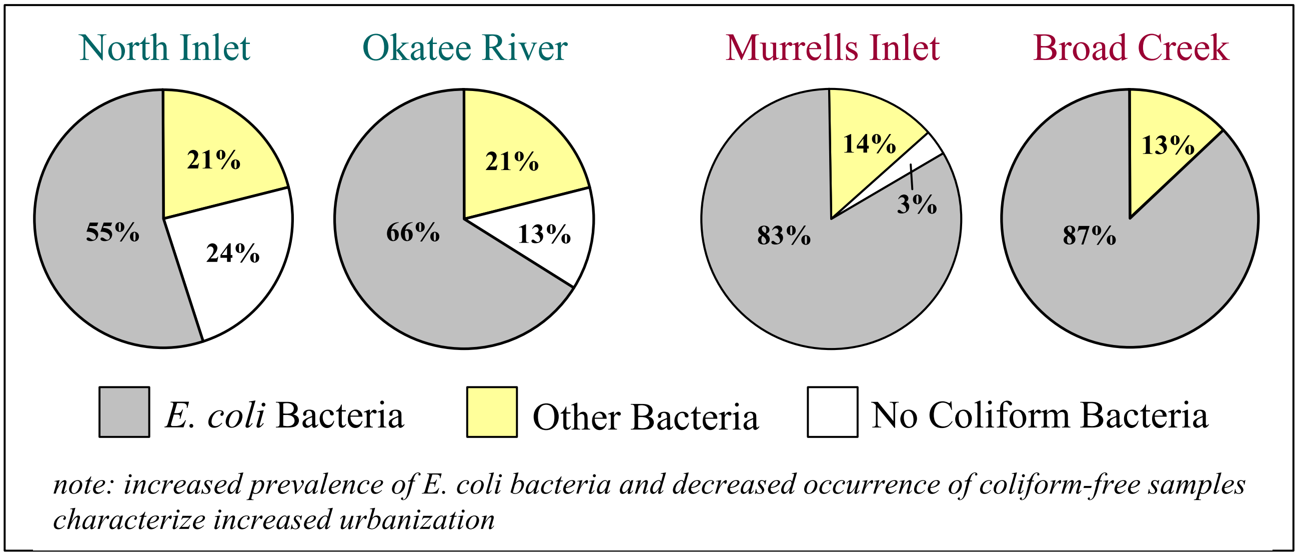

Figure 6: Percentage of bacterial species in water samples from four South Carolina estuarine systems using analytical profiling index (API) biotyping (adapted from Chestnut *et al.* 2000)

boater wastes (Van Dolah *et al.* 2000). When combined with findings from Murrells Inlet and North Inlet, bacterial profiles for the four waterbodies show similarities between the two rural watersheds (North Inlet and Okatee River) and the two urban watersheds (Murrells Inlet and Broad Creek), reflecting the different land uses and development levels in each of the areas (Chestnut *et al*. 2000) (Figure 6).

In many areas of Florida, including Apalachicola Bay, Charlotte Harbor, Tampa Bay, Sarasota Bay and the Florida Keys, researchers have documented widespread and chronic microbial contamination caused by coastal development (Griffin *et al*. 1999; Lipp *et al*. 2002, 2001a, 2001b; Lipp and Rose 2001; Marchman 2000; Rose *et al*. 2001a). In Apalachicola Bay—site of approximately 90 percent of the state's oyster harvest—Marchman (2000) identified extensive nonpoint pollution in the lower Apalachicola River watershed and correlated bacterial loadings in the bay with rainfall events, river flows and urbanization. The analysis also identified impervious surfaces, deteriorating infrastructure, poor ground cover, inadequate pollution control and inappropriate land uses as contributing factors. In Charlotte Harbor, Lipp *et al.* (2001b) studied the spatial and seasonal distribution of fecal coliform bacteria and enteric pathogens and documented higher concentrations of fecal bacteria in areas of low salinity (greater freshwater influence) and high septic-system densities. The researchers also strongly correlated fecal indicator organisms with rainfall, streamflow and cooler water temperatures. Studies of Sarasota Bay also documented a strong relationship between septic-system densities and bacterial levels, and determined that subsurface flow was a primary transport mechanism for the contaminants (Lipp *et al*. 2001a). "These studies reveal a high level of pollution in tidally influenced streams and canals of southwest Florida and highlight the importance of physical factors such as tides, surface runoff and streamflow in the distribution of human pathogens in coastal areas" (Lipp and Rose 2001, p. 1).

Coastal development and microbial contamination have also received significant attention in the New England states, but with more pointed emphasis on the remediation of stormwater impacts. An assessment of bacterial pollution sources, loadings and pathways in the Buttermilk Bay watershed in southeastern Massachusetts by Weiskel *et al*. (1996) determined that waterfowl and surface flows (storm drains and streams) accounted for most of the bay's annual bacterial loading at 67 and 24 percent respectively, with lesser inputs attributed to beach wrack (decaying shoreline vegetation), sediment resuspension and subsurface flow from on-site sewage systems. Although the waterfowl loadings were substantial, related effects appeared to be mitigated by seasonal and spatial distribution and other factors. In contrast, surface runoff carrying feces from domestic pets and wildlife had a disproportionately high impact on nearshore bacterial levels. Bacterial loadings were also strongly correlated with urban land uses, especially high-density residential development. Overall, bacterial yields from impervious surfaces served by storm drains were 300-8,000 times higher than from low-intensity land uses drained by streams. Among other conclusions, the researchers recommended that direct stormwater discharges to coastal waters should be prevented and, where feasible, infiltrated to capitalize on the soil's natural capacity to filter and adsorb pollutants (Weiskel *et al*. 1996).

In nearby Cape Cod, rapid coastal development caused extensive shellfish closures that were attributed primarily to bacterial contamination from stormwater runoff, on-site sewage systems and wildlife (Macfarlane 1988). In the Town of Orleans, resource managers identified stormwater discharges as the main problem and retrofitted the town's five largest drainages with stormwater treatment systems[4] to reduce bacterial loadings to the shellfish beds. The treatment systems achieved substantial reductions in bacterial concentrations and the shellfish beds were subsequently reopened to harvest (Macfarlane 1997, 1996, 1988; Bingham *et al.* 1996). Similar remediation approaches have been employed in other coastal areas of New England using a variety of systems to treat stormwater flows. These projects have achieved mixed results but show great promise and have generally proven effective in helping to reduce bacterial loads when the systems are properly designed, installed and maintained (Castonguay 1998; Krahforst *et al.* 2002; Taber and Costa 1998; USEPA 2002).

Stormwater Remediation Projects in Shellfish Growing Areas of New England

Greenwich Bay, Warwick, RI: Nutrient, sedimant and bacterial reduction using Vortechs™ Systems with detention basins and vegetated swales. *www.pollutionengineering.com/CDA/ArticleInformation/features/BNP__Features__Item/0,6649,103950,00.html*

Buttermilk Bay, Bourne and Wareham, MA: Storm drain retrofits using catch basins and infiltration structures such as leaching chambers and galleys.

Spragues Cove, Marion, MA: Constructed wetland system consisting of settling basin,first shallow marsh, deep pond and second shallow marsh. http://www.buzzardsbay.org/sprafact.htm

Pleasant Bay and Nauset Harbor, Orleans, MA: Four retrofits using pretreatment settling tanks and leaching chambers and one retrifit using innovative surface filter system. http://www.epa.gov/owow/watershed/Proceed/bingham.htm

Evaluations of California's coastal waters have highlighted significant microbial contamination problems associated with the state's intense coastal development. Studies by Ackerman and Weisberg (2003), Bay *et al*. (2003, 1999), Dwight *et al*. (2002), Jiang *et al*. (2001) Noble *et al*. (2003c, 2000a, 2000b), Schiff *et al*. (2003), Schiff and Kinney (2001) and others have documented widespread coastal contamination in Southern California correlated with rainfall, river flows and stormwater discharges. Further north and more specific to shellfish, Pitman (1995) evaluated the impact of two marine sewage outfalls on shellfish beds located midway between the coastal California communities of Goleta and Santa Barbara, and concluded that the treated discharges from the two outfalls did not adversely affect the shellfish growing areas. However, surface runoff and creek discharges from the coastal watersheds between the two outfalls (about 8.5 miles apart) did correlate with high bacterial levels in the shellfish growing areas. The study documented bacterial levels in the tens of thousands per 100 ml during

[4] The town retrofitted four stormwater drainage pipes with pretreatment settling tanks (gross particle separators) followed by infiltration leaching chambers surrounded by stone, each designed to handle 150,000 gallons of runoff during first-flush, one-inch rain events. An innovative surface filter system was installed at the fifth site, consisting of five concrete tanks and a sand/geotextile filter media designed to treat over 300,000 gallons of runoff (Macfarlane 1996; Bingham *et al*. 1996).

storm events and concluded that the mass loading of bacteria from the creeks during one rainy day exceeded the year-long mass loading in the disinfected discharges from the two sewage treatment plants. The authors did not attempt to characterize the watershed pollution sources or to correlate the bacterial loadings with land uses in the area.

And in a study of Whangateau Harbor in northeast New Zealand, De Luca-Abbott *et al*. (2000) detected peak levels of enterococcus bacteria during wet winter months that they attributed to cumulative loadings from numerous stormwater outfalls, nonpoint source runoff and leaching from on-site sewage systems in the surrounding watershed. They also correlated rainfall events with increased bacterial levels in stormwater discharges and harbor water quality, and concluded that worst-case conditions for the harbor would be high rainfall events coupled with high wastewater loadings during the summer tourist season. Despite establishing these relationships, the authors conclude that "documentation of ecological impacts in harbors and estuaries is problematic due to natural temporal and spatial variability" and a "better approach may be to focus on stormwater treatment rather than identification of effects" (p. 428).

CONCLUSIONS

Evaluation of the many issues and studies documenting the effects of development on shellfish growing areas and other aquatic ecosystems reveals an array of findings that range from virtual truisms to more general themes that, in their application, must take into account a number of important variables and local site characteristics. Synthesis of the available scientific literature points to the following conclusions.

1. Coastal areas are highly productive and sensitive environments. They are also highly valued places to live, work and play. Two dramatic and related trends—population growth and development—are stressing and degrading coastal ecosystems.

2. Bivalve molluscan shellfish are effective vectors or carriers of human viruses and other pathogens, which is why shellfish growing areas are very vulnerable to pollution from human and animal feces. As such, controlling fecal pollution sources in shoreline areas where shellfish are grown and harvested is vital for safeguarding public health and environmental quality.

3. Urbanization is arguably the most forceful of all land use changes, dramatically altering the natural capacity of watersheds to absorb and attenuate flows and contaminants. The imprint of urbanization is largely irreversible and many of the related environmental impacts, including the contamination of shellfish growing areas, are similarly intractable.

4. Microbial contamination is chronic and pervasive in many coastal areas of the United States, and is closely correlated with population and development levels, rainfall events, stormwater runoff and river flows.

5. Research documenting the effects of human development on the health of stream systems is extensive and compelling. The available research examining the effects of development on estuarine systems is more limited, but reveals strong and comparable correlations.

6. Impervious cover is the most widely researched landscape indicator for gauging the effects of development on aquatic ecosystems. Studies indicate that watersheds with moderate levels of development — approximately 10 to 20 percent impervious cover — generally have impaired water quality conditions and shellfish classifications that trend toward closure as development increases.

7. Watershed hydrology has a significant effect on water quality. Shellfish growing areas can be degraded at low levels of development if there are raw sewage inputs or if hydrologic processes are severely disrupted (e.g., ditching, loss of land cover, loss of wetlands) and there is high connectivity between the pollution sources and receiving waters. Protection of natural hydrologic features and reduced connectivity can help mitigate development impacts.

8. Stormwater runoff is a defining characteristic of urbanizing landscapes. Microbial concentrations in stormwater are consistently and universally high, due in part to significant loadings from unmanaged wastes from pets, other

domestic animals and urban wildlife. In situations where communities convert from on-site sewage systems to centralized sewage treatment, the added growth and development that tends to follow can have a marked, negative effect on water quality if the increased stormwater flows and contaminants are not effectively managed.

9. The available research validates long-standing observations that concentrated urban development is incompatible with safe shellfish harvesting. However, there is no simple formula or rule, no single indicator or threshold for determining the limits of growth in all shellfish watersheds.

10. Pollution impacts can be prevented and mitigated using a variety of approaches and techniques, but there are practical limits in our ability and willingness to preserve beneficial uses and resources in the shoreline environment as watershed development increases in intensity and area. There is no replacement for sound land use planning and personal stewardship that recognize and preserve the inherent qualities of natural systems for buffering impacts and preserving clean water.

As stated at the start of the paper, many factors affect the condition and suitability of shoreline areas for growing and harvesting shellfish, and none is more vital than clean water. Coastal urbanization may be relentless in some parts of the world, but the contamination and closure of shellfish growing areas is not unavoidable. Better understanding of the tradeoffs and consequences associated with development can and should lead to better decision-making with land use plans, pollution control programs and other measures that play a central role in shellfish protection. Still more research is needed to better understand the relationship between coastal development and microbial contamination in shoreline areas, but the current state of knowledge points to a number of important actions that can be undertaken now to preserve shoreline areas for shellfish harvesting in Puget Sound and other coastal areas of the country.

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