Impervious Surface Target and Limit Reference Points for Chesapeake Bay Subestuaries Based on Summer Dissolved Oxygen and Fish Distribution

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Abstract

Impervious surface (IS) reference points (ISRPs) were developed as potential guidelines for managing fisheries in urbanizing Chesapeake Bay tributary watersheds and for communicating limits of fish habitat to withstand development. Creation of ISRPs involved determining functional relationships between IS, summer dissolved oxygen (DO), and presence of “iconic” species (blue crab, white perch, striped bass, and spot) in bottom waters of brackish Chesapeake Bay tributaries. Logistic regression indicated IS had a significant, negative influence on the odds of these species being present in mid-channel bottom trawl samples during summer. Bottom DO was strongly and negatively associated with IS ($r = -0.82$; $P < 0.0001$). Hypoxic thresholds ($\leq$ 2 mg/L) and normoxic targets ($\geq$ 5 mg/L) for fish and blue crab habitat were supported by a nonlinear asymptotic ascending function describing bottom DO and proportions of bottom trawls with each iconic species (pooled into a single analysis); these proportions stabilized at a positive asymptote by 5 mg/L and dropped nearly in half by 2 mg/L. The 5 mg/L DO target was almost 3-times more likely to have been observed in bottom waters at IS of 5% or less (rural watersheds) than when IS was 10-17% (suburban watersheds). The chance of measuring DO below the 2 mg/L threshold was nearly 3-times greater when IS was 10% or more. In systems with target IS (less than 5%), habitat would generally be considered unimpaired and managing harvest of resident fishes would be effective. Preserving watersheds at or below 5% IS would be a viable fisheries management strategy. Increasingly stringent regulation might compensate for habitat stress as IS increases from 5 to 10%. Above a 10% IS threshold, habitat stress mounts and successful management by harvest adjustments alone becomes unlikely.

Introduction

Fishing has been the focus of assessments of human-induced perturbations of fish populations (Boreman 2000) and biological reference points (BRPs) have been developed to guide how many fish can be safely harvested from a stock (Sissenwine and Shepherd 1987). Managers also take action to avoid negative impacts from habitat loss and pollution that might drive a fish population to extinction (Boreman 2000) and typically control fishing to compensate for these other factors. Recovery of striped bass *Morone saxatilis* is a case in point – conservative management of harvest compensated for possible water quality problems as well as overfishing (Richards and Rago 1999). A habitat-based corollary to the BRP approach would be to determine to what extent habitat can be degraded before adverse consequences cause the safe harvest level to decline.

Human development along the U.S coast brings with it ecologically stressful factors that conflict with demands for fish production and fishing opportunities (Pearce 1991). The U.S. coast hosts more than half of its human population on less than one-fifth of the nation's land and, at more than five-times the density of the interior of the country, coastal population pressure is already great and will increase in the future (Beach 2002).

Impervious surface (IS; paved surfaces, buildings, and compacted soils) has been used as an indicator of development because of compelling scientific evidence of its effect in freshwater systems and because it is a critical input variable in many water quality and quantity models (Arnold and Gibbons 1996; Cappiella and Brown 2001). Impervious surface increases runoff volume and intensity in streams, leading to increased physical instability, erosion, sedimentation, thermal pollution, contaminant loads, and nutrients (Beach 2002). Measurable adverse physical and chemical changes in South Carolina tidal creek ecosystems occurred when IS exceeded 10-20% and living resources responded negatively when IS exceeded 20-30% (Holland et al. 2004). Fecal coliform loading from North Carolina coastal watersheds was a linear function of IS (Mallin et al. 2000).

Increased urban sprawl associated with human population growth has been identified as a threat to Chesapeake Bay (or Bay; Chesapeake Bay Program or CBP 1999). Habitat reference points based on IS (ISRPs) for estuarine watersheds could provide a quantitative basis for managing fisheries in increasingly urbanizing Chesapeake Bay watersheds and enhance communication of limits of fisheries resources to withstand development-related habitat changes to fishers, land-use planners, watershed-based advocacy groups, developers, and elected officials.

We applied the target and limit BRP concept (Caddy and McGarvey 1996) to develop ISRPs. Fisheries are managed for a target BRP, a safe level of fishing mortality and/or biomass for example, and not towards the overfishing threshold (limit BRP; Caddy and McGarvey 1996)). In terms of habitat quality, target ISRP represents a "safe" level of development associated with maintenance of nursery and adult habitat requirements, while an ISRP threshold represents degradation to the point where a significant portion of a waterbody cannot meet those requirements. Fisheries management options could also reflect intensity of watershed development - an IS target would reflect a point where harvest management is expected to achieve its objectives, while a limit would reflect a level of IS where harvest regulation would not be expected to overcome habitat degradation. Watershed conservation and restoration would become explicit fisheries management tools.

Development of ISRPs involved determining relationships of IS, habitat quality, and species responses. We chose summer dissolved oxygen (DO) as an indicator of habitat degradation associated with IS because fish require well-oxygenated water, it provides insight into both the metabolic and pollution status of a waterbody, it is responsive to urbanization, and it is a habitat parameter used to portray degradation of Chesapeake Bay (Limburg and Schmidt 1990; Hagy et al. 2004; Kemp et al. 2005). We set 5 mg/L DO as our habitat target and 2 mg/L as our limit DO for ISRPs. Concentrations of DO 5.0 mg/L or greater were considered desirable for many Chesapeake Bay living resources (Funderburk et al. 1991; US EPA 2003). There is general recognition that hypoxia (DO

< 2 mg / L) impacts a substantial portion of Chesapeake Bay in summer, has increased in extent, causes significant ecological harm, and is the target of substantial nutrient management efforts (Breitburg 2002; Hagy et al. 2004).

Fisheries are often the major focal point in judging ecosystem status (Kelly and Harwell 1990) and we focused on occupation of bottom habitat by a suite of "iconic" target species that support important Chesapeake Bay fisheries as the measurable response to degradation. White perch *Morone americana*, striped bass, spot *Leiostomus xanthurus*, and blue crab *Callinectes sapidus* support fisheries in Chesapeake Bay, their habitat requirements were considered in development of water quality criteria (US EPA 2003), they are sampled well by commonly applied seine and trawl techniques (Bonzek et al. 2007), and the Bay serves as an important nursery for them (Lippson 1973; Funderburk et al. 1991).

We sampled brackish Bay tributaries with IS representing a range of rural to suburban development. We hypothesized that increased IS would lead to declines in DO in bottom waters and that occupation of bottom waters by target species would decline. Fish and blue crabs become restricted to oxygenated shallows when hypoxia is extensive (Eby and Crowder 2002) and occupation of shallow water would have a much wider range of potential responses, from decline to increase.

Methods

We sampled nine Chesapeake Bay watersheds of less than 60,000 ha with brackish sub-estuaries from two regions (mid-Bay and Potomac River) of Maryland's portion of Chesapeake Bay during 2003 and eight tributaries during 2003-2005 (Figure 1; Table 1). Eight of these watersheds were less than 18,000 ha. Impervious cover estimates in these systems spanned 3-18% of watershed area (Table 1). In general, watersheds at 5% or less IS were considered rural landscapes and suburban landscapes were well established by 10% IS. We used IS estimates made by Towson University from Landsat, 30-meter pixel resolution satellite imagery (Eastern Shore of Chesapeake Bay in 1999 and western shore in 2001) for each watershed (Barnes et al. 2002). Watershed area estimates (minus water) were obtained from MD DNR (1999).

In general, four evenly spaced sample sites were located in the upper two-thirds (linear distance along center from head to mouth) of each tributary's estuary. Sites were not located near the tributary mouth to reduce influence of mainstem Chesapeake Bay or Potomac River waters on measurements of watershed water quality. All sites on one river were sampled on the same day during daylight and there were two visits a month during July-September.

A 4.9-m semi-balloon otter trawl sampled mid-channel bottom habitat. The trawl was constructed of treated nylon mesh netting measuring 38 mm (all measurements are stretch mesh) in the body and 33 mm in the codend, with an untreated 12 mm knotless mesh liner. A single tow (six minutes at 3.2 km/hr) was made in the same direction as the tide during each site visit. Trawl sites were located in the deepest portion of the channel at a station. Upstream trawl sites were shallowest: station 1 (furthest upstream), median depth ≈ 2.0 m, range 0.8-3.5 m; station 2, median ≈ 3.0 m, range 1.8-6.2 m; station 3, median depth ≈ 4.0 m, range 2.0-6.8 m; and station 4 (furthest downstream), median ≈ 4.2 m, range 3.2-7.0 m.

A 30.5 m • 1.2 m bagless beach seine made of knotted 6.4 stretch-mesh was used to sample inshore habitat adjacent to a trawl site. One end of the seine was held on shore, while the other was stretched perpendicular to shore as far as depth permitted. The end furthest from shore was then pulled with the tide to the beach in a quarter-arc and pursed. A single seine haul was made at a site, except where permanent obstructions or lack of beaches prevented it.

Maximum depth of the trawl sample was recorded and water temperature (ºC), DO (mg/L), and salinity (‰) were measured at the surface, middle and bottom of the water column at the trawl site and at the surface of the seine site with a hand-held YSI model 85 instrument. Mid-depth measurements were omitted at shallow sites with less than 1.0 m difference between surface and bottom.

Temperature, salinity, and DO from each system were summarized annually over all sites by depth category (surface, mid-depth, and bottom). Correlation analysis determined direction and strength of associations of median annual temperature, salinity, and DO at each depth category with IS in each watershed. Strong associations of temperature and salinity on DO might be expected because of their influence on oxygen saturation (Reid and Wood 1976), especially if IS was weakly correlated with DO. Level of significance was adjusted to account for multiple comparisons by dividing the desired α (0.05) by the number of comparisons (9 comparisons with IS + 3 temperature-DO comparisons + 3 salinity-DO comparisons; adjusted $\alpha = 0.003$; Ricker 1975). We also correlated observed bottom DO with depth; chronically low DO is usually associated with deeper, below pycnocline waters (Hagy et al. 2004). In each case, scatter plots were examined to determine if transformations or non-linear associations might be appropriate (Sokal and Rohlf 1981).

Catch distributions of each target species and life stage (white perch ages 1+ or young-of-year (YOY), striped bass YOY, spot YOY, or all stages of blue crab; hereafter, target species) were not normally distributed and normality could not be induced by transformation because of high frequency of zero catches. Catch data were treated as presence-absence because it reduced statistical concerns about contagious distributions and high frequency of zeros, and it was robust to errors and biases in sampling (Green 1979; Bannerot and Austin 1983).

To minimize ambiguity in interpreting absence (Green 1979), we determined the chance that each of our species would occur at least once at a given site during 2003-2005. We compiled seine and trawl catches at each site, and calculated percentage of sites where each species was encountered once or more with either gear.

Bottom DO was categorized into 1 mg/L increments and proportion of trawls with each target species was estimated within each DO increment. Proportion of trawls (Pt_i) with each target species within a DO increment and its 95% confidence interval was calculated using the normal distribution approximation of the binomial distribution (Ott 1977). We used a criterion (sample size greater than five divided by the smaller proportion, Pt_i or 1-Pt_i) to determine whether the number of samples was adequate for use of the normal distribution approximation of the binomial distribution (Ott 1977). If this criterion was not met, this estimate was excluded from further analysis.

A Weibull function described the increase in Pt_i as an asymmetric, ascending, asymptotic function of DO category midpoint: $Pt_i = Pt_k\{1 - \exp[-(DO / S)^b]\}$; where Pt_i was the proportion of bottom trawls with each target species at a given one mg/L category of DO; Pt_k was the asymptotic Pt_i of target species in bottom trawls as DO approached infinity; S was the value of DO where $Pt_i = 0.63 \bullet Pt_k$; and b was a shape factor (Prager *et al.* 1989). Dissolved oxygen categories were eliminated from analysis if the sample size criterion for estimation of Pt_i (described previously) was not met. The Weibull model was fit using Proc NLIN in SAS (Gauss-Newton algorithm; Freund and Littel 2000) and 95% confidence intervals (CIs) of the model parameters for each target species were compared to determine if significant differences were indicated. If all three parameters were not found different, data were pooled to develop relationships among species exhibiting similar responses.

The influence of IS and several other variables on presence of target species in individual bottom tows or seine hauls was examined with logistic regression. Other variables considered were mean water temperature and salinity (Table 2), distance from major spawning or nursery area (for white perch ages 1+ and YOY, and striped bass YOY; Table 3) or distance from the mouth of Chesapeake Bay (spot YOY and all blue crab life stages; Table 3), and relative regional abundance of each target species life stage (Table 4). Dissolved oxygen was not featured as a parameter in logistic regression analyses with IS because of their strong association (described below).

Distance of a tributary from a major striped bass spawning area or white perch nursery area was measured from the approximate center of either area illustrated in Lippson (1973) to mouth of each tributary (Table 3). Potomac River tributaries were assigned a distance from the Potomac River spawning area and remaining Bay tributaries were assigned a distance from the Head-of-Bay spawning area. For spot and blue crabs, distance from the mouth of Chesapeake Bay was used to test whether the occupation of a site and date was influenced by distance from marine waters (Table 3).

Regional (Potomac River or Head-of-Bay) relative abundances of YOY white perch, striped bass, and spot were estimated as geometric mean catches per seine haul by the Maryland Juvenile Striped Bass Survey (Bonzek et al. 2007; Durell and Weedon 2008; Table 4). Annual regional geometric mean seine catches of ages 1+ were also used for ages 1+ white perch (E. Durell, MD DNR, personal communication). Annual densities of all life stages of blue crabs in a Chesapeake Bay winter dredge survey were used as an index of baywide relative abundance (Maryland Fisheries Service 2008; Table 4).

Stepwise selection, a combination of forward and backward logistic model building that tests variables for entry and removal, was used to derive models for each species and life stage combination (SAS 1995; Wright 1998). Only main effects were considered. There should have been at least 50 times as many observations as predictor variables and N equaled 588 for trawls and 519 for seines in our analysis (Wright 1998). Stepwise selection is iterative and involves many tests of individual coefficients that increases the Type I error rate because multiple comparisons are made without adjustment to the level of significance (SAS 1995; Wright 1998). Specification of a very small significance level and cross-validation samples are recommended (SAS 1995; Wright 1998). Additional samples were unavailable for cross-validation, but we specified $P \leq 0.0001$ to retain variables. Likelihood ratios, maximum rescaled R^2, Wald Chi-square test statistics, and odds ratio estimates with 95% Wald CI's described overall fit of models featuring the subset of parameters selected (SAS 1995; Wright 1998).

Results

Median annual bottom DO and IS were the only significantly correlated variables ($r = -0.82$, $P < 0.0001$; Figure 2) out of 15 possible associations. Surface and mid-depth DO were not significantly associated with IS, nor were annual median temperature and salinity significantly associated with IS or DO in the three depth strata.

Five of 19 estimates of annual median DO exceeded the 5 mg/L target criterion in bottom waters when IS was ≈ 5% or less, four medians were near the target (4.7-4.9 mg/L), and a near hypoxic median bottom DO was present in one instance (Figure 2). Median annual bottom DO was near the hypoxic limit in 2 of 3 years at 10% IS, and was always at or below the limit at 17% IS ($N = 4$; Figure 2). Median annual surface and mid-depth DO were above the target at all levels of IS.

Bottom DO measurements were negatively correlated with depth, but the association was not strong ($r = -0.35$, $P < 0.0001$, $N = 570$; Figure 3). When bottom DO observations were categorized into IS less than 5% (low IS - rural) or greater than 10% (high IS - suburban) to reflect breaks in the distribution of values in Figure 2, the association of depth and bottom DO was significant when IS was low ($r = -0.23$, $P < 0.0001$) but not when IS was high ($r = -0.07$, $P = 0.36$). At low IS ($N = 391$), probability of meeting or exceeding the target criterion (5 mg/L) in bottom waters was 0.429 (SD = 0.025), while the probability of meeting or falling below the limit criterion (2 mg/L) was 0.166 (SD = 0.029). At high IS ($N = 179$), the probability of bottom DO meeting or exceeding its target was 0.140 (SD = 0.026) and the probability of meeting or falling below the limit was 0.508 (SD = 0.100). Generally, high IS systems were deeper (Figure 3), but restricting analysis to depths in common between high and low IS systems did not change results (not presented).

Target species had nearly a 90% or greater chance of occurring at least once at any site; absence was likely to represent a loss of suitable habitat rather than an area that was unsuitable to begin with. Spot YOY were found at least once at 89% of sites; ages 1+ white perch were found at 97% of sites; and blue crabs, YOY white perch and YOY striped bass were found at all sites.

Weibull functions describing the relationship of Pt_i and bottom DO category (DO midpoints from 1.0 to 8.0 by 1.0) for each species and life stage were not well estimated (in some cases parameters were not different from zero), reflecting low degrees of freedom (N = 8 for each species in a 3 parameter model). Confidence intervals of parameters overlapped among target species. Data were pooled into a single relationship (N = 40). The asymptotic relationship of Pt_i and bottom DO category was described by $Pt_i = 0.541 \bullet \{1 - \exp[-DO/2.709^{1.704})]\}$ ($r^2 = 0.85$, $P < 0.0001$; Figure 4). Approximate standard errors for Pt_k, S, and b were 0.030, 0.273, and 0.519, respectively. This Weibull function supported 2.0 mg/L limits and 5.0 mg/L bottom DO targets. The 2.0 mg/L threshold was below the Pt_i and DO inflection point, and 5.0 mg/L was near where Pt_i became asymptotic with DO (Figure 4).

Log-likelihood ratios of all logistic regression models were significant at $P < 0.0001$ (Table 5). Maximum rescaled R^2 indicated small to modest amounts of variation were explained by the models. The two best fitting models explained 50-58% of variation (white perch YOY in shore-zone or bottom habitat, respectively), while remaining models explained 9-40% (Table 5).

Impervious surface had a significant, negative influence on the odds of any target species being present in trawl samples taken in mid-channel bottom habitat (i.e., these species were more likely to be present in bottom waters as IS decreased; Table 6). Impervious surface was the only variable to appear as a significant parameter in all five sets of logistic regressions for bottom-channel habitat. Blue crabs were only influenced by IS, but additional parameters influenced odds that target species of finfish were present (Table 6).

Odds of white perch YOY being present in bottom trawls increased as regional abundance and water temperature increased, and decreased with salinity (Table 6). The odds of ages 1+ white perch being present were positively influenced by regional abundance and negatively influenced by salinity. Increasing mean water temperature decreased odds of striped bass YOY being present in bottom channel trawls. The odds of YOY spot being present were positively influenced by mean water temperature and salinity (Table 6).

Logistic regressions of presence in the shore-zone did not indicate an influence of IS on the odds of our target finfish being present, but did indicate a positive influence on blue crabs (Table 7). Regional relative abundance and distance, parameters associated with potential for migration, influenced presence of target species in the shore-zone. Regional abundance indices positively influenced the odds of all target species being present in the shore-zone, while distance had a negative influence on odds of white perch (YOY and ages 1+) and blue crabs being present. Salinity and temperature influenced the odds of white perch YOY being present in shore-zone samples (Table 7).

Discussion

Increased IS associated with transition from rural to suburban landscapes had a significant, negative influence on the odds of YOY and ages 1+ white perch, YOY striped bass and spot, and all ages of blue crab being present in mid-channel bottom habitat, but did not negatively influence presence in the shore-zone of brackish Chesapeake Bay tributaries. Bottom DO in channel waters was strongly and negatively associated with IS. Hypoxic DO thresholds (2 mg/L) and normoxic targets (5 mg/L) for fish and blue crab habitat were supported by an ascending, asymptotic relationship of bottom DO category and Pt_i. Impervious surface levels of about 5% or less exhibited about a 3-times greater chance that target DO would be met in bottom channel waters than when IS was 10% or more. The chance of falling below the 2 mg/L DO threshold was about 3-times greater when IS was 10% or more.

Changes in DO with IS in Chesapeake Bay sub-estuaries agreed with general findings that (1) habitat quality in fluvial and tidal streams declined with IS and (2) streams in watersheds with greater than 10% IS were degraded (Arnold and Gibbons 1996; Cappiella and Brown 2001; Beach 2002; Holland et al. 2004). In headwater streams of Chesapeake Bay tributaries, invertebrate biodiversity was high in agricultural watersheds where best management practices were widely applied and declined linearly with IS, although maintaining large areas of riparian forest buffers mitigated IS impact (Moore and Palmer 2005). Brackish-Marine headwater tidal creeks in South Carolina exhibited adverse changes in hydrography, salinity variation, sediment characteristics, contaminants, and fecal coliform loadings once IS exceeded 10-20% (Holland et al. 2004). Once IS exceeded 20-30%, stress-sensitive macrobenthos and shrimp abundance was reduced, and food webs were altered (Holland et al. 2004).

Smaller Hudson River watersheds (< 40 km^2) appeared to be more susceptible to capture by urban sprawl than larger ones (Limburg and Schmidt 1990), so perhaps caution is in order when considering “scaling-up” DO-IS results from these smaller tributaries to the whole Chesapeake Bay. Hypoxia already occurs over an extensive area of Chesapeake Bay while its watershed is still largely rural and agriculture represents the largest human land-use (Hagy et al. 2004; Kemp et al. 2005). Given the similarities of IS and habitat guidelines in fluvial and tidal waters, converting agricultural and forest lands to suburbs is not likely to lead to improvement in Chesapeake Bay hypoxia.

Striped bass, spot, and blue crabs migrated into tributaries we sampled, but white perch had the potential to spawn in them as well as migrate (Lippson 1973). The combination of distance (from spawning area or nurseries for anadromous species or Bay mouth for marine species) and regional abundance indices was intended to describe potential for migration into a tributary in logistic regression analyses. However, there is often strong regional coherence in year-class success among spawning guilds that reflects climatic patterns (Austin 2002) and successful spawning of white perch within a tributary could have the same pattern as regional indices. Other tributaries also may have contributed migrant striped bass or white perch (Miles River was adjacent to Choptank River, and Corsica River was located within Chester River; Figure 1).

We chose summarized estimates of DO in summer for analysis to capture chronic depression and minimize influence of episodic events driven by wind forcing (Breitburg 2002). Annual differences among median bottom DO estimates in the same tributary were substantial: 1 to 3 mg/L. Dissolved oxygen varies annually due to physical forcing that drives stratification, organic and nutrient loading, sedimentation, temperature and salinity (Baird et al. 2004; Kemp et al. 2005). Salinity is a major source of differences in density that impedes mixing and promotes stratification which influences oxygen depletion (Reid and Wood 1976; Eby and Crowder 2002; Kemp et al. 2005). We suspect that the three lowest DO medians (≈ 2 – 3 mg/L) estimated for watersheds with IS less than 5% in Figure 1 (St. Clements and Breton bays) were the result of wind forcing of low DO waters from the mainstem Potomac River; these bays faced towards their region's prevailing southerly winds in summer (Maryland State Climatologist Office, personal communication) that would have pushed Potomac River water into them.

The Pt_i and bottom DO function we calculated implied that species responses to DO were more general than indicated by DO criteria adopted for Chesapeake Bay (US EPA 2003). These latter criteria, varying from 3-5 mg/L, represented targets based on a mix of experiments and field observations (Funderburk et al. 1991; US EPA 2003). Habitat loss due to hypoxia in coastal waters reflects fish avoiding DO that reduces growth and requires greater energy expenditures, as well as lethal conditions (Breitburg 2002). Several species of fish and blue crabs strongly avoided hypoxic conditions, particularly chronic hypoxia, in the brackish Neuse River Estuary, North Carolina (Bell and Eggleston 2004). Spot, Atlantic croaker *Micropogon undulatus*, and blue crab generally used the entire Neuse River Estuary when it was well oxygenated, but were restricted to oxygenated shallows when hypoxia was extensive (Eby and Crowder 2002). Hypoxic zones altered habitat use by fish and blue crabs - potentially increasing bioenergetic costs, sublethal effects such as reduced growth and condition, and overlap with competitors and predators (Breitburg 2002; Eby and Crowder 2002). Crowding in nearshore habitat, if accompanied by decreased growth due to competition, could lead to later losses due to size-based processes such as predation and starvation (Breitburg 2002; Eby and Crowder 2002; Bell and Eggleston 2004). Even shallow areas may not offer complete refuge from hypoxia once IS surpasses 10%. Uppermost sites sampled in this study were often no deeper than 2 meters, but bottom DO measurements were as low there as at deeper sites downstream when IS was 10% or more.

Once severe hypoxia becomes established, fish yields and abundances plummet (Breitburg 2002). Hypoxia in the Gulf of Mexico has been implicated in reduced food resources, reduced abundance of fishes and panaied shrimp, declining shrimp harvest efficiency, and has possibly blocked shrimp migration (Zimmerman and Nance 2000; Stanley and Wilson 2004). White shrimp *Litopenaeus setiferus* catches in Louisiana were high between the hypoxic zone and shoreline, reflecting high concentrations of shrimp blocked from migrating offshore by hypoxia (Zimmerman and Nance 2000).
Hypoxia in Chesapeake Bay degrades benthic communities and may kill fish if wind- and tide-driven tilting of the pyncnocline brings hypoxic waters into shallow areas (Breitburg 2002; Hagy et al. 2004). There is evidence of cascading effects of low DO on demersal fish production in marine coastal systems through loss of invertebrate populations on the seafloor (Breitburg et al. 2002; Baird et al. 2004). Exposure to low DO appears to impede immune suppression in fish and blue crabs, leading to outbreaks of lesions, infections, and disease (Haeseker et al. 1996; Engel and Thayer 1998; Breitburg 2002; Evans et al. 2003). Exposure of adult common carp *Cyprinus carpio* to 1 mg/L oxygen for 12 weeks depressed reproductive processes such as gametogenesis, gonad maturation, gonad size, gamete quality, egg fertilization and hatching, and larval survival through endocrine disruption even though they were allowed to spawn under normoxic conditions (Rudolph et al. 2003).

This study has focused on the extent that our target species occupied habitat during summer in Chesapeake Bay brackish tributaries subject to different levels of IS, but there are indications that viability and survival of anadromous and catadromous fish eggs and larvae could be impaired by other IS related conditions. Development leads to altered hydrologic features in streams needed for anadromous fish spawning habitat (Limburg and Schmidt 1990; Konrad and Booth 2005). An increase in salinity to potentially lethal levels for yellow perch *Perca flavescens* eggs and larvae may have occurred between the 1950s and 2001-2003 in the estuarine portion of Severn River, Maryland; increased salinity reflected putative hydrologic and groundwater recharge changes associated with watershed development to 17% IS (Uphoff et al. 2005). Significant PCB concentrations in white perch fillets were closely related to IS in 14 Chesapeake Bay tributaries (King *et al*. 2004). Anthropogenic chemicals such as PCBs disrupt endocrine function associated with reproduction in fishes and are associated with depressed survival, malformation, abnormal chromosome division of eggs and larvae, and reduced growth and survival skills of larvae (Longwell *et al.* 1992, 1996; Colborn and Thayer 2000, Rudolph *et al.* 2003; McCarthy et al. 2003). Catadromous American eel *Anguilla rostrata* are a valuable commercial species in Chesapeake Bay that live in streams and estuarine waters until maturity (Weeder and Uphoff 2003). Development alters stream and estuarine habitat for American eel (Haro et al. 2000) and yield from specific tributaries could be lowered by IS related changes to habitat. American eel exhibited localized PCB contamination in Hudson and Delaware rivers because of their limited home range (Ashley et al. 2003). Dioxin-like compounds, including PCBs, impaired normal embryonic development of European eels *Anguilla anguilla* and may have contributed to their collapse (Palstra et al. 2005).

Several methods of estimating IS are available (Cappiella and Brown 2001) and comparability of IS estimates made by different techniques should be evaluated before applying ISRPs across watersheds. Estimates of IS of Chesapeake Bay tributaries we used were consistently higher than CBP estimates (Uphoff 2008) but were similar to those estimated by MD DNR (1999). Census-based estimates of human population density in watersheds may provide an alternative measure of relative development. Holland et al. (2004) found a significant linear relationship between IS and human population density in coastal South Carolina watersheds.

We propose a general precautionary framework based on IS for decisionmakers to consider as lower branches of a decision-tree when managing resident species such as white perch, yellow perch, and American eel in Chesapeake Bay estuarine tributaries in the face of increasing development pressure. These species exhibit similar mobility and fidelity to Chesapeake Bay and its tributaries (King et al. 2004). Yellow perch have been managed on a tributary-specific basis in Maryland's portion of Chesapeake Bay and negative effects of development were mentioned when yellow perch moratoria were imposed in 1989 in Chesapeake Bay tidal tributaries located in the Washington D.C. - Baltimore, Maryland, metropolitan corridor (Jensen 1993; Yellow Perch Workgroup 2002; Uphoff et al. 2005).

In systems with low IS (rural, less than 5% IS), fish habitat would generally be considered unimpaired and management actions that deal with harvest would be most appropriate. Preserving watersheds at this level of IS would be a viable fisheries management strategy. As IS increases from 5 to 10% (development proceeds towards a suburban landscape), habitat loss likely increases its negative influence on population dynamics. Fisheries managers would need to contemplate compensating for additional habitat-related losses by increasing adjustments to harvest or by lobbying successfully for land-use changes or increased pollution control with responsible agencies. Above 10% IS (suburban landscape), habitat stress mounts and successful preservation or restoration of resident stocks by harvest adjustments alone becomes unlikely. Comprehensive watershed management strategies (stormwater management, sewage treatment, riparian buffers, stream restoration, etc) will likely be needed. Unfortunately, we are not able to find examples of successful restoration of estuarine habitat degraded by watershed development that would suggest something other than a general listing of possible measures. Endangered species or sensitive habitats may need greater protection from development than these guidelines for estuarine waters provide.

These ISRPs apply beyond managing for sustainability of local fisheries resources and allow for portrayal of losses of services such as fishing opportunities and nursery habitat for species that migrate into Chesapeake Bay tributaries from the ocean (blue crab and spot) or from other Bay spawning areas (striped bass). In the case of striped bass, lost nursery habitat may have implications beyond Chesapeake Bay because of the region's large contribution to Atlantic Coast fisheries (Richards and Rago 1999). As development impacts a greater portion of a watershed, effectiveness of management shifts from harvest control (fisheries agencies) to habitat conservation and restoration. In the Chesapeake Bay region, these latter responsibilities now lie with agencies other than those concerned with fisheries management. Fisheries managers need to effectively and openly portray potential loss of sustainability and services (fish, fishing opportunities, and ecological services) due to degraded habitat so that stakeholders, responsible agencies, and governing bodies can make informed, overt decisions about trade-offs with development.

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Table 1. Chesapeake Bay region, watershed, years sampled, watershed area and percent of watershed in impervious surfaces. See Figure 1 for locations.

Region	Watershed	Years sampled	Hectares	Impervious Surface %
Mid-Bay, East	Corsica R.	2003-2005	9,699	4.0
Mid-Bay, East	Miles R.	2003-2005	11,078	3.4
Mid-Bay, West	Magothy R.	2003	9,131	17.4
Mid-Bay, West	Severn R.	2003-2005	17,907	17.5
Mid-Bay, West	South R.	2003-2005	14,745	10.2
Mid-Bay, West	West and Rhode R.	2003-2005	6,586	4.8
Potomac River	Breton Bay	2003-2005	14,205	5.1
Potomac River	St. Clements Bay	2003-2005	11,990	4.3
Potomac River	Wicomico R.	2003	59,363	3.8

Table 2. Mean salinity (‰) and temperature (°C) for tributaries during July-early October, 2003-2005 sampling. Blank indicates sampling was discontinued.

Tributary	Parameter	2003	2004	2005
Magothy River	Salinity	4.9		
	Temperature	25.7		
Severn River	Salinity	5.4	6.4	8.4
	Temperature	26.2	27.4	28.0
South River	Salinity	6.2	7.3	10.2
	Temperature	25.5	25.8	27.6
Rhode River	Salinity	6.9	8.4	11.1
	Temperature	25.1	27.0	27.8
West River	Salinity	7.5	8.5	11.4
	Temperature	25.0	26.8	28.0
Corsica River	Salinity	4.2	6.1	7.5
	Temperature	25.7	27.2	28.5
Miles River	Salinity	8.2	9.9	11.1
	Temperature	25.6	25.7	28.0
Breton Bay	Salinity	6.9	8.9	9.8
	Temperature	26.6	27.0	28.6
St. Clements Bay	Salinity	7.8	9.6	11.3
	Temperature	26.0	26.1	27.9
Wicomico River	Salinity	5.6		
	Temperature	25.4		

Table 3. Distance to mouth of tributary (km) from mouth of Chesapeake Bay (marine), or center of Potomac or Head-of-Bay striped bass spawning areas illustrated in Lippson (1973), or center of white perch nursery in Lippson (1973).

Tributary	Marine	Region	Striped bass	White perch
Magothy River	240.3	Head of Bay	57.1	47.6
Severn River	229.8	Head of Bay	67.6	58.1
South River	221.4	Head of Bay	76.0	66.5
Rhode River	217.6	Head of Bay	81.1	70.3
West River	216.9	Head of Bay	80.5	71.0
Corsica River	261.0	Head of Bay	82.1	70.3
Miles River	232.1	Head of Bay	101.1	55.8
Breton Bay	165.6	Potomac	99.5	49.6
St. Clements Bay	169.0	Potomac	96.1	46.2
Wicomico River	178.3	Potomac	86.7	36.9

Table 4. Regional indices of relative abundance used in logistic regression analysis of target species and life stages. Indices for fish are geometric means per standard seine haul (Durell and Weedon 2008); crab relative abundance is indicated by density estimated by a winter dredge survey (Maryland Fisheries Service 2007).

		Index		
Species and stage	Location	2003	2004	2005
White perch YOY	Potomac	20.1	5.6	6.4
White perch YOY	Head-of-Bay	69.1	22.2	15.4
White perch adult	Potomac	3.2	4.7	2.0
White perch adult	Head-of-Bay	2.1	4.4	6.2
Striped bass YOY	Potomac	12.8	2.4	7.9
Striped bass YOY	Head-of-Bay	11.9	4.2	8.5
Spot YOY	Potomac	0.5	0.7	1.9
Spot YOY	Head-of-Bay	0.02	0.03	1.3
Blue crab, all	Baywide	39.8	30.7	45.3

Table 5. Maximum (Max) rescaled R^2, likelihood ratio (LR), and degrees of freedom (DF), for final logistic regression developed from stepwise selection. All models were significant at $P < 0.0001$.

	Gear and habitat			
	Trawl bottom channel		Seine shore-zone	
Species and life stage	Max R^2	LR (DF)	Max R^2	LR (DF)
White perch YOY	0.58	323.7 (4)	0.50	234.5 (4)
White perch ages 1+	0.23	104.7 (3)	0.15	59.2 (2)
Striped bass YOY	0.24	114.4 (2)	0.09	28.0 (1)
Spot YOY	0.40	209.4 (3)	0.35	152.0 (1)
Blue crab, all stages	0.22	104.9 (1)	0.13	51.0 (2)

Table 6. Summary statistics of parameters selected by stepwise logistic regressions of target species presence in bottom trawls in mid-channel versus percent impervious surface (IS, %), mean temperature (°C) or salinity (‰), regional relative abundance (Index), and distance (Distance, in miles) from major spawning area (white perch or striped bass) or mouth of Chesapeake Bay (spot and blue crab). Each retained parameter has a single degree of freedom. All reported terms are significant at $P \leq 0.0001$. N = 588.

Parameter	Coefficient	SE	Wald $\chi2$	Odds ratio	Odds lower 95%	Odds upper 95%
			White Perch YOY			
Intercept	-16.8394	4.3136	15.24			
IS	-0.4351	0.0402	116.98	0.647	0.598	0.700
Index	0.0592	0.0079	56.48	1.061	1.045	1.078
Salinity	-0.8257	0.0977	71.40	0.438	0.362	0.530
Temperature	0.8861	0.1722	26.49	2.426	1.731	3.399
			White Perch Adult			
Intercept	2.6580	0.4725	31.64			
IS	-0.1720	0.0209	67.73	0.842	0.808	0.877
Index	0.3971	0.0756	27.60	1.488	1.283	1.725
Salinity	-0.4042	0.0619	42.67	0.667	0.591	0.754
			Striped Bass YOY			
Intercept	17.0022	2.4033	50.05			
IS	-0.15471	0.0227	47.91	0.855	0.817	0.894
Temperature	-0.6154	0.0898	47.00	0.54	0.453	0.644

Spot YOY						
Intercept	-18.7912	2.7887	45.40			
IS	-0.163	0.0275	36.07	0.848	0.803	0.895
Salinity	0.3149	0.0652	23.36	1.370	1.206	1.557
Temperature	0.6348	0.1136	31.23	1.887	1.510	2.357
Blue Crab (all stages)						
Intercept	1.1891	0.1669	50.77			
IS	-0.1938	0.0234	68.72	0.824	0.787	0.862

Table 7. Summary statistics of parameters selected by stepwise logistic regressions of target species presence in shore-zone haul seines versus percent impervious surface (IS, %), mean temperature (°C) or salinity (‰), regional relative abundance (Index), and distance (Distance, in miles) from major spawning area (white perch or striped bass) or mouth of Chesapeake Bay (spot and blue crab). Each retained parameter has a single degree of freedom. All reported terms are significant at $P \leq 0.0001$. $N = 519$.

Parameter	Coefficient	SE	Wald $\chi 2$	Odds ratio	Odds lower 95%	Odds upper 95%
			White Perch YOY			
Intercept	-18.1072	4.0059	20.43			
Salinity	-0.3227	0.0808	15.94	0.724	0.618	0.849
Temperature	0.8835	0.1591	15.94	2.419	1.771	3.305
Distance	-0.1462	0.0230	40.25	0.864	0.826	0.904
Index	0.1219	0.0198	37.98	1.130	1.087	1.174
			White Perch Adult			
Index	0.4888	0.0706	47.86	1.630	1.419	1.872
Distance	-0.664	0.0162	16.88	0.936	0.907	0.966
			Striped Bass YOY			
Index	0.1738	0.0338	26.52	1.190	1.114	1.2721

			Spot YOY			
Intercept	-1.8845	0.1624	134.66			
Index	1.9525	0.1800	117.68	7.046	4.952	10.026
			Blue Crab (all stages)			
Intercept	4.7209	0.7071	44.57			
IS	0.0732	0.018	16.55	1.076	1.039	1.114
Distance	-0.034	0.00548	41.82	0.965	0.955	0.976

Figure 1.

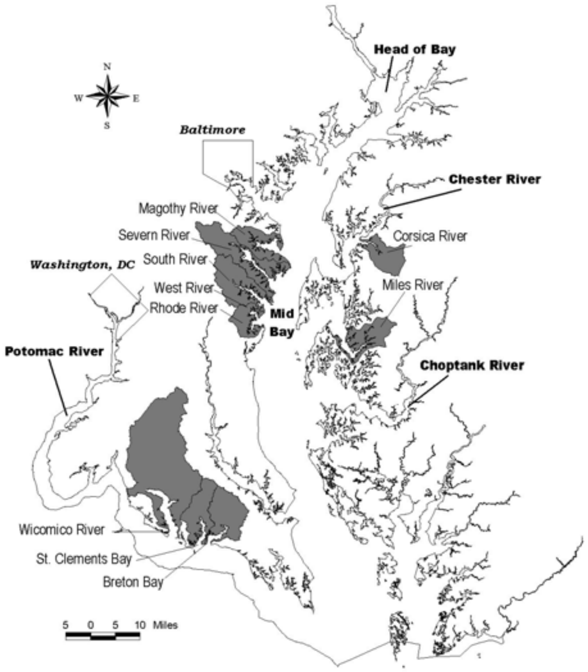

Figure 1. Location of tributaries in Maryland's portion of Chesapeake Bay that were sampled during 2003-2005, their watershed boundaries (in grey; MD DNR 1999), and general geographic regions (bold letters).

Figure 2.

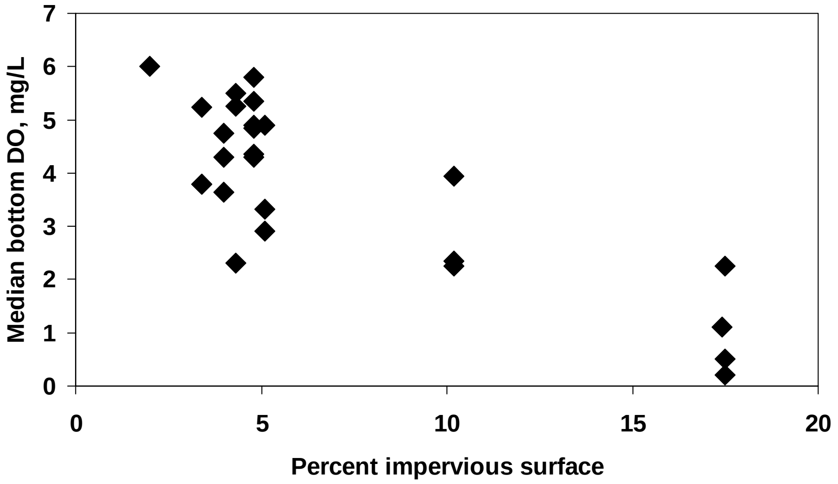

Figure 2. Plot of annual median dissolved oxygen during July-September and percent impervious surface for Chesapeake Bay tributaries sampled during 2003-2005.

Figure 3.

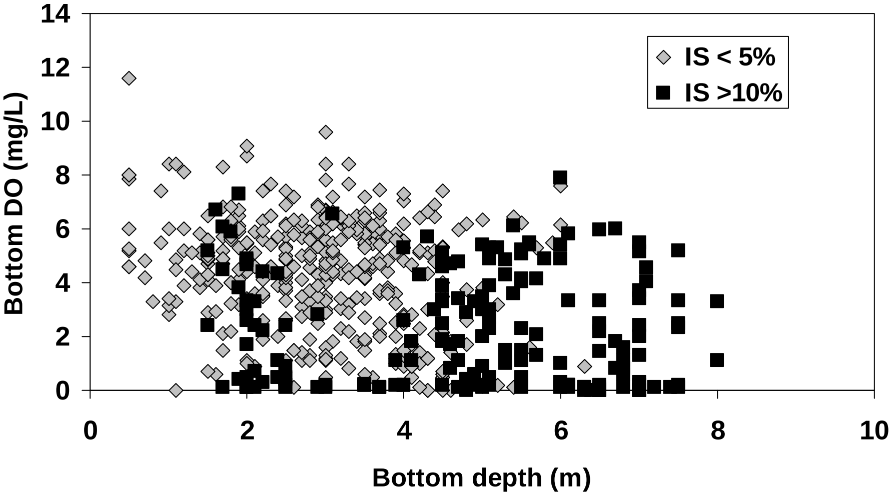

Figure 3. Plot of bottom dissolved oxygen measurements during July-September for tributaries with less than 5% and greater than 10% impervious surface (grey diamonds and black squares, respectively) versus bottom depth for Chesapeake Bay tributaries during 2003-2005.

Figure 4.

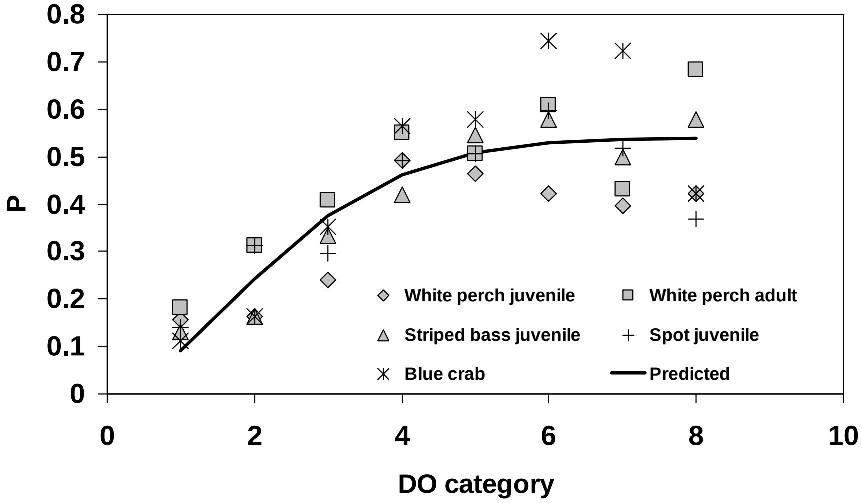

Figure 4. Observed and predicted proportion of tows (P) with target species versus bottom dissolved oxygen category midpoint. Species were pooled into a single Weibull function.