memorandum

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Subject Literature Review on the Potential Threshold Effects of Impervious Cover on Surface Waters

1 Introduction

Abt Associates is conducting literature reviews to identify, acquire and assess literature in support of the post-construction rulemaking. This review pertains to the impacts of impervious cover (IC) on surface waters including aquatic habitat and life, hydrology, water quality, and geomorphology and the potential existence of threshold effects associated with these impacts.

2 Environmental Threshold Analysis

The detection and estimation of threshold responses to anthropogenic environmental gradients depend on several factors (King and Baker 2010):

- selection of response variable(s) especially whether they are individual or aggregate metrics,
- assumed shape of the response and appropriateness of corresponding statistical model, and
- statistical approach.

In comparing results across studies, it is also important to consider the independent or driving variable. In studies examining the impact of urban land use on surface waters, the most common independent variables are urban land use, total impervious area (TIA) and effective impervious area (EIA)[1]. Each independent variable will have different values for the same watershed and potentially yield different results in determining the existence and value of a threshold[2]. In addition, the high temporal and spatial variability of watersheds introduces additional confounding factors in threshold analyses. For example, riparian buffers have been shown to mitigate IC effects (e.g., Miltner et al. 2004, Schiff and Benoit 2007, May et al. 1999) and this factor is not captured when using aggregate measures of watershed land use characteristics.

The significance of selecting response variables and a statistical approach on the existence and location of a threshold effect in biological responses to IC has been shown by King and Baker (2010). King and Baker (2010) analyzed the same dataset on IC and macroinvertebrate community using different response variables. The dataset was collected at 295 sites in Maryland's Coastal Plain streams and included 177

[1] Effective impervious area is the impervious area that is hydrologically connected to a surface water.

[2] While IC is the most common metric among studies, several studies have shown that EIA is a more effective predictor of stream biological and chemical response than TIA (e.g., Wang et al. 2001, Hatt et al. 2004 and Walsh et al. 2004a as cited in Wenger et al. 2008, Booth and Jackson 1997). However, calculating EIA can require significantly more detailed spatial analysis than calculating TIA and may be the reason for its less commonly use in the literature.

taxon abundances from 100 individual fixed counts. They selected two commonly used aggregate macroinvertebrate community metrics – Ephemeroptera, Plecoptera and Trichoptera (EPT) taxon and Maryland's Benthic Index of Biotic Integrity (B-IBI) – and used locally weighted quantile regression to analyze the data for thresholds. Although the B-IBI data showed a steepened decline between 18-28% IC suggesting a rapid change in condition, this analysis showed the data as a wedge-shaped decline with little evidence for a threshold.

King and Baker (2010) also analyzed the data for each of the 177 taxa using Threshold Indicator Taxa ANalysis (TITAN) approach and software. TITAN integrates the occurrence, abundance and directionality of taxa responses. It tests various potential thresholds to determine the optimal value that partitions sample units while maximizing taxon-specific scores. TITAN also tracks the cumulative response of increasing and decreasing taxa in the community. TITAN showed declining taxa at 0.5-2% IC and change points for increasing taxa from 1-33% IC. The asynchronistic change in species taxon produces a weak signal when measured at the aggregate community level. However, the declining taxa showed a highly statistically significant sharp decline at a threshold of ~1% IC.

In contrast, Randhir and Ekness (2009) analyzed the threshold effect of IC on habitat potential of vertebrates using coarse-scale species distribution for amphibians, reptiles, birds, and mammals. They identified threshold effects between 10-13% IC for amphibians, reptiles, mammals, and birds. This significant difference between aggregate versus single taxa metrics, in addition to the other factors mentioned at the beginning of the section, explain the wide range of thresholds identified in literature. In *Section 3*, we summarize thresholds identified in literature and specify the response variables to distinguish between single versus aggregate metrics.

3 Thresholds

3.1 Geographic coverage

There is extensive literature documenting the impact of urban land use on surface waters across the United States (U.S.); however, not all studies analyze for threshold effects. Among studies that document threshold effects, we only identified one study in an arid climate (Coleman et al. 2005) that explicitly links IC and environmental response variables. Other arid climate studies that we identified use urban land use as the metric. For example, Riley et al. (2005) found that EPT abundance declined and habitat segmentation increased around 8% urban land use but do not provide the corresponding IC; however, since urban land use is not 100% impervious, it is possible to infer that the IC is less then 8%. In addition, they used an aggregate metric for the response variable which as demonstrated by King and Baker (2010) results in identifying higher thresholds. Considering these study design details, the results are in-line with other studies that document impacts at low levels of IC. Other arid-region studies documenting the biologic impact of IC on surface waters but without explicit IC thresholds include White and Greer (2006) and Busse et al. (2006). Threshold papers may be lacking in arid regions due to the environmental stress imposed by the climate on aquatic life, thereby excluding sensitive species (Kashuba et al. 2009). Therefore, the more tolerant species show a weaker response to additional stress that is introduced by anthropogenic activities[3]. With respect to hydrogeomorphic response, however, Coleman et al. (2005) found that ephemeral streams draining small watersheds in Southern California were more sensitive to enlargement with increasing IC starting at ~2-3% IC than perennial streams in other regions. As a final

[3] Kashuba et al. (2009) showed a similar relationship for areas with antecedent agricultural land use. Areas where development occurs on agricultural land compared to forested land, the sensitive species may have already been lost during the initial land conversion to agricultural use. Therefore, the additional disturbance of urban development produces a weaker signal.

consideration, ephemeral streams impose practical limitations due to their intermittent nature which may limit the opportunity for research.

3.2 Upper and lower thresholds

Numerous studies identify threshold but do not discuss whether they are upper or lower thresholds. For example, Shaver et al. (1995, as cited in Horner et al. 1999) describe a "sharp decline" in aquatic insect diversity at 8-15% IC. We interpret this as an upper threshold beyond which the aquatic insect community begins to collapse rather than the first point at which impacts are measureable.

Additional confounding of results for low IC% occur because some studies assume that watersheds with low IC% are reference streams and compare other watersheds to these reference streams. This method of analyzing and presenting results implies an a priori decision that impacts are not present or negligible at low IC%. For example, May et al. (1999) grouped all watersheds with less than 5% IC as reference streams and compared the values of response variables with those from watersheds with IC between 5% and 45%. However, examining the figures presented in May et al. (1999) shows impacts at all values of IC% for various response variables such as 2-year storm to baseflow discharge and coho to cutthroat ratio. We note where we describe trends or thresholds based on figures presented in the study rather than on explicitly stated conclusions of the authors.

3.3 IC Thresholds Identified in Literature to Date

Below we summarize thresholds identified in the literature that were published between 1990 and 2010 with the terminology used by the authors to describe the effect of the thresholds. In most cases, it is evident whether the threshold is an upper or lower threshold. In some cases *no thresholds are identified and impact was observed for the entire range of IC.*

3.3.1 Biotic Responses

- Declining macroinvertebrate taxa between 0.5-2% IC with threshold at ~1% (King and Baker 2010)
- No lower threshold identified; 5.5% decrease in fluvial-fish relative abundance and 2.5% decrease in fluvial-fish species richness per 1% increase in IC; significant correlation between decline in brook trout and increase in IC (Armstrong et al. 2010)
- Abrupt decline in EPT and total insect taxonomic richness above 6% IC (Morse et al. 2003)
- Occurrence probability for three of four fish species approaches zero at levels of development equivalent to about 2%–4% *effective IC,* or approximately 8% IC (Wenger et al. 2008)
- Macroinvertebrate assemblage impairment begins at 5% IC with constant level of degradation above 10% IC (Schiff and Benoit 2007)
- Significant decline in Index of Biotic Integrity (IBI) above 13.8% IC but IBI affected ~4% *urban land use* (Miltner et al. 2004)
- Incremental degradation in fish and benthos assemblages up to 5-10% IC (depending on assumptions) beyond which no relationship or no further degradation is observed (Stanfield and Kilgour 2006)
- Sharp decline in aquatic insect diversity at 8-15% IC (Shaver et al 1995 as cited in Horner et al. 1999)
- Marked shift from less tolerant coho salmon to more tolerant cutthroat salmon at 10-15% IC (Luchetti 1993 as cited in Horner et al. 1999)
- Loss in diversity of fish at 10-12% IC (Schueler and Galli 1992 as cited in Horner et al. 1999)

- Threshold effect between 10-13% IC for amphibians, reptiles, mammals, and birds (Randhir and Ekness 2009)
- Decrease in fish species richness and biotic integrity with *effective* IC with a sharp decline between 8-12% *effective* IC and consistently low values at higher values of effective IC (Wang et al. 2001)
- Brook trout were not found above 2% IC; four salamander species were not found above 3% IC; species of herpetofauna declined from 29 to 25 to 7 species as IC increased from <3% to between 3-25% and >25% (Boward et al. 1999)
- Coho dominance was rapidly replaced by cutthroats without an evident threshold and a steady decrease in benthic index of biological integrity from ~1-60% IC (based on figure in May et al. 1999)
- High biological integrity (IBI and coho to cutthroat ratio) were only seen for streams with less than 15% IC for invertebrates and less than 8% IC for fish (Horner and May 1999)
- Decline in community index and sensitive species index over the range of IC between ~1-65%; no significant difference between sites with and without stormwater retention basins but all sites with basins had greater than 20% IC (Maxted and Shaver 1998)
- Precipitous decline in percent sensitive EPT species by 8% *urban land use* (based on figure in Riley et al. 2005)

3.3.2 Habitat Quality/Geomorphology

- No thresholds; decrease in riparian width and median particle size of stream bed and increased bank erosion with IC; negative correlation between Quality Habitat Index and IC; positive correlation between Stream Reach Inventory and Channel Stability Index and IC suggesting decreasing stream bed stability (Morse et al. 2003)
- Habitat quality drops off above 5% IC and consistently in a degraded state above 10% IC (Schiff and Benoit 2007)
- Incremental changes in width to depth ratio and percent stable banks with no narrow streams at IC greater than 10% (Stanfield and Kilgour 2006)
- Clear and consistent trend in aquatic system degradation (e.g., fish habitat, channel stability) beyond 8-10% *effective* IC with significant loss of aquatic-system function (Booth and Jackson 1997)
- Fish habitat and channel stability declines rapidly after 10% IC (Booth 1991 as cited in Horner et al. 1999)
- Stream health as an aggregate metric of biotic and physical parameters were rated as excellent, good, fair, and poor at <8%, 10%, 20%, and >29% IC, respectively (Snyder et al. 2005)
- Channel erosion impacts in headwater streams seen at 5% IC (Walker 2000)
- High quantities of large wood debris only found at <5% IC; on average, percent riparian buffer greater than 30m in width linearly declined from ~1-60% IC(May et al. 1999)
- Ephemeral streams in Southern California draining less than 13 square kilometers exhibited a threshold response at 2-3% IC with respect to channel enlargement (Coleman et al. 2005)
- Precipitous decline in pool habitat segments by 8% *urban land use* (based in figure in Riley et al. 2004)

3.3.3 Water Quality

- No lower threshold; linear increase in chloride and logarithmic increase in nitrate with increasing IC (Cunningham et al. 2009)
- Linear change with IC, no threshold (total suspended solids, dissolved oxygen, nitrate, specific conductance) (Morse et al. 2003)
- Sharp decline in multi-parameter water quality index from 0-10% IC leveling out beyond 10% IC (Schiff and Benoit 2007)
- Incremental changes in temperature up to 10% IC with no cold water streams beyond 8% IC (Stanfield and Kilgour 2006)
- A threshold of 2.4-5.1% IC is suggested for changes in pH (Conway 2007)
- Water quality constituents and metal sediment concentration showed slight change with imperviousness until ~40% IC; 40% IC water column concentration remained below aquatic life criteria and freshwater sediment guidelines (May et al. 1999) [therefore, water quality criteria may not be protective of stream ecosystems based on the impacts demonstrated by other metrics in the study, see Sections 3.3.1, 3.3.2, and 3.3.3]

3.3.4 Hydrology

- Increase in flow and runoff metrics with IC with a greater rate of increase beyond 10% IC (Olivera and DeFee 2007)
- Decreased baseflows with *effective* IC with a sharp decline between 8-12% *effective* IC and consistently low values at higher values of *effective* IC (Wang et al. 2001)
- Linear increase in two-year storm to baseflow discharge ratio from ~1-60% IC; no thresholds evident (based on figure in May et al. 1999)
- Ratio of 10-year forested discharge to 2-year current discharge declines with increasing *effective* IC from ~1-54% *effective* IC with (Booth and Jackson 1997)

4 Conclusion

There is abundant literature on the effects of IC on surface waters. The data from the majority of the studies cited above indicate no lower threshold for measuring the impact of increasing IC on indicators of water quality, habitat quality and aquatic community health but rather identify upper thresholds of IC around 5-15% beyond which sharp declines are observed in indicators. A few studies such as King and Baker 2010 and Boward et al. 1999 that examined individual species rather than aggregate indices explicitly demonstrate impacts at low levels of IC (i.e., 1% IC) and the potential lack of a lower threshold of impact.

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