APPENDIX A

REGIONAL PATTERNS OF CLIMATE CHANGE PROJECTIONS AND CONSEQUENCES FOR RIVERS AND STREAMS

A.1. CLIMATE CHANGE AND FUTURE PROJECTIONS

The rate of global warming has increased over the last century, with the linear average over the last 50 years (0.13 ^{o}C per decade) almost doubling the linear rate over the last hundred years (Alley et al., 2007). The current rate is estimated at about 0.2 ^{o}C per decade (Alley et al., 2007; Rahmstorf et al., 2007; Hansen et al., 2006) and may increase in the future. There also have been widespread changes in precipitation. Frequency of heavy precipitation events is predicted to increase over most areas, as is frequency of droughts (Alley et al., 2007). Projections for future changes are affected by the scenarios used to estimate future greenhouse gas and aerosol conditions and associated climatic forcing.

Climate change will continue and temperatures will potentially increase in the future (Alley et al., 2007). General projections for the year 2100 include global average temperature increases of 1.1–2.9 ^{o}C for the lowest emissions scenario to 2.4–6.4 ^{o}C for the highest emissions scenario. Increases in precipitation are predicted, with a higher percentage of total precipitation occurring in more frequent and intense storms. Other projections include more precipitation in winter and less precipitation in summer; more winter precipitation as rain instead of snow; earlier snow-melt; earlier ice-off in rivers and lakes; and longer periods of low flow and more frequent droughts in summer (Alley et al., 2007; Barnett et al., 2007; Hayhoe et al., 2007; Fisher et al., 1997). Changes in temperature and precipitation will have regional differences that will be important for assessing ecological effects.

A.1.1. Regional Patterns

Several points must be considered to understand how the existing and future climate changes are likely to affect aquatic ecosystems, specifically streams and rivers. Ecosystems do not respond to global averages but to regional and local patterns (Walther et al., 2002). Regional patterns of climate change are affected by factors that include atmospheric circulation patterns, topography, land use, and region-specific feedbacks (Hayhoe et al., 2007) and are more difficult to project. Within the United States, regional projections for future temperature increases are variable among models, but almost all regions project greater temperature increases in winter than summer (NAST, 2001). Increased frequencies of extreme hot days (and decreases in extreme cold days) are also projected throughout the US, with the greatest increase projected for the Southwest. Other notable increases are projected for high-elevation areas of California, central Utah, central Idaho, and the Appalachian Mountains (Diffenbaugh et al., 2005).

There are substantial regional and model differences in projections for precipitation changes. The biggest average increases are projected for the Pacific Northwest and Midwest (10–30% by 2100) and the Northeast (up to 25% by 2100), with smaller increases in the Great Plains (13% by 2100), and variable projections for the Southeast (10% decrease to 20% increase by 2100) and the West (e.g., doubling of winter precipitation over California, but decreased precipitation over some parts of the Rockies) (NAST, 2001). Most of the increase in precipitation is projected to occur during the winter, with more frequent and/or more intense storm events, and with more winter precipitation as rain instead of snow (e.g., Polsky et al., 2000; Magnuson et al., 1997).

Most models project increases in evapotranspiration—due to increased temperature rather than increased summer precipitation—leading to a net decrease in soil moisture and a greater likelihood of late-summer drought (NAST, 2001).

A.1.2. Hydrology

There are also secondary drivers that are important in structuring aquatic ecosystems that will be altered by climatic changes, especially hydrologic regimes (e.g., Richter et al., 1996). Projected hydrologic changes, driven by climate-associated changes in temperature and precipitation, include changes in the magnitude, timing, frequency and duration of various flow events. Together these projected hydrologic changes will result in redistributing stream flow (Hayhoe et al., 2007).

In North America, projected changes in average stream flow range from an increase of 10–40% at high latitudes to a decrease of about 10–30% in mid-latitude western North America by 2050 (Milly et al., 2005). Consistent with this large-scale pattern, Hayhoe et al. (2007) predict an increase in stream flow in the northeastern United States, ranging from and increase of 9-18% in the southwest part of the region to an increase of 11-27% in the northeast part of the region. In an earlier study in the US Northeast, however, average stream flow was projected to decrease by an average of 21–31%, reflecting a temperature-associated increase in evapotranspiration that will exceed small net changes in precipitation (increases in winter and spring and decreases in summer and fall) (Moore et al., 1997). Hayhoe et al. (2007) attributes these differences to their use of updated forcing scenarios that include projected increases in winter precipitation. Patterns of stream flow also are projected to change in the Northeast, with increases in stream flow occurring mainly in the winter and spring, but with lower stream flow in the summer and fall (Hayhoe et al., 2007). Climate changes in the Northeast may also include more intense thunderstorms, especially in the summer. If this happens, it could result in greater variability and “flashiness” of stream flows (Moore et al., 1997). In the Great Lakes Basin, average basin runoff is projected mainly to decrease up to 32% in response to increased temperatures, despite precipitation increases (Magnuson et al., 2001).

In snow-pack dominated regions, the combination of warming temperatures, a shift toward less winter precipitation falling as snow, and snow-melt occurring earlier will shift the peak runoff from spring to late-winter/early spring (Barnett et al., 2005). Predicted shifts in peak runoff (anywhere from about two weeks to one month earlier) by the end of the century are typical (Dettinger et al., 2004; Hayhoe et al., 2007).

Rain-dominated streams are expected to be especially responsive to altered precipitation patterns, with runoff, flow variability and flood frequency responding directly to changes in precipitation. These streams may also respond to increased variability in precipitation, impacting flood frequency and variation in flow; and to increasing temperatures, causing decreases in runoff (Poff at al., 1996). In a Mid-Atlantic perennial flow (rain-dominated) stream, Poff et al. (1996) predicted mean flow (runoff) to increase about 10–15%, flow variability to increase about 20–25%, and flood frequency to more than double (from 1.1 to 2.5 floods per year) with a 25% modeled increase in precipitation. Doubling the coefficient of variation of precipitation had an even more dramatic effect on these hydrologic characteristics.

In the Mid-Atlantic region, using the Susquehanna River as a model, Neff et al. (2000) estimated annual changes in stream flow by 2100. Estimated changes range from -4%, based on the Canadian Climate Center (CCC) model (Flato et al., 2000; McFarlane et al., 1992) to +24%, based on the Hadley model (Johns et al., 1997). Both models project increased stream flows during the winter, with peak stream flow occurring up to 1 month earlier.

Even with net projected increases in annual precipitation for many regions of the US, increased durations of low flows and increased frequency of summer droughts are also projected. In California’s Sacramento/San Joaquin Basin, Knowles and Cayan (2002) predict a 20% loss in the amount of annual stream flow occurring during the summer (April-July) by 2100. Dettinger et al. (2004) made a similar prediction for the Merced, American and Carson Rivers in California, including a decrease in summertime low flows and reduced soil moisture.

Finally, the increased temperatures will lengthen the growing season, as well as increase evapotranspiration during the warm months. These could have the net effect of reducing groundwater recharge of streams, increasing the severity of summer dry periods independent of rainfall. This could be mediated to some extent by the increased CO_2 concentrations, which reduce evapotranspiration (e.g., Gedney et al., 2006).

A.1.3. Water Temperature

In addition to hydrologic alterations, changes in stream temperature are also expected. The IPCC report projects that global air temperature will continue to increase at approximately 0.2º C each decade (Alley et al., 2007). Although these are global averages, regional models also support these projections. For example, Mid-Atlantic regional models project that average air temperature will increase 2.6–5.0 ºC by 2100 (Polsky et al., 2000; Barron, 2001). These temperature changes will increase the maximum, average, and minimum stream temperatures as well as the number of degree days and the rate of degree day accrual (Note: degree days are the cumulative sum of average daily temperatures above a baseline. For example, if the baseline is 10 ºC, then one day with an average temperature of 12 ºC contributes 2 degree days).

Though a relationship between increasing air and water temperatures is expected, the magnitude and seasonal patterns of changes in stream and river water temperatures are likely to vary regionally. These regional differences will be due to water source influences (surface versus ground water), watershed characteristics, and season. Stephan and Preudhomme (1993) estimated weekly average water temperatures in ºC (excluding the ice cover period) to be a factor of 0.86 times the weekly average air temperatures for 11 streams in the Mississippi River Basin. Eaton and Scheller (1996) used this same linear relationship between air temperature and stream water temperature to estimate probable loss of fish habitat due to global warming projections. However, Mohseni et al. (2003) claim that the relationship between air and water temperatures is better explained by an S-curve such that at higher air temperatures, stream temperature increases level off due to evaporative cooling. In the Upper Rhone River, Daufresne et al. (2003) showed a clear though non-linear correspondence between long-term increases in annual average air temperature (increase of about 1.0 ºC, 1979–1999) and annual average water temperature (increase of about 0.6 ºC, 1979–1999). Annual patterns were similar, but average water temperature did not track average air temperature perfectly, suggesting possible influences of other factors such as annual variations in flow conditions or snow melt. In a review of the thermal regime of rivers, Caissie (2006) shows that thermal regime is strongly influenced by meteorology, river conditions, and geographic setting.

A.1.4. Habitat

Stream hydrologic patterns control habitat stability, channel formation and maintenance (Poff et al., 1996) and define composition, structure, and functioning of aquatic assemblages (Richter et al., 1996, Poff and Allan, 1995). Changes in hydrologic pattern, especially flood frequency, frequency and intensity of episodic runoff events (including "flashiness"), magnitude of peak runoff, and total flow, will alter stream habitat and its dynamics. Flow dynamics not only influence sediment supply and transport and, therefore, channel form, but water volume also influences the amount of available habitat and water quality. Seasonal patterns of flow magnitude, duration and frequency of runoff events, and other parameters strongly influence the types of species that can inhabit an area (Poff et al., 2002). As a result, regional changes in hydrologic regime are expected to modify habitat, species composition, and ecological interactions over time.

In the Southwest, Grimm et al. (1997) conclude that neither hydrologic nor climate models were sufficiently developed at that time to predict magnitude and direction of future climate changes. Instead, they identified stream and river surface flows in the arid Southwest as being particularly vulnerable to even small changes in precipitation, with even modest decreases in precipitation potentially causing large decreases in stream flow. In addition, increased temperatures could increase the likelihood of winter/early spring precipitation as rain instead of snow and could increase the likelihood of severe episodic flooding, while increased temperatures may also be associated with increased drought conditions during the summer. Associated habitat changes could include changes in riparian vegetation, shifts from perennial to intermittent flow, loss of aquatic habitat, and alterations in nutrient retention and instream production (Grimm et al., 1997). More recent evaluation of the numerous climate model outputs available provide consistent projections for existing and future decreases in annual precipitation minus evaporation (increased aridity), especially during the winter (Seager et al., 2007), which will have substantial negative impacts on availability and condition of stream and river aquatic habitat.

A.1.5. Pollutant Behavior

Stream water quality is expected to respond to changes in runoff magnitude and timing. Reduced flow in summer combined with increased temperatures will likely decrease dissolved oxygen concentrations, while increased storm frequency and magnitude are likely to increase introduction of silt and pollutants (Poff et al., 2002). In the Mid-Atlantic region, increased stream flow in winter and spring is expected to degrade water quality due to increased inputs of nutrients, sediments, and toxicants (Neff et al., 2000; Rogers and McCarty, 2000). For example, nitrate loads have a high positive correlation with stream flow in this area, r^2=0.8, (Neff et al., 2000). However, nitrate loads are projected to decrease in July and August associated with projected decreases in stream flow, which could in part ameliorate low dissolved oxygen conditions. In boreal streams in northwestern Ontario, Schindler et al. (1996) reported substantially reduced runoff during warm, dry periods in the 1970s and '80s that coincided in magnitude with similar increases in temperature and decreases in precipitation that are projected for future climate change in that region. There was also a substantial reduction in stream export of phosphorus in association with these periods, though they reported little trend in nitrogen export. In the Northeast, overall drier conditions and reduced stream flow are expected to increase watershed retention of non-point source nutrients, to reduce nutrient runoff, and to reduce erosion; increased thunderstorm intensity could increase episodic erosion and nutrient loading (Moore et al., 1997). These region-specific examples help define general expectations (i.e., for all regions) for pollutant loading and other water quality (e.g., dissolved oxygen) changes that should be expected in association with climate-driven changes in temperature and runoff.

APPENDIX B

BACKGROUND INFORMATION ON DATASET FOR CASE STUDIES

B.1. CASE STUDIES

Biological assemblages integrate effects from all impinging sources of stress, including "conventional" anthropogenic stressors which are commonly the focus of state programs assessing and regulating water quality, and any other significant source of environmental change, including climate change. This integrative characteristic makes biological assemblages effective monitoring tools, but it also means that all major sources of stress must be reasonably accounted for in order to reliably attribute observed responses to particular sources of stress and to effectively regulate the stress and/or manage the resource. The ongoing success of biological monitoring and assessment programs will require an understanding of what climate-associated changes are occurring in monitored aquatic communities and how monitoring programs can account for them. Accounting for climate change influences will support effective attainment of management goals using monitoring program results as a foundation.

B.1.1. Case Study Approaches

Two case studies were undertaken to examine how climate change effects can be taken into account through program design and/or analytical approaches and how climate change may affect the ability of biological monitoring and assessment programs to meet key goals. Climate change can be viewed as a "global stressor" that affects both reference and non-reference locations monitored for the effects of more "conventional" stressors. The ability to account for climate change requires an understanding of how vulnerable monitoring data are to climate change effects, and how effectively differences that are a result of climate change can be detected within existing monitoring programs.

The first case study (Chapter 2 "Assessing trends: the power of biological assessments to detect climate change") approaches these problems by evaluating the ability, or power, of a typical biological monitoring program to detect expected levels of change in a particular biological attribute, in this case species richness. Statistical power is a critical issue in designing monitoring programs to detect meaningful effects that are unknown at the present, and it is expressed as a probability. The approach in this case study explores, from several points of view, how much sampling would be needed to distinguish expected levels of climate change effects. It also examines how long it would take to detect climate change effects with a specified probability of detection, given a particular monitoring framework.

The second case study (Chapter 3 "Accounting for trends: biological assessment in the presence of climate change") examines our ability to differentiate between reference conditions and locations of reduced biological condition and the ability to assign cause to impaired conditions, using existing monitoring data and proxy estimates of expected climate changes. This approach is a foundation for defining how monitoring may have to be modified in the face of climate change and how data can be analyzed to account for climate change and remain viable.

B.1.2. Data Set Used for Case Studies

The Maryland Biological Stream Survey (MBSS) (Boward et al., 1999; URL: http://www.dnr.state.md.us/streams/mbss/) dataset was selected for use in these case study analyses because:

- The dataset was known to have had good quality control (QC) applied;
- Sampling included repeat visits at selected "sentinel" sites (i.e., fixed reference locations that are resampled annually);
- There was a sufficient duration of data collection under comparable methods (> 10 years);
- The data include excellent physical, chemical, and habitat information;
- The data include sampling for both invertebrates and fish; and
- We have worked with this dataset in the last 6 months, and therefore were both familiar with the data and knew its availability.

The MBSS sampling design is a multi-stage probability based design. It uses a 5-year rotating basin sampling approach. Basins are 8-digit HUCs (Hydrologic Unit Code), and the initial order of basin sampling was random. Within each basin, streams are grouped by order ("Strahler" orders are defined starting with headwater streams above any confluences as first order, the confluence of two first order streams as second order, etc.). Total stream miles within each order in a basin is a sampling stratum, within which random sampling locations are selected. Equal numbers of first, second and third order non-tidal streams are sampled, and replicate sampling effort within each watershed is based on stream miles within orders. Repeat visits to the same stream segment are probable in subsequent rounds, but repeat visits to the exact location are unlikely. (A smaller statewide set of sentinel sites is sampled every year; see Section 2.3.3.1).

MBSS data are available with uniform collection methods for the period 1994-2004. Each basin was sampled twice in this 10 year period. Sampling for the MBSS is conducted during index periods – the spring reproduction/recruitment period for benthic macroinvertebrates (March – early May), and the summer-fall low flow period for fishes (July - September). A wide range of physical, chemical and habitat variables are measured and/or calculated in association with the biological collections. These include water chemistry variables (e.g., temperature, pH, dissolved oxygen concentration, various nutrient concentrations, conductivity); numerous physical habitat variables (e.g., the Maryland physical habitat index (PHI), instream habitat condition, epifaunal substrate, water velocity, water depth, embeddedness, shading, distance to road, riffle quality, etc.); and land use characteristics (17 detailed categories aggregated to the larger categories of agriculture, urban, water, wetland, barren, and forest).

Benthic macroinvertebrates are collected using D-nets, employing a multi-habitat approach over a 75-m reach. Only a 100-organism subsample is processed for each sample. Identifications are made to the genus level. Fish are collected using quantitative, double-pass electrofishing in 75 meter stream segments, with a blocking net at the end of the segment. Fish are identified to the species level.