

1
2
3
4
5
6
7
8
9
10
11
12
13
14

APPENDIX A

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

1 A.1. CLIMATE CHANGE AND FUTURE PROJECTIONS

2 The rate of global warming has increased over the last century, with the linear average
3 over the last 50 years (0.13 °C per decade) almost doubling the linear rate over the last hundred
4 years (Alley et al., 2007). The current rate is estimated at about 0.2 °C per decade (Alley et al.,
5 2007; Rahmstorf et al., 2007; Hansen et al., 2006) and may increase in the future. There also
6 have been widespread changes in precipitation. Frequency of heavy precipitation events is
7 predicted to increase over most areas, as is frequency of droughts (Alley et al., 2007).
8 Projections for future changes are affected by the scenarios used to estimate future greenhouse
9 gas and aerosol conditions and associated climatic forcing.

10 Climate change will continue and temperatures will potentially increase in the future
11 (Alley et al., 2007). General projections for the year 2100 include global average temperature
12 increases of 1.1–2.9 °C for the lowest emissions scenario to 2.4–6.4 °C for the highest emissions
13 scenario. Increases in precipitation are predicted, with a higher percentage of total precipitation
14 occurring in more frequent and intense storms. Other projections include more precipitation in
15 winter and less precipitation in summer; more winter precipitation as rain instead of snow; earlier
16 snow-melt; earlier ice-off in rivers and lakes; and longer periods of low flow and more frequent
17 droughts in summer (Alley et al., 2007; Barnett et al., 2007; Hayhoe et al., 2007; Fisher et al.,
18 1997). Changes in temperature and precipitation will have regional differences that will be
19 important for assessing ecological effects.

20 A.1.1. Regional Patterns

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

1 There are substantial regional and model differences in projections for precipitation
2 changes. The biggest average increases are projected for the Pacific Northwest and Midwest
3 (10–30% by 2100) and the Northeast (up to 25% by 2100), with smaller increases in the Great
4 Plains (13% by 2100), and variable projections for the Southeast (10% decrease to 20% increase
5 by 2100) and the West (e.g., doubling of winter precipitation over California, but decreased
6 precipitation over some parts of the Rockies) (NAST, 2001). Most of the increase in
7 precipitation is projected to occur during the winter, with more frequent and/or more intense
8 storm events, and with more winter precipitation as rain instead of snow (e.g., Polsky et al.,
9 2000; Magnuson et al., 1997).

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

13 **A.1.2. Hydrology**

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

20 In North America, projected changes in average stream flow range from an increase of
21 10–40% at high latitudes to a decrease of about 10–30% in mid-latitude western North America
22 by 2050 (Milly et al., 2005). Consistent with this large-scale pattern, Hayhoe et al. (2007)
23 predict an increase in stream flow in the northeastern United States, ranging from an increase of
24 9-18% in the southwest part of the region to an increase of 11-27% in the northeast part of the
25 region. In an earlier study in the US Northeast, however, average stream flow was projected to
26 decrease by an average of 21–31%, reflecting a temperature-associated increase in
27 evapotranspiration that will exceed small net changes in precipitation (increases in winter and
28 spring and decreases in summer and fall) (Moore et al., 1997). Hayhoe et al. (2007) attributes
29 these differences to their use of updated forcing scenarios that include projected increases in
30 winter precipitation. Patterns of stream flow also are projected to change in the Northeast, with
31 increases in stream flow occurring mainly in the winter and spring, but with lower stream flow in

1 the summer and fall (Hayhoe et al., 2007). Climate changes in the Northeast may also include
2 more intense thunderstorms, especially in the summer. If this happens, it could result in greater
3 variability and “flashiness” of stream flows (Moore et al., 1997). In the Great Lakes Basin,
4 average basin runoff is projected mainly to decrease up to 32% in response to increased
5 temperatures, despite precipitation increases (Magnuson et al., 2001).

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

11 Rain-dominated streams are expected to be especially responsive to altered precipitation
12 patterns, with runoff, flow variability and flood frequency responding directly to changes in
13 precipitation. These streams may also respond to increased variability in precipitation, impacting
14 flood frequency and variation in flow; and to increasing temperatures, causing decreases in
15 runoff (Poff et al., 1996). In a Mid-Atlantic perennial flow (rain-dominated) stream, Poff et al.
16 (1996) predicted mean flow (runoff) to increase about 10–15%, flow variability to increase about
17 20–25%, and flood frequency to more than double (from 1.1 to 2.5 floods per year) with a 25%
18 modeled increase in precipitation. Doubling the coefficient of variation of precipitation had an
19 even more dramatic effect on these hydrologic characteristics.

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

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

1 Finally, the increased temperatures will lengthen the growing season, as well as increase
2 evapotranspiration during the warm months. These could have the net effect of reducing
3 groundwater recharge of streams, increasing the severity of summer dry periods independent of
4 rainfall. This could be mediated to some extent by the increased CO₂ concentrations, which
5 reduce evapotranspiration (e.g., Gedney et al., 2006).

6 **A.1.3. Water Temperature**

7 In addition to hydrologic alterations, changes in stream temperature are also expected.
8 The IPCC report projects that global air temperature will continue to increase at approximately
9 0.2° C each decade (Alley et al., 2007). Although these are global averages, regional models also
10 support these projections. For example, Mid-Atlantic regional models project that average air
11 temperature will increase 2.6–5.0 °C by 2100 (Polsky et al., 2000; Barron, 2001). These
12 temperature changes will increase the maximum, average, and minimum stream temperatures as
13 well as the number of degree days and the rate of degree day accrual (Note: degree days are the
14 cumulative sum of average daily temperatures above a baseline. For example, if the baseline is
15 10 °C, then one day with an average temperature of 12 °C contributes 2 degree days).

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

1 thermal regime of rivers, Caissie (2006) shows that thermal regime is strongly influenced by
2 meteorology, river conditions, and geographic setting.

3 **A.1.4. Habitat**

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

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

29 **A.1.5. Pollutant Behavior**

30 Stream water quality is expected to respond to changes in runoff magnitude and timing.
31 Reduced flow in summer combined with increased temperatures will likely decrease dissolved

1 oxygen concentrations, while increased storm frequency and magnitude are likely to increase
2 introduction of silt and pollutants (Poff et al., 2002). In the Mid-Atlantic region, increased
3 stream flow in winter and spring is expected to degrade water quality due to increased inputs of
4 nutrients, sediments, and toxicants (Neff et al., 2000; Rogers and McCarty, 2000). For example,
5 nitrate loads have a high positive correlation with stream flow in this area, $r^2=0.8$, (Neff et al.,
6 2000). However, nitrate loads are projected to decrease in July and August associated with
7 projected decreases in stream flow, which could in part ameliorate low dissolved oxygen
8 conditions. In boreal streams in northwestern Ontario, Schindler et al. (1996) reported
9 substantially reduced runoff during warm, dry periods in the 1970s and '80s that coincided in
10 magnitude with similar increases in temperature and decreases in precipitation that are projected
11 for future climate change in that region. There was also a substantial reduction in stream export
12 of phosphorus in association with these periods, though they reported little trend in nitrogen
13 export. In the Northeast, overall drier conditions and reduced stream flow are expected to
14 increase watershed retention of non-point source nutrients, to reduce nutrient runoff, and to
15 reduce erosion; increased thunderstorm intensity could increase episodic erosion and nutrient
16 loading (Moore et al., 1997). These region-specific examples help define general expectations
17 (i.e., for all regions) for pollutant loading and other water quality (e.g., dissolved oxygen)
18 changes that should be expected in association with climate-driven changes in temperature and
19 runoff.

1
2
3
4
5
6
7
8
9
10
11

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.

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

8 **B.1.2. Data Set Used for Case Studies**

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

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

20 The MBSS sampling design is a multi-stage probability based design. It uses a 5-year
21 rotating basin sampling approach. Basins are 8-digit HUCs (Hydrologic Unit Code), and the
22 initial order of basin sampling was random. Within each basin, streams are grouped by order
23 (“Strahler” orders are defined starting with headwater streams above any confluences as first
24 order, the confluence of two first order streams as second order, etc.). Total stream miles within
25 each order in a basin is a sampling stratum, within which random sampling locations are
26 selected. Equal numbers of first, second and third order non-tidal streams are sampled, and
27 replicate sampling effort within each watershed is based on stream miles within orders. Repeat
28 visits to the same stream segment are probable in subsequent rounds, but repeat visits to the

1 exact location are unlikely. (A smaller statewide set of sentinel sites is sampled every year; see
2 Section 2.3.3.1).

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

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

19

20