

August 2006
External Review Draft
EPA/600/R-07/086
www.epa.gov/ncea

Climate and Land Use Change Effects on Ecological Resources in Three Watersheds: A Synthesis Report

External Review Draft Report

EPA Global Change Research Program

Susan H. Julius
Britta G. Bierwagen
Thomas E. Johnson

ICF International, Inc.

Randall Freed
Susan Asam
Sarah Shapiro

August 2006

U.S. Environmental Protection Agency
Office of Research and Development
National Center for Environmental Assessment
Global Change Research Program

Preface

The Environmental Protection Agency's Global Change Research Program (GCRP), located within the Office of Research and Development, focuses on assessing how potential changes in climate and other global environmental stressors may impact water quality and aquatic ecosystems, air quality, and human health in the United States. The Program's focus on aquatic ecosystems is consistent with the *Research Strategy* of the U.S. Climate Change Research Program – the federal umbrella organization for climate change science in the U.S. government – and is responsive to EPA's mission and responsibilities as defined by the Clean Water Act.

The GCRP's aquatic ecosystem assessments also address an important research gap identified in the 2000 report entitled *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States* (Gleick and Adams, 2000) that contributed to the 2001 U.S. National Assessment. In this document, the authors express the need for methods to represent the underlying mechanisms linking food webs and hydrologic regimes in order to make more useful projections of the effect of climate-induced changes in the hydrologic regime on habitat, species, and the overall health of aquatic ecosystems.

Since 1998, the National Center for Environmental Assessment's office of the GCRP has assessed the consequences of global change on aquatic ecosystems. Through its assessment projects, this Program has provided timely scientific information to stakeholders and policy makers to support them as they decide whether and how to respond to the risks and opportunities presented by global change.

Effects of global change drivers differ by place and in scale, necessitating place-specific impacts information to enable stakeholders to respond appropriately. Place and scale also determine appropriate adaptation strategies and expected outcomes. This report is a synthesis of three watershed case-study assessments conducted by GCRP to advance the capability of managers to consider climate and land use change in watershed management decisions. The goal of this report is three-fold: (1) to understand the potential impacts of global changes and the availability of effective responses at the watershed scale across different geographic regions, (2) to learn how GCRP and other research programs might improve the process of conducting future assessments, and (3) to improve GCRP's and other research programs' understanding about effective ways to inject climate change impacts and adaptation information into decision making processes.

Toward that end, this report compares and contrasts methods and processes employed by the three case study teams to learn effective analytic, project management, and decision support approaches.

Peter Preuss, Ph.D.
Director
National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Research Program

Acknowledgements

The contributions of many people's experiences and insights made this report possible. The authors would like to thank those individuals whose help was particularly valuable. First and most important are those individuals who participated on the watershed case study teams funded by EPA. They devoted their excellent scientific and leadership skills to the conduct of each case study and made impressive methodological advances in the science of climate change impacts. They also gave of their time and energy to help us understand how we might improve the process of doing assessments that produce information befitting the needs of decision makers. These teams of researchers are:

*Maryland Case Study Glenn E. Moglen, Principal Investigator, University of Maryland
Nancy Bockstael, University of Maryland
Karen Nelson, University of Maryland
Margaret Palmer, University of Maryland
James E. Pizzuto, University of Delaware*

*San Pedro Case Study Jeff T. Price, Principal Investigator, California State Univ, Chico
Kate Baird, University of Arizona
Mark D. Dixon, Arizona State University
Hector Galbraith, Galbraith Environmental Sciences LLC
Thomas Maddock, University of Arizona
Juliet Stromberg, Arizona State University*

*Sacramento Case Study Annette Huber-Lee, Principal Investigator, Tellus Institute
Hector Galbraith, Galbraith Environmental Sciences LLC
David Purkey, National Heritage Institute
Jack Sieber, Tellus Institute
David Yates, National Center for Atmospheric Research*

We would also like to thank Catriona Rogers who helped develop the Ecosystems Focus Area aquatic research, and who contributed to the vision and direction of the watershed assessments discussed in this report. Dr. Rogers also managed the case study conducted by the University of Maryland.

A number of internal reviewers earned our appreciation for identifying improvements and corrections that had escaped us. Their suggestions as well as their challenging questions helped us to prepare a report that will be useful to a larger audience of readers. They are Naomi Detenbeck (EPA ORD/NHEERL), Bruce Herbold (EPA Region 9), Chris Weaver (AAAS at EPA), and Kate Schofield (EPA ORD/NCEA).

Executive Summary

Purpose of the Report

The effects of global change drivers differ by place and in scale, necessitating place-specific impacts information to enable stakeholders to respond appropriately. Place and scale also determine appropriate adaptation strategies and expected outcomes. This report is a synthesis of three watershed case-study assessments conducted by the Global Change Research Program (GCRP) – a unit of the National Center for Environmental Assessment within the Office of Research and Development – to advance the capability of managers to consider climate and land use change in watershed management decisions. The report provides a summary of the scientific findings from those three case studies conducted in the San Pedro River Watershed, the Sacramento River Watershed, and several small watersheds in Maryland. It also provides insights we gained from a comparison across case studies of the process of conducting watershed assessments to improve our capability to support decisions.

Case Study Results

The goal of the Maryland case study was to better understand how the effects of climate variability and change on stream ecosystems depend on land use choices in surrounding areas in order to assist regional planners to adapt to climate change and variability. The team developed and applied the Forecasted Index Simulation System (FISSh) to model the combined effects of land use change and climate change on stream fish assemblages over the next century. Two scenarios were used in their analyses: (1) baseline scenario with managed growth and no climate change; and, (2) urban sprawl with climate change (USCC). Mean annual air temperature increased by 3.2 degrees Celsius and maximum air temperature rose by 10.5 degrees Celsius over the baseline scenario. These temperature changes represent the difference between the mean and maximum air temperatures from the time period of 1995-2004 to the time period of 2085-2094, as projected by the HadCM3 model. Although total precipitation was relatively unchanged, the number of large storms increased from 4 to 10 per decade. Streamflow increased, sediment delivery increased, and annual mean water temperature rose by 0.9 degrees Celsius. Fish food sources showed significant seasonal fluctuations under the USCC scenario, and the availability of detritus dropped to only 2 percent of the baseline level. Because of the lower levels of detritus, invertebrates had food deficits from April to July and small fish showed deficits for most of the year. Non-native warm water fish species were relatively advantaged by projected land use change and climate change. Under the combined influence of climate change and projected land use change, there could be a considerable change in community composition and a loss of diversity.

The goal of the San Pedro case study was to model the likely effects of climate change, urbanization, and groundwater withdrawals on ecological resources and biodiversity in the San Pedro Riparian National Conservation Area (SPRNCA) in order to aid in managing the area's development and hydrologic conditions. Five climate scenarios were evaluated. The team analyzed species, vegetation, and habitat suitability first, and then used linked models to incorporate vegetation data into the groundwater and surface water models and to tie the fluctuations of groundwater level to evapotranspiration processes. Results showed that altered hydrology and climate change would fragment existing riparian and wetland communities and lead to their replacement by more mesic or xeric communities (i.e., vegetation more typical of the desert matrix). The influence of climate change on pioneer riparian communities depended

on the magnitude and direction of precipitation changes: less winter precipitation would result in fewer winter floods, lower rates of channel migration, and much lower cottonwood and willow recruitment rates; increased winter precipitation would result in larger and more frequent winter floods, higher channel migration rates, and higher cottonwood and willow recruitment rates. Avian biodiversity would be affected, with some of the most abundant bird species being the most adversely affected by changes in the vegetative community. Results from the three driest climate scenarios suggested that the gallery forest would be fragmented or non-existent and would result in biodiversity loss and a likely drop in ecotourism. However, results from the warm and very wet scenario suggested that the water supply to the ecosystem would be adequate enough to maintain ecosystem services and ecotourism.

The goal of the Sacramento case study was to assess how global change-related alterations in water supply and water demand would affect important freshwater ecosystem services in the Sacramento Basin using an integrated decision support tool that would inform on issues such as reservoir location, Federal Energy Regulatory Commission (FERC) dam re-licensing, and system operations to preserve the ecosystem services of interest or of regulatory necessity. The case study team applied the Water Evaluation and Planning (WEAP21) modeling system to link climate and land use/land cover conditions with watershed conditions, water supply and anticipated demands, ecosystem needs, infrastructure, the regulatory environment, and water management options. Four downscaled climate scenarios were evaluated and all four showed reductions in water availability -- there were large impacts on supply at the end of the 100-year simulations. Reservoir levels were much lower in the late summer and early fall and groundwater pumping increased, except when adaptation measures were simulated. The Sacramento River's water temperature regime would be altered, leading to further reductions in habitat for Chinook salmon due to exceedences of critical spawning and rearing temperatures. Adaptations, such as cropping practices -- *e.g.*, improving irrigation efficiency and changing cropping patterns -- resulted in a decline in water supply requirements. Managing the releases of cold water stored in reservoirs alleviated some of the future impacts of climate change on habitat for Chinook salmon.

Cross-cutting Findings and Recommendations

The three case studies contributed both methodological advances and new results to the body of knowledge on climate change impacts that will be broadly useful in three ways: the results themselves may be extrapolated to similar systems; the methods used to link process models across disciplines may be used by other assessment teams and in other geographic regions of the country, and the insights gained about the assessment process will be helpful to any research institution seeking to produce useful climate impacts information for decision makers.

One significant methodological advance across the three case studies was the development of integrated, interdisciplinary models. Advantages to linking models included: a reduction in uncertainties associated with ignoring system interactions that could not be modeled without an integrated approach; a reduction in uncertainty for decision makers in terms of forecasting effects; an improved ability to provide new information more quickly and easily about a whole suite of components that address decision-relevant questions; and, an improved ability to analyze multiple scenarios quickly. Results from the case studies also show that investing time up-front to clearly define inputs, outputs, and interactions among submodels helps facilitate a smooth linkage between submodels.

Across the case studies, several keystone capabilities or practices were identified that would be useful for EPA to provide to researchers conducting the assessments. Recommendations were to:

- Develop and apply best practices for converting GCM output to watershed modeling input
- Provide tools to develop or apply trend analysis of precipitation and hydrology to complement GCM output
- Provide consulting services in keystone skills, such as climate scenario development and habitat suitability analysis
- Provide guidance and techniques for expressing uncertainty

While each of the case studies was thorough and innovative in assessing climate change impacts, it was found that attaining the objective of providing decision support was more difficult. To better attain this objective, criteria for selecting and planning future assessments should consider (1) where decisions are being made that are sensitive to climate change, and (2) where there are existing relationships with decision makers that would enable the project team to provide relevant decision support products. To produce good science and provide effective decision support, spatial and temporal scale should also be considered – the scale at which GCM and watershed-level information is available, the scale at which key endpoints are assessed, and the uncertainty introduced by bridging the gap.

No uncertainty bounds were estimated for the results produced by each case study, making it difficult to assess whether downscaled climate data from general circulation models can credibly be used at those spatial scales. The inability to address this issue suggests that it is important to develop a set of best practices or tools appropriate for analyzing uncertainty in assessments and decision support, and that future assessments should include a requirement to develop an uncertainty analysis plan as an initial deliverable that reflects feedback from decision makers on what types of uncertainty analysis would be most relevant to decision-making. Uncertainty should be addressed more comprehensively, and, where possible, quantitatively to ensure scientific rigor and decision relevance.

It would be useful to set out an uncertainty analysis plan as one of the initial deliverables in the process, and to design the plan to reflect feedback from decision makers on what types of uncertainty analysis would be most relevant to decision-making. This feedback would help determine whether the plan should focus on developing several alternative scenarios, or a risk analytic approach that explicitly assigns probabilities to various components, or some other qualitative or quantitative characterization of uncertainty.

Finally, because stakeholder engagement is resource and time intensive, it was determined that streamlining and focusing stakeholder-related efforts is necessary and desirable.

Recommendations to improve stakeholder processes include:

- Focus on decision makers rather than a generic definition of stakeholders and develop a working partnership that builds technical capacity within the decision making body to increase the likelihood that climate change impacts will be considered beyond the particular assessment
- Build on existing stakeholder relationships to save time and resources and to open doors to collaboration with new stakeholders who may be similarly interested in study findings
- Facilitate interaction of researchers and decision makers through use of common terminology (e.g., ecosystem services), and through developing Agency expertise to manage public inputs to the study itself, rather than relying on the assessment team alone

- 1 • As part of the assessment process, set aside time to establish credibility with decision makers
2 to make them more comfortable with the assessment process and findings and how such
3 findings fit into ongoing decision processes
- 4 • Ensure that capacity for doing assessments is in place before the project starts by establishing
5 and applying a set of critical success factors, such as: available, high quality data and models,
6 clear goals, public awareness of the issue, etc.
- 7 • To better support decisions, ensure that assessment methodologies and model results are
8 transferable and widely applicable
- 9 • Develop a framework and method for identifying and prioritizing research that is decision-
10 driven and where the information will be most useful

Table of Contents

	<u>Page</u>
1.	Introduction..... 1
1.1	Purpose of the Report..... 1
1.2	The Case Studies..... 2
1.2.1	Motivation for the Watershed Case Studies..... 2
1.2.2	Criteria for Selecting Case Studies 4
1.2.3	The Portfolio of Case Studies 4
2.	Case Study Results..... 8
2.1	Maryland..... 8
2.1.1	Goals of the Case Study Assessment 8
2.1.2	Major Stressors 8
2.1.3	Assessment Methods..... 9
2.1.4	Impacts & Findings..... 10
2.1.5	Methods and Results Applicable to Other Watersheds..... 11
2.2	San Pedro 11
2.2.1	Goals of the Case Study Assessment 12
2.2.2	Major Stressors 12
2.2.3	Assessment Methods..... 12
2.2.4	Impacts & Findings..... 14
2.2.5	Methods and Results Applicable to Other Watersheds..... 15
2.3	Sacramento..... 15
2.3.1	Goals of the Case Study Assessment 16
2.3.2	Major Stressors 16
2.3.3	Assessment Methods..... 17
2.3.4	Impacts & Findings..... 18
2.3.5	Adaptation Options 19
2.3.6	Methods and Results Applicable to Other Watersheds..... 19
3.	Cross-cutting Findings..... 21
3.1	Assessment Processes 21
3.1.1	Team Composition and Management 21

1	3.1.2	Research Approach	22
2	3.1.3	Scale	23
3	3.1.4	Uncertainty	24
4	3.2	Stakeholder Processes	26
5	3.2.1	Defining and Identifying Stakeholders	26
6	3.2.2	Balancing Stakeholder and Researcher Interests	27
7	3.2.3	Engaging Stakeholder Communities	28
8	3.2.4	Establishing Credibility	29
9	3.2.5	Communicating Results	29
10	3.3	Relevance of Impacts and Adaptation to Decision Making	29
11	4.	Conclusions and Recommendations for Future Watershed Assessments	32
12	4.1	Contributions to Body of Knowledge on Climate Change Impacts	32
13	4.1.1	Methodology Development	32
14	4.1.2	Key Results	33
15	4.2	Assessment Process	34
16	4.2.1	Provide Keystone Capabilities and Tools to Assessment Teams	34
17	4.2.2	Emphasize Model Linkages	36
18	4.2.3	Change Selection Criteria for Assessments	36
19	4.2.4	Establish Forum for Researchers to Compare Notes	36
20	4.2.5	Require an Uncertainty Analysis Plan	36
21	4.3	Stakeholder Process	37
22	4.3.1	Focus on Decision Makers	37
23	4.3.2	Build on Existing Stakeholder Relationships	38
24	4.3.3	Facilitate Interaction of Researchers and Decision Makers	38
25	4.3.4	Establish Credibility with Decision Makers	38
26	4.3.5	Communicate Results using Common Language	38
27	4.4	Final Thoughts and Future Directions for GCRP	39

1. Introduction

1.1 Purpose of the Report

The effects of global change drivers differ by place and in scale, necessitating place-specific impacts information to enable stakeholders to respond appropriately. Place and scale also determine appropriate adaptation strategies and expected outcomes. This report is a synthesis of three watershed case-study assessments conducted by the Global Change Research Program (GCRP) to advance the capability of managers to consider climate and land use change in watershed management decisions.

The watershed case studies were initiated in 2002 to better understand the effects of global change on aquatic ecosystems within watersheds and to build capacity at appropriate levels of decision making to respond to these effects. The case studies are now complete, and all three have yielded valuable scientific findings and provided important lessons about assessment and stakeholder processes. This report sets out to document and synthesize the results, findings, and lessons learned by:

1. Summarizing the assessment methods developed by the case studies and key results, emphasizing those that are applicable elsewhere and those that support decision making to adapt to climate change;
2. Synthesizing insights on cross-cutting issues related to the assessment and stakeholder processes (e.g., selecting endpoints, identifying and engaging stakeholders);
3. Assessing the relevance of the case studies to decision making and adaptation to climate change and land use change; and
4. Discussing implications for future directions on watershed analyses.

Chapter 1 of this report provides an introduction, Chapter 2 describes the methods and results of the case studies, Chapter 3 provides a discussion of cross-cutting findings, and Chapter 4 summarizes conclusions and implications for future watershed assessments.

The watershed case-study assessments were conducted by three EPA-funded research teams. GCRP staff provided technical direction to each assessment team, and contributed directly to the synthesis results presented in this report. Additional support with this synthesis was provided by ICF International. The locations selected for our case studies are the San Pedro River watershed led by the American Bird Conservancy, the Sacramento River watershed led by the Tellus Institute, and watersheds in the Washington, D.C. metropolitan area conducted by the University of Maryland. GCRP solicited proposals from these research teams based on criteria established prior to our selection of these locations. Criteria included having a diversity of geographic regions and river ecosystem types represented, different land-use pressures (e.g., agricultural pressures, urban growth pressures), different future climate-induced changes (e.g., increased versus decreased streamflow), and different highly-valued ecosystem services. This synthesis is based on each case study's scientific publications, final reports, an expert meeting of case study team members held partway through their assessment process, and a series of interviews held with each case study team at the conclusion of their projects. The questions to which they responded to in the interviews are the following:

1. What are the major methodological advances developed in your case study?
2. What is the applicability of the methodologies that you employed to other watersheds? Is applicability tied to scale, assessment endpoints, regions, or some other factor(s)?
3. What do you regard as the most important/ interesting results?
4. To what extent do the case study findings apply to other watersheds? Is applicability tied to scale, assessment endpoints, regions, or some other factor(s)?
5. To what extent could the outputs of your project support decisions and what types of decisions are they? More specifically, would your results affect watershed management practices, and if so how? If you suspect they won't, what are the obstacles, if any?
6. To what extent did you isolate land use change and climate change as driving factors and what were the results?
7. If you were to propose additional work, what do you think the next phase of the project should entail? What steps would be natural extensions of the work that has already been done?
8. What do you consider to be the most important lessons learned or recommendations for future watershed assessments?

The watershed case study assessments and this report support EPA's strategic goal 4 (Healthy Communities and Ecosystems) and the EPA Office of Water's responsibilities under the Clean Water Act to "restore and maintain the chemical, physical and biological integrity of the Nation's waters." Under the EPA GCRP 2008 annual performance goal #333, this synthesis report fulfills the 2006 annual performance measure #529: *"External Review Draft report to develop and evaluate information and tools on global change impacts in key watersheds."*

1.2 The Case Studies

1.2.1 Motivation for the Watershed Case Studies

The Global Change Research Act of 1990 established the U.S. Global Change Research Program (GCRP) to coordinate a comprehensive, multi-agency research program on global change.¹ Within EPA, the Office of Research and Development (ORD) has the lead for conducting research and assessments that examine the effect of climate, land use, and other factors on aquatic ecosystems and providing decision support resources and adaptation options to stakeholders.

GCRP initiated watershed case studies to gain a better understanding of the effects of global change on aquatic ecosystems and water quality, and to build capacity to respond to these effects at appropriate levels of decision making. That led to the choice of case study sites that differed hydrologically and bioclimatically from each other, but were representative of a broader array of conditions within larger regions of the United States. These regions were the Western U.S., the arid/semiarid Southwest, and the Eastern U.S. We chose to focus at the watershed scale based on the knowledge that the properties of aquatic systems are strongly influenced by the surrounding land and are often managed and analyzed as a component of a larger watershed. The case study approach stems from a motivation to conduct assessments that fit into the existing watershed-based strategy used by U.S. water management programs to integrate water management

¹ <http://www.epa.gov/osp/myr.htm#global>.

activities within hydrologically defined drainage basins or watersheds. Additionally, GCRP has historically had a program-wide emphasis on examining site- or region-specific impacts and adaptation measures.

The assessment approach used for each case study integrates methods and concepts of ecological risk assessment, ecosystem services, scenario analysis, and stakeholder engagement processes. Climate change scenarios are used in conjunction with scenarios of other relevant global change stressors and quantitative and conceptual models to examine the potential impacts of global change on aquatic ecosystems. Therefore, the following list of desired case study design elements were identified prior to selecting the case study sites:

- Address the interaction of climate change with other stressors, especially land use change. Over the past century, there has been a trend for a higher proportion of precipitation to fall in intense events (*e.g.*, more than 2 inches per event), and these intense events contribute to non-point source pollution (Karl and Knight 1998). Climate change is anticipated to amplify this effect. Land use change (especially urbanization) modifies stream hydrology by affecting the proportion of precipitation that immediately enters the stream as runoff, and, thus, can also result in a “flashier” flow pattern (or hydrograph) (Karl and Knight 1998). The case studies are designed to examine these (and other) interactions.
- Emphasize ecosystem services. The concept of ecosystem services enables individuals from a cross section of society to express the values they hold for ecological processes or functions using a common language that helps frame assessment questions relevant to decision making. Most of the watershed management decisions address a subset of ecosystem services that aquatic systems provide. These services—which include water supply, hydropower, recreational amenities, habitat for species, and transportation—are the amenities that motivate stakeholders. Thus, the case studies attempt to identify assessment endpoints that relate to these services.
- Involve stakeholders. The goals of an assessment are to communicate insights about the possible consequences of global change and the potential for adaptive responses. Stakeholder involvement is crucial throughout this process to ensure that the assessment is timely and relevant, and that results are communicated effectively.
- Use a risk assessment approach. Consistent with the human health and ecological risk assessment programs within ORD, we apply a risk assessment paradigm to our global change assessments. The case studies were thus designed to clearly articulate the problem and develop an analysis plan (problem formulation), conduct an exposure assessment, effects assessment, and risk characterization, and to use best practices to produce high-quality scientific results. Watershed assessments employ a modification of the strict exposure-effects approach because multiple stressors are being examined. Climate and land use scenarios are intended to serve as exposure scenarios in order to project a range of potential effects.

With these design elements serving as the genesis for the effort, EPA formulated the problem that the case studies would address and selected a portfolio of three case studies.

1.2.2 Criteria for Selecting Case Studies

The goal of the case studies was to build capacity at appropriate levels of decision making to assess and respond to potential global change impacts on aquatic ecosystems within watersheds. The scientifically complex environmental problems associated with global change are beginning to be addressed under circumstances of increasingly complicated decision making processes. Watershed management has become a process of balancing multiple objectives, such as drought and flood protection, habitat and species protection, and provision of adequate supplies of water for withdrawals for municipal, industrial, and agricultural uses. Waters and watersheds increasingly are seen as complex systems comprising both ecological and human processes (Webler and Tuler 1999). Undertaking a set of watershed case studies enabled us to do an integrated examination of the processes of interest at scales that are amenable to decision making and scientific analysis.

Potential case studies were evaluated using the following criteria:

- The sites chosen should represent:
 - different geographic scales of a watershed system with respect to ecosystem services and stakeholders;
 - different climate stressors;
 - different land use pressures; and
 - different vulnerabilities and intensities of use in the context of a variety of current/existing stressors.
- Each site chosen should have services that are highly valued by the local community (and beyond the local community, if possible)
- Because of limited resources, gathering original data was beyond the capability of the GCRP. Therefore, sites chosen needed to have fairly detailed and comprehensive data sets. Supporting research conducted in the selected location(s) was considered an additional benefit.

These criteria were used to select three watershed case studies that address different scales, assessment endpoints, and hydrologic regimes.

1.2.3 The Portfolio of Case Studies

Three case study locations were chosen based on the above criteria. The selected case study sites represented diverse geographic regions and aquatic ecosystem types, different land use pressures (e.g., agricultural pressures, urban growth pressures), and different future climate-induced changes (e.g., increased versus decreased runoff). Each site provided highly-valued ecosystem services and had substantial amounts of data and existing research on which the study teams were able to build. Table 1 provides a comparison of some of the key aspects of each of the case studies and Figure 1 shows the location of the case studies across the United States.

The Maryland case study focused on riverine systems and their associated riparian zones in four selected watersheds of the greater Washington, DC, metropolitan area. Ecosystem services of interest involved the maintenance of water quality, fish and invertebrate species, and primary production and the availability of detritus. Primary stressors of concern included climate change

and land use change, specifically disturbances resulting from urbanization, increasing imperviousness in watersheds, and destruction of streamside vegetation.

Table 1: Comparison of the Three Watershed Case Studies

	Maryland	Sacramento	San Pedro
Size	Sub-watershed scale (13–28 mi ²).	Basin scale (42,000 mi ² SF Bay watershed).	Watershed scale (~2,500 mi ²).
Flow	Variance in daily streamflow has changed dramatically over the past 50 years; enhanced peak flows and reduced baseflows are attributed to increased urbanization. ¹	Flow maxima typically occur during the late winter through spring period and flow minima (dramatically reduced relative to peak flows) in the late summer and early autumn.	The majority of the flow in the San Pedro River comes from the groundwater aquifer, but there is some seasonal run-off.
Ecosystem Services (and assessment endpoints)	Habitat suitability for fish (temperature, siltation, flashiness, riparian zone condition, riffle vs. pool habitat).	Services related to water use (flow and seasonality), ecological functioning (flow and seasonality), and water quality improvement by wetlands (flow, seasonality, sediment rate, toxic and nutrient loads, and salinity fluctuations).	Maintenance of avian biodiversity, sustained urban water supplies, and recreational uses (groundwater and surface water flow, structure and composition of vegetation, avian habitat suitability, and indicator species).
Major Stressors (other than climate change and land use change)	Changes in water temperature, siltation rates, streamflow, riparian zone condition, and stress on aquatic habitats due to urbanization.	In-stream water withdrawals for urban populations, agriculture, and industry.	Groundwater withdrawals for agricultural and municipal uses; increasing water demand due to population growth.
Modeling Approach	Linked climate, hydrology, ecosystem, land-use economics, and geomorphology models.	Linked climate, hydrology, ecosystem, and wetland models.	Linked climate, hydrology, ecosystem, groundwater flow, and geomorphology models.

¹ Source: Moglen G. E., K. C. Nelson, M. A. Palmer et al. 2004. Hydro-ecologic responses to land use in small urbanizing watersheds within the Chesapeake Bay watershed. Pages 41-61 in R. DeFries, G. Asner, and R. Houghton, editors. Ecosystems and Land Use Change. American Geophysical Union, Washington, DC.

The San Pedro case study was located in the Upper San Pedro River riparian ecosystem in southeastern Arizona and northern Sonora, Mexico. This area supports a riparian ecosystem that maintains biodiversity at the ecotones between the Sonoran and Chihuahuan deserts and the plains grassland. The area contains one of the richest assemblages of species and supports one of the most important migratory bird habitats in western North America. The ecosystem services of interest thus included the maintenance of avian biodiversity, sustained urban water supplies, and recreational uses. Primary stressors of concern included groundwater pumping, climate change, and population growth.

The Sacramento case study was located in the Central Valley of California from the headwaters of the San Joaquin River in the south to the headwaters of the Sacramento River in the north. The area's ecosystem services included maintaining water quality and freshwater habitat for aquatic life; the watershed also provides water to the regional agricultural, municipal and industrial sectors. Primary stressors of concern included land use change, population growth, and climate change.

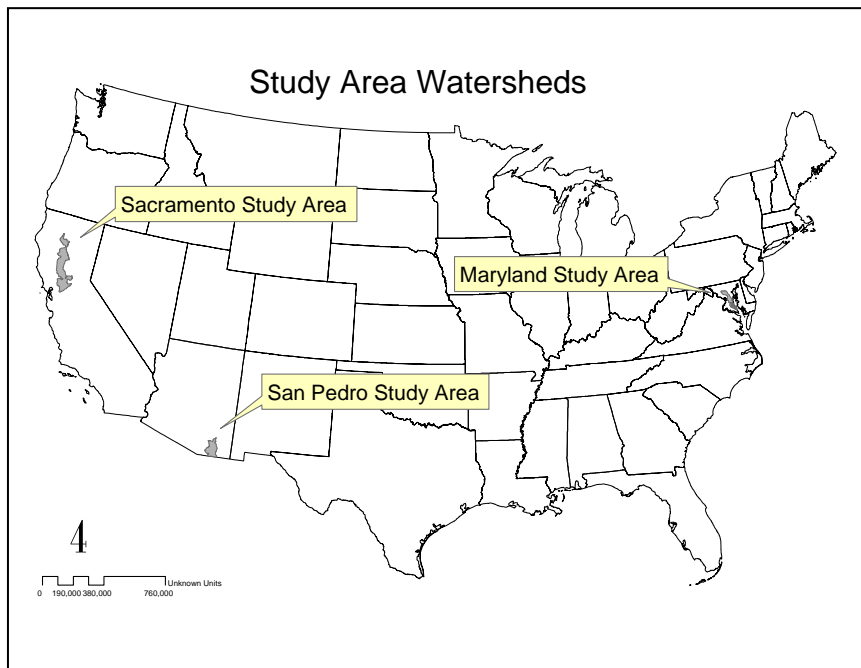


Figure 1: Geographic locations of case studies across United States.

The studies' fundamental approaches were similar; all three case studies linked climate, hydrology, and ecosystem models. At their core, the analytic frameworks of all three studies were driven by integrated modeling systems that start by simulating the effect of climate change on hydrologic characteristics, and subsequently address how changes in these characteristics affect ecosystem functioning. All three case studies also used results of large-scale climate models – known as General Circulation Models, or GCMs – to provide the bounds for, or to drive the climate scenarios. In the Sacramento and Maryland case studies, GCM outputs provided the basis for creating downscaled scenarios of temperature, precipitation, and derivative climate parameters. The San Pedro case study team developed climate scenarios that represent a reasonable set of potential climate trajectories, given the range of projections for the region

1 derived from climate models (SRAG, 2000). They used a 52-year daily time series of historic
2 weather data (1951-2002) to create transient climate scenarios for the period 2003-2102. All case
3 studies used multiple climate scenarios rather than limiting their investigation to one particular
4 future projection. This attempt to bound the range of plausible futures was used in recognition of
5 the documented uncertainties inherent in simulating future climate.

6 The three case studies all examined climate change along with population and other land use-
7 related stressors, but the choices of specific stressors were different. For example, the
8 Sacramento River Watershed study included in-stream water withdrawals; the San Pedro study
9 carefully examined groundwater withdrawals; and the Maryland study focused on sediment load
10 due to land use change. Because of the differences in focus, there were also differences in model
11 components that supplemented the core climate-hydrology-ecosystems models. In the
12 Sacramento River Watershed, model components were added to simulate ground water flow and
13 geomorphology. The San Pedro study team developed a model to simulate the effects of flow
14 changes on riparian vegetation. The Maryland team developed geomorphological models to
15 simulate changes in sediment load and bed sediment composition.

16 The relative effects of climate change, land use change, and other stressors demonstrated by each
17 of the groups showed a mixed response, with each of the systems exhibiting different
18 sensitivities based on the region, the current stressors, management goals, and anticipated
19 changes.

20

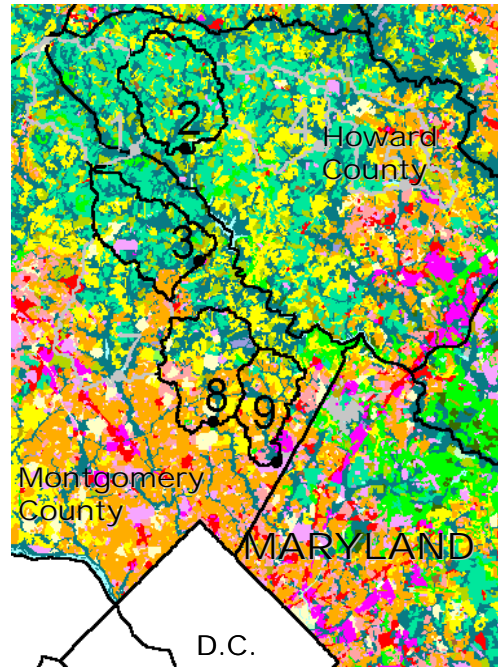
2. Case Study Results

The following section discusses the three case studies, including background on each of the regions, goals of the project, major stressors, assessment methods, results, adaptation options (if analyzed), and how the case studies are applicable to other regions.

2.1 Maryland

The research team for this study assessed the potential effects of the interaction of climate variability and change with land use change, in terms of ecological structure and functioning of stream ecosystems in four selected watersheds of the greater Washington, DC, metropolitan area. The watersheds lie primarily within the Piedmont physiographic province, and range in size from 13 to 28 square miles—much smaller than the watersheds addressed by the other case studies. These sites were selected because they are all experiencing major changes in land use but with differing patterns.

As shown in the accompanying map, three of these watersheds (marked 3, 8, and 9 in the map) are in a single county (Montgomery County) but one of them (Cattail, number 2 in the map) lies in adjacent Howard County, which has different growth and planning policies. All four watersheds have similar amounts of land left in forest; however, Northwest Branch and Paint Branch (numbers 8 and 9 in the map, respectively) have more residential development, whereas Hawlings (number 3 in the map) and Cattail have more agricultural land. Most of the urban development in these watersheds occurred since World War II, with additional development episodes in the late 1960s and early 1970s. The study area includes first-order through third-order streams in the four watersheds.



2.1.1 Goals of the Case Study Assessment

The project's goal was to better understand how the effects of climate variability and change on stream ecosystems depend on land use choices in surrounding areas. This understanding was intended to provide decision makers with information about the ecological consequences of alternative land use configurations that will assist them in developing potential strategies for adapting to climate change and variability.

2.1.2 Major Stressors

Climate change and land use and land cover change, specifically urbanization, increases in impervious surface, and destruction of streamside vegetation are all causing stream degradation at the Maryland case study sites (Nelson et al. 2006). Streams, which occupy topographic lows, collect runoff and sediment discharge, making them highly vulnerable to land use and climate change. Urbanization, in particular, is a major stressor on habitats in Maryland, causing changes in aquatic temperature, siltation rates, streamflow, riparian zone condition, and the availability of riffle versus pool-type habitats for fish (Nelson and Palmer 2006).

Climate change is projected to cause a 3 to 5 degree Celsius warming nationally by 2100 (Nelson and Palmer 2006), but the consequences of this warming depend on the seasonality of temperature shifts. Fewer but more intense storms could produce drought- and storm-related heating in much the same way that urbanization does (Nelson and Palmer 2006).

The specific stressors resulting from climate change and land use change addressed in the case study include water temperature increases, changes in sediment transport regimes, increases in runoff-associated pollution, streambed disturbance, and several other closely related factors (Moglen et al. 2006.).

2.1.3 Assessment Methods

As the endpoint of interest for their watershed study, the research team chose the suitability of a stream environment for selected fish species. Fish, with their relatively long lifespans, dependence on numerous resources, and sensitivity of reproductive success to environmental conditions, are effective integrators of systemic stressors (Nelson et al. 2006).

The team developed and applied the Forecasted Index Simulation System (FISSh) (Nelson et al. 2006) to model the combined effects of land use change and climate change on stream fish assemblages over the next century. FISSh integrates five submodels, including downscaled climate projections, stream hydrology, geomorphology, water temperature, and biotic responses, to forecast future habitat availability on a day-to-day basis. The continuous streamflow model includes three different forms of runoff production: surface runoff, subsurface runoff, and groundwater runoff (Pizzuto et al. 2006). FISSh also models the food resource base as a daily function of the input submodels and then combines and forecasts conditions for fish growth and reproduction in Piedmont headwater streams by modeling the entire fish assemblage using readily available information and seasonal variability (Nelson et al. 2006).

The case study team chose two scenarios to evaluate the impacts of land use change and climate change. The first was termed managed growth/no climate change (MGNCC) and the second was termed urban sprawl/climate change scenario (USCC). MGNCC used downscaled HadCM3 General Circulation Model (GCM) data from 1995-2004 for daily precipitation and temperature, with a year-round average temperature of 13.1 degrees Celsius. This scenario assumed 10 percent impervious surfaces, 20 percent forested lands with intact forested buffers, and no construction in the watershed; this scenario served as the baseline. The USCC model used downscaled HadCM3 GCM data from 2085-2094 with an average year-round temperature of 16.7 degrees Celsius. This model assumed an imperviousness of 30 percent, 1 percent forested lands with no forested buffers, and 2 percent construction in the watershed (Pizzuto et al. 2006; Nelson et al. 2006). Table 2 summarizes these scenarios.

The hydrological submodel used projected daily streamflow over the course of the scenario and required a daily precipitation and temperature time series as well as characteristics of the land

Table 2: Comparison of Maryland Climate and Land Use Change Scenarios

	USCC	MGNCC
Mean annual air temperature	16.7 °C	13.1 °C
Total precipitation	1308 cm	1188 cm
Rainfall events > 4 cm	40	43
Max single day precipitation	26.7 cm	17.4 cm

use and geology of the system. The model output is a daily time series of discharge (Nelson et al. 2006). The geomorphological submodel, a sediment transport model, was used to compute changes to the stream bed. Output was on a daily time-step and included particle size distribution, bedload and suspended material discharge, turbidity, areal fraction of the bed in motion, and interstitial clogging (Pizzuto et al. 2006). The instream temperature submodel predicted minimum and maximum instream temperature using a daily air temperature series derived from the downscaled GCM. The model used air temperatures from the same day and two earlier days (Nelson and Palmer 2006).

2.1.4 Impacts & Findings

The two climate change and land use change scenarios differed in that the mean annual air temperature increased by 3.2 degrees Celsius in the climate stressed scenario (USCC) relative to the baseline, and the maximum air temperature rose by 10.5 degrees Celsius (Nelson et al. 2006). While total precipitation was similar in the USCC and MGNCC scenarios, the number of large storms per decade increased from 4 in MGNCC to 10 in USCC. In particular, there was a more than two-fold increase in discharge associated with the very large storms under USCC, which was due to both the increased precipitation per storm event and decreased infiltration capacity (Nelson et al. 2006). The projected precipitation trends were more significant than future temperature trends in their influence on hydrological and ecological processes (Moglen et al. 2006).

In addition, results of the geomorphologic submodel indicated that sediment delivery increased in the USCC scenario due to projected construction in the study area and the frequency of runoff events. The increased sediment delivery resulted in a higher frequency of high turbidity conditions. Annual mean water temperature rose by 0.9 degrees Celsius and annual maximum water temperature rose 5.4 degrees Celsius between the MGNCC and USCC models. Due to the presence of riparian buffers, there were no storm-related temperature surges in the MGNCC model; however, the USCC model showed surges on about 11 percent of summer days. In addition, fish food sources showed significant seasonal fluctuations under the USCC scenario, and the availability of detritus dropped to only 2 percent of the MGNCC level. Because of the lower levels of detritus, invertebrates had food deficits from April to July in the USCC scenario and small fish showed deficits for most of the year (Nelson et al. 2006).

Results from FISSh included results for each of the following indices for each species: spawning day availability; spawning substrate; juvenile growth; washout on eggs and young-of-year; adult growth; feeding efficiency, and thermal maximum (Nelson et al. 2006). The two indices of fish ecology most affected by land use change and climate change were the index of adult growth and index of washout on eggs; they were both influenced by hydrological alterations and siltation. When all seven of the indices were considered jointly, modeling showed that up to three-quarters of the fish species would be highly stressed. This finding suggests that under the combined influence of climate change and projected land use change, there could be a considerable change in community composition and a loss of diversity. Almost three-fourths of the present fish species (30 out of 39) in the Maryland Piedmont watersheds were projected to be negatively affected by urban sprawl / climate change scenario conditions such as: a shift in spawning times due to shift in temperature (14 species); reductions in growth due to either reduced food or increased temperature (14 species); reduced feeding efficiency due to turbidity (22 species); loss of coarse woody debris needed for spawning structure (3 species); and surges of lethally hot water running off of pavement during summer thunderstorms (2 species). (Nelson et al. 2006).

Not all ecological processes are negatively influenced by the projected climate and land use changes, but when they are combined, predominantly negative effects emerge. In addition, non-native warm water fish species may be relatively advantaged by projected land use change and climate change (Nelson et al. 2006).

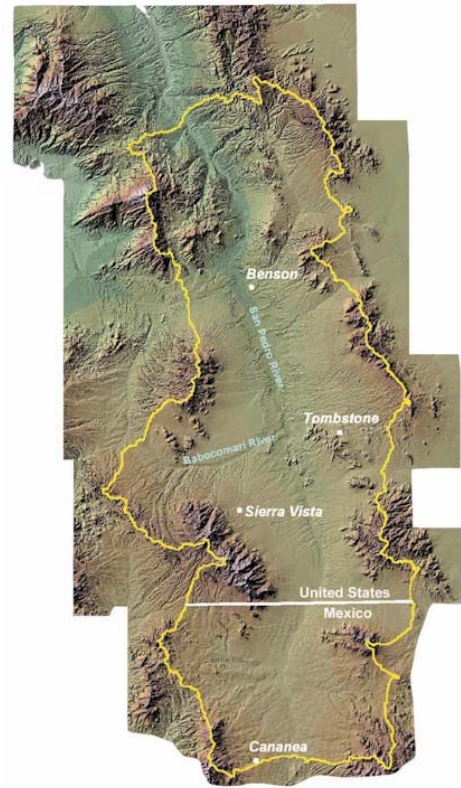
2.1.5 Methods and Results Applicable to Other Watersheds

The models used in the Maryland case study are transferable to regions where similar processes are dominant; however, all of the models would require re-parameterization to be used in other locations. The ecological models were designed specifically for the purpose of being portable; they use readily available information and could be applied in other regions. The fish assemblage is specific to the Maryland Piedmont and would be easier to apply to a similar region such as the North Carolina Piedmont rather than the Maryland coastal plain, even though the latter is geographically closer to the current site.

2.2 San Pedro

The Upper San Pedro River riparian ecosystem in southeastern Arizona and northern Sonora, Mexico, is of critical importance in maintaining regional biodiversity at the ecotones between the Sonoran and Chihuahuan deserts and the plains grassland. It contains one of the richest assemblages of species and supports one of the most important migratory bird habitats in western North America. The biodiversity found along the Upper San Pedro River matches or exceeds that found almost anywhere else in the United States. More than 20 different biotic communities occur in the basin, and the river sustains 3 biotic types that are considered threatened: Fremont cottonwood/Goodding willow forests, cienegas, and big sacaton grasslands (Price et al. 2005).

Riparian ecosystems are fragile, especially those found in arid climates. Water is crucial to these communities, and the abundance, diversity, and health of these ecosystems are strongly influenced by the hydrologic regime, including the amount, timing, and pattern of surface and groundwater flow. Surface water flow varies considerably both between and within years. During periods of storm flows, the shallow alluvial aquifer is recharged by the stream. This, in turn, supports the riparian vegetation and provides groundwater flow back to the stream from the shallow aquifer following storms. During periods of low precipitation, the flow in the river comes primarily from groundwater inflow. Many portions of the Upper San Pedro have had perennial water flow, and this is reflected in the plant communities (Price et al. 2005). However, the number and extent of areas with intermittent flows has increased in recent times (Price et al. 2005). Because the flow of water is essential for the survival of the riparian biota, it is of critical importance in maintaining the vegetation and, in turn, the wildlife of the region.



2.2.1 Goals of the Case Study Assessment

The primary goal of this case study was to model the likely effects of climate change, coupled with existing stressors (urbanization and groundwater withdrawals), on ecological resources and biodiversity in the San Pedro Riparian National Conservation Area (SPRNCA). Specifically, the case study evaluated the future ability of the SPRNCA to remain a high-quality, self-sustaining riparian ecosystem capable of maintaining the plant and wildlife habitat that results in its unique biodiversity. Researchers sought to model the effect of existing stressors and changes in the climate on the hydrologic conditions of the region, which would affect the structure, composition, and representation of vegetation communities in the SPRNCA. Changes in the plant communities would, in turn, affect their ability to continue to support important ecological resources and alter water quality and water supply (Price et al. 2005).

2.2.2 Major Stressors

The main climatic and geophysical drivers of the condition and quality of the San Pedro riparian ecosystem include aquifer depletion, climate change, and population growth. The primary stressor in the San Pedro River Ecosystem is water extraction through pumping, and much of this water goes to agricultural use. Although some of the water pumped returns to the aquifer via percolation, 70 percent of the water used for agriculture is lost. Other uses of water include municipal water supply wells, domestic water wells, stock wells, and some military and industrial use. From 1940-1997, anthropogenic water use has caused a reduction in San Pedro River streamflow, a reduction in evapotranspiration by riparian vegetation along the floodplain of the river, and the formation of significant cones of depression near many communities which accompany large losses of groundwater storage. Over the next few decades, agricultural water use in the area is expected to decrease, while the amount of urbanized land and concomitant water use is expected to increase (Price et al. 2005).

Climate change is another significant stress on the already threatened ecosystem. Climate change projections suggest an increase in mean seasonal temperatures of 2-7 degrees Celsius over the next 100 years. While all GCMs broadly agree with this temperature increase, they differ in their projections for precipitation (Price et al. 2005). Case study findings indicate that a warmer wetter future climate does not pose as significant a threat for vegetation as a warmer drier climate projection.

The case study did not separately quantify the effects of aquifer depletion and climate change. Climate change will cause changes in the ecosystem and aquifer even without water extraction and other forms of human interaction. The impact of aquifer depletion, however, is expected to be more dramatic in terms of scale than the effect of climate change alone on the San Pedro River ecosystem. Together, these two stressors will have a major synergistic effect (Price et al. 2005).

2.2.3 Assessment Methods

The ecological endpoints modeled included changes in the main vegetation communities (including riparian, mesic, and xeric), river baseflow, soil water content, channel migration, and the incidence and intensity of wildfires.

The team created five climate projections for 2003-2102 using a 52-year daily time series of historic data from 1951-2002 from the National Weather Service station in Tombstone, Arizona. The five scenarios included one with no climate change where the 1951-2002 daily temperature

and precipitation data was repeated. A second scenario (warm) had increasing temperature over 100 years with a 6 degree Celsius increase in the minimum daily temperature and a 4 degree Celsius increase in the maximum daily temperature by 2102. The third scenario (warm dry) had the same temperature assumptions as the second scenario, but included a progressive decline in winter daily precipitation. The fourth (warm wet) and fifth (warm very wet) scenarios both had the same warming as in the second scenario but increased the precipitation by 50 percent and 100 percent respectively by 2102 (Price et al. 2005).

The team used a mechanistic bottom-up approach that combined multiple interdisciplinary methods to link hydrological, vegetation, habitat, and climate change models. The team first analyzed species, vegetation, and habitat suitability and then used linked models to analyze the impacts of existing stressors and their interaction with projected climate change. The team linked models to incorporate vegetation data into the groundwater and surface water models and to tie the fluctuations of groundwater level to evapotranspiration processes. It also linked the above models to a geomorphic model (MEANDER) to drive vegetation dynamics (Price et al. 2005).

The vegetation model was developed using the STELLA II Dynamic Simulation software (Peterson and Richmond 1996), which can be used to simulate the habitat response to changes in environmental drivers such as groundwater, streamflow, precipitation, temperature, or fire. The specific vegetative groups measured included ten species or functional groups of southwestern riparian plants including Fremont cottonwood, Goodding's willow, salt cedar, velvet mesquite, velvet ash, a hydromesic shrub group, a xeric riparian shrub group, herbaceous annuals, wetland perennials, and mesic perennial grasses. Climate inputs to the vegetation model included solar radiation, average minimum and maximum temperature, daily precipitation, relative humidity, and maximum daily wind speed, all averaged over the 5-day time step of the model. The team ran the vegetation model under four of the five climate scenarios: no change, warm, warm wet, and warm dry. Initial conditions for vegetation were represented by stem density and mean effective diameter in study plots for five of the six most abundant tree species in the riparian corridor. Additionally, all plots began with a 20 percent cover of both annuals and wetland plants. The model also included simulation of fire occurrence and its effects on vegetation and structure. (Price et al. 2005)

The case study also used the Soil Water Assessment Tool (SWAT), a physically-based hydrologic model designed to project the effects of land management practices on water and sediment yield in complex watersheds over long time periods (Srinivasan et al. 1998). Input data for SWAT included daily weather, soils, topography, vegetation, and land management practices, and includes input parameters representing streamflow-groundwater interactions. The team used SWAT outputs of daily streamflow data to run MEANDER (Odgaard 1989), a model used to project changes in channel location under different climatic scenarios (Price et al. 2005).

The avian biodiversity methodology focused on 87 abundant bird species in the SPRNCA. Four variables were used to predict future population changes, including the species' dependence on (1) dominance by riparian species in the vegetative community; (2) extensive and non-fragmented stands of riparian forest; (3) wetland habitat; and (4) running or standing water. In addition, five species were evaluated using Habitat Suitability Index (HSI) models developed for this case study. These models evaluated the likely impacts of changes in habitat quality on a species' carrying capacity (Price et al. 2005).

The team found that a major constraint with the model linkages is that the various models produce output with different resolutions and scales. For example, the surface water modeling operated at a finer scale than the groundwater and geomorphology models (Galbraith et al. pers. comm.)². Linking the various models was one of the major methodological challenges in this study.

2.2.4 Impacts & Findings

Vegetation modeling indicated that changing hydrology and climate change may fundamentally impact vegetation in the SPRNCA by fragmenting existing riparian and wetland communities and leading to their replacement by more mesic or xeric communities (i.e., vegetation more typical of the desert matrix). Model results suggested a decreasing trend in coverage by pioneer woody vegetation across the floodplains of the upper San Pedro over the next 100 years. The influence of climate change on pioneer riparian communities will depend on the magnitude and direction of precipitation changes. A decrease in winter precipitation will likely result in fewer winter floods, lower rates of channel migration, and much lower cottonwood and willow recruitment rates. An increase in winter precipitation is expected to result in larger and more frequent winter floods, higher channel migration rates, and higher cottonwood and willow recruitment rates. Models indicated that coverage by later successional communities such as mesquite, ash patch types, and sacaton grassland should increase over the next 100 years. Finally, the dominant factor influencing vegetation patterns along the San Pedro today may be its geomorphic history; Price et al. (2005) noted that “the channel incision and widening events of the late 19th through early 20th century set the template that influenced subsequent development of the new floodplain and riparian ecosystem.”

The avian biodiversity modeling projected that 26 percent of the most abundant bird species would likely to be vulnerable to and adversely affected by changes in the vegetative community due to climate change. An additional 25 percent could be relatively unaffected, and 43 percent could benefit. Results of the HSI models indicated that the species most dependent on the cottonwood/willow gallery forest would show the greatest projected decreases. Even without factoring climate change into future conditions, marked changes in habitat quality are projected for two of the five species. This change is caused by a maturation and contraction of the cottonwood/willow forest in the middle of this century; the change will result in decreased habitat for the yellow-billed cuckoo and an increase in habitat for the Botteri’s sparrow as the forest is replaced with grassland and shrublands (Price et al. 2005).

The no change, warmer, and warmer drier climate modeling scenarios all resulted in a loss of riparian forest and wetlands and their replacement by mesic or xeric vegetation communities. High avian biodiversity in the SPRNCA is supported by the proximity of riparian gallery forest and wetland habitats within a matrix of desert scrub and grassland (Price et al. 2005). Loss of either of the habitats would reduce the biodiversity of the SPRNCA, since the birds that currently inhabit these areas are expected to be replaced by current occupiers of the desert scrub matrix. These findings suggest that the ecosystem services provided by the SPRNCA could be greatly affected by climate change (Price et al. 2005).

² Subsequent citations of personal communication with the San Pedro team refer to the interview at the conclusion of the case studies. Team members interviewed included H. Galbraith, M. Dixon, and T. Maddock.

A decline in ecosystem services that sustain ecotourism could adversely impact demand for those activities within the region. The SPRNCA is a major attraction to wildlife viewers and ecotourists. If the gallery forest were to be fragmented or entirely lost as is projected under the three driest climate change scenarios, the area would be less attractive to the public. If future climate changes more closely resemble the warm and very wet scenario, adequate water supply to the ecosystem might help maintain ecosystem services (Price et al. 2005).

2.2.5 Methods and Results Applicable to Other Watersheds

The vegetation, hydrology, and wildlife data inputs used in the models make them specific to the Southwestern U.S. and other arid environments with groundwater-dependent riparian systems. The evapotranspiration model (RIPET) is a riparian modeling system, but is applicable to any system where vegetation is affected by changes in the water table. Currently, the model is being applied in the Rio Grande and Kern watersheds in California. The general approach of linking vegetation to channel migration is useful in other regions, as long as the specific vegetation data are adapted. However, the approach is not applicable to systems where vegetation uses water from the unsaturated zone (Price et al. 2005).

The results from this case study and, in particular, the challenges of aquifer depletion are applicable to other areas. The San Pedro ecosystem could be a model for future changes of similar riparian systems in the Southwestern U.S. due to climate change and other anthropogenic stressors.

2.3 Sacramento

The Central Valley of California extends approximately 450 miles, from the headwaters of the San Joaquin River in the south to the headwaters of the Sacramento River in the north. This area of approximately 42,000 square miles is referred to as the Sacramento River Watershed. The main water inputs are derived from the two rivers and their tributaries, which drain into the delta and, eventually, into Sacramento and the Pacific Ocean. The hydrology of the Sacramento River Watershed is dominated by winter snow fall with subsequent spring melt and runoff, giving rise to spring peak flow maxima and later summer flow minima in most of the streams. Winter (November-April) is the season of maximum rainfall, so the variability of wintertime precipitation dominates the hydrology. Although this dominance is still a characteristic of the natural hydrology of the region, human intervention in the hydrologic cycle has greatly disrupted this natural hydrology.

Extreme variability in precipitation throughout the Sacramento River Watershed makes California particularly vulnerable to climate variability and change. Greater variability means that many of the area's ecosystem values are already coping with years of adverse conditions. Climate change, however, could make water supplies more vulnerable due to reduced snow packs and, consequently, lower summer streamflows, which would threaten aquatic ecosystem services such as the provision of water for the agricultural sector and for valued aquatic wildlife habitat.



The existence of suitable spawning and rearing habitat for Chinook salmon in the upper Sacramento River is currently dependent on releases of cool water from reservoir hypolimnia between May and September. Without these releases, the water temperatures would exceed the physiological tolerances of the eggs and juveniles of the winter and spring runs by three or more degrees Centigrade. The Chinook salmon are able to reduce their vulnerability to the temperature increase by spawning earlier and later in the year, and, therefore, are less dependent on changes in water management practices. The midsummer high water temperatures in the lower river are controlled by high ambient air temperatures and slow and low flows. Releases from dams currently keep the river water temperatures below the physiological thresholds for migrating fish like Chinook salmon (Yates et al. 2006). If releases of cool waters from the dams were not continued under the climate change scenarios, the mid-summer monthly mean water temperatures in the lower Sacramento River would be about 6 degrees Celsius higher, a potentially lethal temperature for adult and juvenile Chinook salmon (Yates et al. 2006).

The main land uses in the Sacramento River Watershed, particularly at lower elevations, are agricultural, municipal, and industrial. Eight of California's 15 most agriculturally productive counties are in the Central Valley, which makes it one of the most productive areas in the world (California Research Bureau 1997). The area of agricultural land is currently stable or decreasing slightly, at about 1.5 million hectares (these lands are irrigated using water from the main rivers). The main crops are generally water-demanding (e.g., cotton, grapes, tomatoes, fruits, hay, and rice). The annual crop value is typically in excess of \$14 billion, and more than 30 percent of the total economy is attributed to agriculture (California Research Bureau 1997).

2.3.1 Goals of the Case Study Assessment

The broad goal of this case study was to assess how global change-related alterations in water supply and water demand may affect important freshwater ecosystem services in the Sacramento Basin. The objectives of the case study were five-fold: (1) to understand the relationships among stressors and ecological processes and the aquatic ecosystem services they provide; (2) to use this information, along with water resource models, climate change scenarios, and assumptions about the future intensities of existing stressors to project effects on the future functioning of these services; (3) to provide stakeholders with information on how valued ecosystem services are likely to be affected, so that they can make informed decisions; (4) to develop appropriate methodologies for assessing effects on ecosystem services that will be transferable to other large watersheds in different locations and settings; and (5) to provide integrated decision support for issues of reservoir location, Federal Energy Regulatory Commission (FERC) dam re-licensing, and system operations to preserve the ecosystem services of interest or of regulatory necessity. This case study found that the challenge was to balance the complex tradeoffs and interactions of the multiple uses of water (e.g., water for food and water for environment), some of which are in conflict and others which are not. Climate change presents the possibility that the existing balance will be upset and that adaptation will be required (Yates et al. 2006).

2.3.2 Major Stressors

The most crucial stressors on the Sacramento River Watersheds are population growth, land use change, and climate change. Steady growth in population, particularly around existing urban areas and transportation corridors, directly affects the demand for water in the Sacramento River Basin. In addition, changing land use, in particular the extension of urban area into other land use

types, stresses water supply and demand in the basin. Climate change is expected to exacerbate these demands on water (Yates et al. 2006).

The primary problem caused by land use change and population growth in the Sacramento Basin is the movement of water out of the irrigated agricultural systems and into the urban environment (Yates et al. 2006). The scale of water development in California is among the most substantial in the world, with water often being shifted from one basin to another over distances of hundreds of kilometers to satisfy water demands (Yates et al. 2006). Much of the water in the basin is exported through pumps in the Delta in order to satisfy municipal and industrial demands along the Southern California Coastal Plain and agricultural water demands in other basins (Yates et al. 2006). Land use change and water development – particularly the construction of major reservoirs on all of the major rivers – has altered surface water hydrology in the basin and created peak flow conditions earlier in the winter and reduced spring flows. In addition, summer flows are higher than under natural conditions since operators attempt to meet summer irrigation demands by releasing water downstream (Yates et al. 2006).

Climate change – particularly projected increases in summer temperatures – is expected to cause an increase in water supply requirements for all land uses (Yates et al. 2006). Modeling for this case study took cropping and irrigation management patterns and climate change into account using two simulations. Cropping and irrigation management patterns remained fixed over the course of a 100-year simulation in the first formulation, while cropping and irrigation management patterns evolved along with climate in the second. Climate and land use stresses were not isolated to determine their individual effects on the system (Yates et al. 2006).

2.3.3 Assessment Methods

In California's diverse and highly regulated environment, the ecosystem services deemed most necessary for examination by this study included a reliable water supply for agriculture, urban consumption, and industry; habitat and food resources for salmonids and other fish species; hydropower; recreation; aesthetic beauty; transportation; soil fertility; flood and drought mitigation; water purification; and erosion control. The selection of services was based on the relative importance of the service to the region, the availability of data to relate the service to climate, the tractability of the modeling, and stakeholder priorities.

The case study team applied the Water Evaluation and Planning (WEAP21) modeling system to link natural and anthropogenic considerations to allow for an analysis of tradeoffs, such as water supplies for agricultural, natural, domestic, industrial, or recreational uses (Yates et al. 2005). Biological requirements in the model such as fish mortality or reproduction were related to projected climatic characteristics and hydrological and water quality characteristics. WEAP21 recognizes that water supply is defined by the amount of precipitation that falls on a watershed and is depleted through natural watershed processes with evapotranspiration being the first significant point of depletion (Yates et al. 2006). The residual supply is available to the water management system. WEAP21 is thus able to link climate, land use/land cover conditions, and water management (Yates et al. 2006).

The WEAP21 model extends the original WEAP model by including demand and supply priorities that solve the water allocation problem in a linear programming heuristic. WEAP21 includes a transparent set of model objects and procedures that can be used to analyze a full range of issues faced by water planners through a scenario-based approach. The list of issues includes climate variability and change, watershed condition, anticipated demands, ecosystem

needs, the regulatory environment, operational objectives, and available infrastructure (Yates et al. 2006).

In the modeling process, the Sacramento River Basin was divided into more than 100 subcatchments, groundwater basins, irrigated areas, and urban demand centers in an attempt to completely characterize the forces that act on water in the basin. A monthly climate time series from 1962 to 1998 was used to drive a distributed hydrologic model that simulates runoff, groundwater-surface water interactions, and consumptive water demands. Water management infrastructure, including reservoirs, canals, and diversions, was superimposed over the physical watershed. Results show that the model was capable of reproducing both local and regional water balances for the 37-year period, including managed and unmanaged streamflow, reservoir storage, agriculture and urban water demands, and the allocation of ground water and surface water supplies (Yates et al. 2006)

This study evaluated the impact of four climate scenarios on water management in the region and whether water management adaptation could reduce the potential impacts of climate change. The four climate scenarios were derived by downscaling the output from two GCMs (Parallel Climate Model and Geophysical Dynamics Laboratory) and two emission scenarios (A2 and B1) to a 1/8 degree grid over California. The four climate scenarios were: (1) Parallel Climate Model with an A2 scenario; (2) Parallel Climate Model with a B1 scenario; (3) Geophysical Dynamics Laboratory with an A2 scenario; and (4) Geophysical Dynamics Laboratory with a B1 scenario.

2.3.4 Impacts & Findings

Two of the four scenarios examined predicted a decreasing trend in precipitation over the next century, with the other two scenarios showing less pronounced changes – one scenario predicted slightly wetter conditions at the end of the century and the other showed a decrease in precipitation in normal-dry years and an increase in precipitation in normal-wet years. All four scenarios predicted increases in average winter and summer temperatures over the next century ranging from a lower bound increase of 1.5°C in winter and 1.4°C in summer to the higher bound of 3.0°C in winter and 5.0°C in summer.

Key hydrologic factors were examined by the case study team to determine whether existing water management arrangements in the Sacramento were capable of responding to the potential climate and land use changes. For the first hydrologic factor, annual inflows to reservoirs, two scenarios projected increased annual inflows to the major reservoirs and two projected lower annual inflows. The second hydrologic factor was changes in the timing of stream flows. All scenarios showed an earlier timing in stream flows as compared to historic conditions, which would have the greatest effect on those basins dependent on snow melt runoff (e.g., Sacramento watershed above Lake Shasta). Persistence of drought conditions, the final hydrologic factor, was projected to be less severe than the historical record under two scenarios. A third scenario projected that droughts comparable in magnitude to the early '90s drought would occur with regularity. The fourth scenario projected a very severe drought during the last 15 years of the century. (Yates et al. 2006).

All four scenarios showed an increasing trend in water requirements with time. These increasing supply requirements were due primarily to increasing summer temperatures for each of the four scenarios. The cause was likely the increasing crop water demands as summer temperatures increased. Groundwater pumping was projected to be relatively stable for all scenarios for the periods covering 1960 to 2064. In the last period, 2070–2099, pumping increased significantly in

dry years for one scenario when surface water deliveries were less reliable. Aquifers in the region showed relatively stable fluctuations around a mean for most of the period between 1960 and 2070. During this period the surface water deliveries were increasing with growing crop water requirements so that groundwater pumping levels were only marginally increased. During the final period of analysis (2070–2099), however, an extended ten-year drought in one scenario shifted agricultural water supplies to groundwater. As a result, groundwater levels decreased sharply. (Yates et al. 2006).

Future climate changes, particularly shifts in temperature and precipitation patterns, were projected to alter the river's temperature regime. This change could lead to further reductions of the Chinook salmon's fragmented habitat. Specifically, increased water temperatures were projected to result in exceedences of critical spawning and rearing temperatures, thus jeopardizing the productivity of Chinook salmon (Yates et al. 2006).

2.3.5 Adaptation Options

The Sacramento team considered two forms of adaptation options in this case study. The first was incorporated into the WEAP21 model and consisted of strategies to adapt cropping practices. The cropping options analyzed included improved irrigation efficiency and changes in cropping patterns in response to water supply conditions. The results showed a decline in water supply requirements as improvements in irrigation efficiency were implemented (Yates et al. 2006).

The second adaptation option the team considered was managed releases of cold water stored in reservoirs. This case study demonstrated that the management structures and practices that had historically affected the fish adversely may provide an opportunity to alleviate some of the future impacts of climate change. More 'natural' and unmanaged systems may provide fewer opportunities for adaptation to climate change effects (Yates et al. 2006). Since Chinook salmon are coldwater fish, they may be vulnerable to climate change, particularly increasing water temperatures. Rising water temperatures in their natal rivers could adversely affect the salmon's ability to find suitable breeding habitats, especially since that habitat has already been reduced by dam construction. However, dams allow scheduled releases of cold water stored in reservoirs, such that the frequency and timing of these releases could be used to aid salmon survival during spawning (Yates et al. 2006).

2.3.6 Methods and Results Applicable to Other Watersheds

The WEAP21 model framework has proven resilient, with wide applicability to multiple locations and systems. The intrinsic logic behind WEAP21 is universal and could be easily adapted for other locations using site specific data. Further, the results from this case study would apply to other watersheds that are similar in character and nature. For example, if agricultural sector water demand is scaled back due to improved irrigation efficiency and changes in cropping practices, there will be more water for other sectors. Given that all water resource systems and hydrologic systems are unique, however, the specific results would not be

- 1 transferable. In other words, the results would be applicable qualitatively, but not quantitatively
- 2 (Purkey and Yates pers. comm.)³.
- 3

³ Subsequent citations of personal communication with the Sacramento team refer to the interview at the conclusion of the case studies. Team members interviewed included David Purkey and David Yates.

3. Cross-cutting Findings

The GCRP established broad case study goals from the outset to gain an understanding of the potential consequences of global change by: (1) improving the scientific capabilities and basis for projecting and evaluating effects and vulnerabilities of global change in the context of other stressors and human dimensions (as people catalyze and respond to global change); (2) conducting assessments of the ecological, human health, and socioeconomic risks and opportunities presented by global change; and (3) assessing adaptation options to improve society's ability to effectively respond to the risks and opportunities presented by global change as they emerge (US EPA 2003). All of the case studies clearly addressed and achieved the aims set out in (1) and the relevant ecological aim in (2). The Sacramento team was also able to assess adaptation options (3) due largely to a second round of funding and a decision-driven approach throughout the assessment process.

The case studies have demonstrated that certain factors help ensure that there is sufficient "capacity" for doing assessments. Factors such as public awareness of issues and stressors, good data, good models, clear goals, and clear decisions facilitate the study teams' ability to establish and maintain legitimacy, credibility, and relevance. This section discusses these factors in further detail through a discussion of the lessons learned, or cross-cutting findings, across the case studies. It is broken into three subsections that address the assessment process, the stakeholder process, and the relevance of the case studies to decision making and climate change and land use change.

3.1 Assessment Processes

Given the multidisciplinary nature of the assessments, and the complexity of the models used to produce the results described in Section 2, the processes used by the teams were designed to accommodate multiple investigators and disciplines (addressed below in Section 3.1.1, Team Composition and Management). The teams also addressed several of the key issues we identified in the initial scope of work for the assessments: research approaches, watershed scales, and uncertainty.

3.1.1 Team Composition and Management

All three teams involved a large set of researchers with expertise in different disciplines. The San Pedro and Maryland teams included experts in hydrology, geomorphology, and aquatic and avian ecosystems. The principal challenges in both of those case studies involved defining suitable assessment endpoints and linking a series of separate models to provide an integrated analytical capability. Both San Pedro and Maryland invested considerable effort in developing new research approaches. These innovative approaches required varying levels of modification to existing models and linking the models to provide a complete capability starting with physical effects of climate change and continuing along the assessment chain to culminate in measures of ecosystem services.

The Sacramento team started with a preconceived notion of the key analytic endpoints (i.e., flows and quantities of water). There was consequently less of an emphasis on developing new models and linking existing models, and more of an emphasis on improving and demonstrating an existing analytic framework (i.e., the WEAP model).

The Team Managers/ Principal Investigators of all three teams were faced with a challenging series of tasks, including

- Guiding their research teams through an extensive scoping and method development phase;
- Deciding how to depict climate change and variability in a way that related to the ecosystem services of concern;
- Developing and implementing a plan to engage stakeholders;
- Implementing a model development and integration phase; and
- Reporting results in a variety of forums and formats.

The managers all guided the projects based on the particular expertise they brought to the table. Ecologists led the San Pedro and Maryland teams, and many but certainly not all of the technical advances were related to methods for simulating important ecological processes. A hydroclimatologist led the Sacramento study, and much of the effort on that study - particularly in the initial stages of the project - was devoted to developing an innovative technique to downscale regional climate from larger-scale GCM results.

One of the strategic issues we face is whether future watershed assessments and other similar projects could benefit from some degree of standardization in terms of tools or expertise. One point that was made by all three teams is that there was a common and fundamental need for several “keystone” skills, especially expertise in interpreting climate change scenarios. Dr. David Yates, the hydroclimatologist who led the Sacramento team, acted as an informal consultant to the other two assessment teams in developing their climate scenarios. Similarly, Dr. Hector Galbraith, an ecologist who specializes in evaluating the suitability of habitats for key species of concern, was a member of the San Pedro team and also provided assistance to the Sacramento team.

Despite the emphasis on stakeholder engagement, only one team (Sacramento) included a member whose specific focus was to facilitate stakeholder interactions or to communicate with stakeholders and decision makers. The resources devoted to eliciting stakeholder input were still fairly modest (about \$10,000 out of a project budget of almost \$500k) even in that study. This gap was filled to varying degrees by existing connections between the scientists on the team and decision makers. The success of the Sacramento study in orienting its research to decision-relevant issues was probably less because they included a team member to facilitate interactions with stakeholders and more tied to their enduring and intimate engagement with decision making processes and their understanding of what types of information decision makers in that area need. Moreover, as discussed in more detail in Section 3.2 on stakeholder processes, there was an evolution in the views of both the study teams and the project managers in terms of the types of stakeholder interactions that were productive. In retrospect, it probably improved the cost-effectiveness of the studies that they did not invest in unfocussed stakeholder interactions.

3.1.2 Research Approach

All three case study teams developed approaches that relied on integration of a chain of submodels to simulate physical, hydrological, geomorphologic, and ecological components that ultimately related to ecosystem services. All three of the study teams also reported challenges in coupling the model elements.

The Maryland team invested considerable effort in integration, and even developed a paper on the topic (Nelson et al. 2006). The San Pedro team pushed the state of the art in several of the individual submodels, but those submodels remained largely discrete, and required considerable integration. The Sacramento team started with a pre-existing model framework that linked hydrology and water management. The team invested in improvements in the model's ability to incorporate climate scenarios, but generally appeared to have fewer difficulties in integrating component elements than the other two projects.

Geomorphology took on a central role in two of the three studies (San Pedro and Maryland). One of the key aspects of climate change – more intense precipitation as well as longer dry periods – translates to higher high flows and lower low flows in the hydrographs of streams. This change in the hydrologic regime, in turn, affects the processes that create transitional ecosystems vital for certain avian species, and govern sediment transport and stability that affects spawning success for fish. The resulting changes in avian and aquatic habitat were key drivers in the San Pedro and Maryland studies.

All three teams appear to have benefited from the mid-project workshop held in January 2005. That workshop offered an opportunity to compare notes on methods, assessment endpoints, relevance to decision making, model integration, stakeholder interactions, uncertainty analysis, and other cross-cutting topics. To the extent that we plan to conduct similar large, multi-year projects like the watershed case studies, such mid-project workshops are a worthwhile investment for the research teams.

3.1.3 Scale

Each group worked at a variety of spatial scales, a result both of the phenomena they were investigating and the scale at which decisions are being addressed.

The group investigating small watersheds in Maryland worked at a sub-watershed scale (13 – 28 mi²), in part because urban growth is regulated at the county-level. Individual parcels of land rather than pixelated representations were represented in this analysis, and surrounding land uses fed back into subsequent land use change dynamics for each parcel.

The San Pedro group examined the upper portions of the San Pedro basin (2,500 mi²), where most of the remaining perennial or near-perennial river reaches exist, making this stretch of greatest importance for the study's primary focuses: the maintenance of avian biodiversity, sustained urban water supplies, and recreational uses. Model representations were limited to plot-scale information, however, meaning that the simulations were not run simultaneously for the entire landscape, but only for certain representative patches within it.

The Sacramento River Watershed study worked at the basin scale (42,000 mi²), but designed the study modularly, so that smaller sub-basins that performed ecosystem services of particular value (such as Chinook salmon spawning) were nested separately within the design, and stand-alone results could be produced for those areas. The primary decisions being addressed here, including water allocation and the balance of competing legislative and regulatory authority, occur at the state-level, and consequently, it was necessary to consider the watershed as a whole.

One of the challenges addressed by all three teams was that available data may not be suited to the questions under consideration. For example, the geomorphologic processes that shape channel migration act at a localized level within a stream reach, but information on the hydrologic and geologic factors that control these processes may be available only at a much

broader scale. The case study teams dealt with this issue by developing scenarios and scaling up their results for sample situations to the larger watershed.

Another important scale issue that the teams addressed is that ecosystem services are delivered at varying scales and with different levels of “connectedness” to other resources outside the study area. For example, in San Pedro, with its focus on migratory neotropical birds, the birds are dependent on the availability of suitable habitat at other locations and other times. Similarly, in Sacramento, one of the key endpoints – instream flows to support salmon – is necessary but not sufficient for sustaining threatened and endangered salmon populations. Climate change could affect the other critical resources needed to support these populations, but to keep the scope manageable the study teams assumed that conditions outside their study’s boundaries were essentially static.

3.1.4 Uncertainty

Given the variety of academic disciplines and datasets involved in creating decision support for the effects of climate and land use change on water resources, it is interesting to note that the teams identified the same sources of uncertainty when asked which sources were most important. The first section below discusses these sources, and the second briefly reviews the approaches that were considered to communicate uncertainty to stakeholders.

Types and the Extent of Uncertainty

None of the case studies conducted a comprehensive quantitative uncertainty analysis to determine the relative importance of various inputs. However, in response to a set of queries posed by EPA regarding uncertainty, they all provided a qualitative listing of likely uncertainty sources, and all expressed interest in conducting more detailed uncertainty analysis if additional resources could be made available to support it. Because the findings on types and extent of uncertainty are based primarily on judgment and qualitative analysis, they should be viewed as tentative.

The magnitude and distribution of the hydrologic effects of regional climate change (i.e., how changes in temperature and precipitation affect streamflow and the “downstream” analytic components) were considered by all case study teams to be the primary sources of uncertainty in their study results. The applicability of GCM projections to the regional scale is not generally considered particularly reliable (Wilby et al. 2004). The input requirements of the modeling systems was different for each research team, and the algorithms used by researchers to downscale the datasets to fit with their models varied accordingly. These input requirements and downscaling algorithms were another source of uncertainty.

Study teams applied different approaches to constraining this uncertainty, including generating scenarios based on multiple GCM realizations (assuming that more common results indicate more probable outcomes), and using Monte Carlo-type analysis. The San Pedro research team used a set of scenarios, for example, to bracket a large range of uncertainty regarding projected future precipitation patterns for the area.

Land use and land use change are highly uncertain aspects of the watersheds in question, which also contribute significantly to uncertainty in the study results. Small Maryland watersheds, given their proximity to rapidly urbanizing landscapes, were particularly susceptible to this influence. Land use changes were found to be quite sensitive to regulatory changes, population growth, and income changes. Once the potential land open for development has been developed,

the possible responses by landowners is unknown, but possible outcomes are intensification of developed areas or reclassification of previously undevelopable land and further landscape alteration. Additionally, while land use may be predicted on a large scale with some degree of certainty, the idiosyncrasies of individual land owners and managers may never be anticipated with complete predictability.

Hydrological responses to changing land use were identified by both the Maryland and Sacramento groups as primary contributors to overall uncertainty. Geomorphological responses were another large contributor to uncertainty, particularly in the San Pedro watershed, for which management goals are predicated in part on the occurrence of transitional ecological states. These transitional states are highly dependent upon sporadic hydrological events such as flooding, which translate to the ecosystem through their geomorphological effects. The creation of unvegetated areas on islands within the river or on the river's banks by a flood event allows for colonization by plants which would otherwise be unable to compete with established plant communities, and thereby increases the overall habitat diversity of the area. With time, these colonizing plants are replaced by more stable assemblages, and other unvegetated areas are created by intense hydrological events. Any one plot may show little change, but over a larger area, the patchiness of habitat types allows high avian diversity to be maintained. In general, it is more challenging to predict and monitor processes associated with unusual or extreme events and transitional conditions, and analyses of this type tend to be more uncertain than those dealing with processes that are driven by average conditions.

Other sources of uncertainty listed by the researchers from Maryland include a lack of knowledge regarding the effects of the interactions of multiple stressors in streams, the biology of understudied fish species, and predictions of habitat suitability.

Communicating the Importance of Uncertainty to Stakeholders

In communicating the uncertainty to stakeholders associated with climate and land use change effects on ecological and water resources, a concern of the researchers was that doing so may undermine the contribution that results may have to the decision making processes. At issue was whether managers would be willing to place confidence in results that are initially presented as uncertain, particularly when the uncertainties may be used to justify setting aside the results. This is particularly true under resource-limited circumstances where more pressing and more certain matters may justify immediate attention and action.

Another issue involved determining which form of uncertainty analysis would be most useful to stakeholders. The Sacramento team found that their stakeholders were interested in "stylized" scenarios. For example, the El Dorado Irrigation district currently uses the worst three-year drought of record as the basis for developing drought plans. To be responsive to and consistent with the existing decision framework, the Sacramento team developed alternative scenarios such as a 4-year drought of similar magnitude to the 3 year drought, but one that is also 2°C warmer.

Some decision makers – particularly those who are statistically sophisticated – will only be willing to place confidence in results if researchers are able to provide them with quantitative estimates of uncertainty. Rather than circumventing a quantitative uncertainty analysis, researchers should ideally embrace it; conversations about uncertainty are a very useful frame for engagement between the two communities. As a practical matter, however, it appeared that by the time the teams were prepared to conduct an uncertainty analysis, their resources were dwindling and other priorities took precedence.

The researchers expressed interest in the possibility of framing climate change uncertainty (an unfamiliar type of uncertainty) using comparisons with more familiar sources of uncertainty. For example, long-range water resource plans generally make assumptions on population growth, changes in demand for key uses (*e.g.*, agriculture), and changes in per capita demand. While these assumptions are sometimes heroic, they are nevertheless familiar (unlike climate change-related factors). The teams agreed that comparing sources of uncertainty would help stakeholders realize that all long-term decisions are made in an uncertain context, perhaps reducing reluctance to incorporate climate change in decision making.

Uncertainty issues represented a serious challenge to the research teams, both in terms of developing techniques to address uncertainty within the modeling frameworks, and for communicating their results in a way that is understandable and useful to stakeholders.

3.2 Stakeholder Processes

Given the formidable technical hurdles and advanced scientific nature of the topics under consideration by these investigators, it is surprising that stakeholder interactions were deemed among the most challenging aspects of these projects. Each case study research team approached stakeholder inclusion somewhat differently, though a number of features and impressions were common among them.

In general, the teams relied on existing stakeholder relationships and processes. Interactions with these stakeholder groups were moderate in the frequency, scope, and intensity. The information flows were primarily unidirectional – from the research teams to stakeholders, although stakeholders were given opportunities to provide input on each study’s endpoints. This may have been due to the types of stakeholders who were engaged in these particular case studies. A better understanding of the appropriate stakeholders for whom this information is relevant might result in a closer working relationship with better information flows. A kickoff meeting was a common feature among all of the case studies. After that point, the Sacramento study continued with structured elicitation of stakeholder input. Stakeholder involvement for the Maryland and San Pedro studies was generally less structured and more opportunistic after the initial kickoff. Teams found that stakeholder involvement can be a resource-intensive exercise, which can divert the attentions and drain the ability of researchers to focus on the technical and decision making issues that were of greatest interest to EPA and the study teams. This and other challenges the teams faced in engaging stakeholders are discussed in more detail below.

3.2.1 Defining and Identifying Stakeholders

The concept of stakeholder engagement, required by EPA in its specifications for the case study cooperative agreements, was not clearly defined from the outset. Stakeholders included a wide array of individuals from decision makers to non-governmental organizations to interested citizens. The teams found that determining who to engage and then exchanging meaningful dialogue with those key players could be paralyzing to the assessment process if it was not focused along the way.

The Maryland team initiated a broad-based introductory meeting for stakeholders. Professional, academic, and EPA personnel were the initial contact points for assembling this group. The goal of the meeting was primarily information dissemination from the researchers to interested parties. Subsequent interactions and input from stakeholders was minimal. Researchers did maintain a close collaborative interaction with the Montgomery County Department of

1 Environmental Protection – a primary stakeholder – which resulted in the sharing of data and
2 incorporation of researchers’ findings into a wider planning context.

3 Researchers in the Upper San Pedro Basin began work in a setting that already had an active
4 stakeholder group—the Upper San Pedro Partnership (USPP). The USPP is a consortium of
5 local, state, and federal government organizations, Fort Huachuca Army Base, businesses,
6 citizens, and conservation groups. The USPP had been working to develop decision support tools
7 for the analysis of alternative water management regimes, and members of the case study group
8 became participants in this ongoing process. Additionally, their affiliation with the Sustainability
9 of Semi-Arid Hydrology and Riparian Areas (SAHRA)—a National Science Foundation-
10 supported research center at the University of Arizona—provided them with indirect access to
11 stakeholders.

12 The group working in the Sacramento River Watershed took a more active role in
13 comprehensively identifying stakeholders, particularly with the intention of influencing ongoing
14 decisions regarding water allocations. The team assembled a Technical Advisory Panel (TAP)
15 formed of regionally-based academics from the physical, ecological, and economic sciences.
16 This panel made recommendations regarding other experts to consult and the development and
17 application of the modeling framework. Professional connections and trust in the competence of
18 the study team members were very important to this process because of the access these
19 connections provided to stakeholder groups. Additionally, these researchers hired a consultant
20 (CONCUR) to interview high-level water and ecosystem management organizations and make
21 strategic recommendations regarding potential applications of this research.

22 **3.2.2 Balancing Stakeholder and Researcher Interests**

23 Stakeholders engaged in each case study had diverse views on which services should have
24 highest priority for study resources. Teams had to balance those competing stakeholder interests
25 with their own research interests. The team members recognized the dilemma that the primary
26 professional and career focus of many scientists—credibility—requires academic achievements
27 that can come at the expense of spending time with stakeholders to prove the relevancy and
28 legitimacy of their work to decisions. Stakeholder interactions increase the likelihood of a
29 project’s usefulness. However, efforts to maintain those interactions can be onerous and
30 resource-intensive, and thus come at the expense of other priorities. The inverse of this challenge
31 is also true: managers do not necessarily recognize the relevance of research (especially research
32 on long-term problems), often deeming it merely an academic exercise with no application to
33 their pressing concerns.

34 Climate change is a particularly acute example of this situation. All research teams reported that
35 climate change is simply not recognized by managers and decision makers as a concern that must
36 be addressed within a relevant timeframe. Decision makers generally focus on quantifying water
37 use and supply allocation, for which they do not yet recognize climate change as a significant
38 stressor. They have not yet concluded that investing time in climate change-related work will
39 assist them with what they consider to be the more immediate concerns of their charge. For
40 example, the explicit identification of ecosystem services that depend highly on ongoing climate
41 change and variability may require an interactive stakeholder process that neither side
42 (researchers and stakeholders seem prepared to participate in.

43 The Maryland and San Pedro studies reflected researcher interests. The study findings were later
44 shared with decision makers and supported decision making indirectly. The Sacramento case

study reflected interests of some of the stakeholders. Stakeholders in the Sacramento River Watershed guided the selection and prioritization of analytic activities, helped establish project goals, shared expertise, and provided information on a variety of areas including public values, equity considerations, and relevant decision processes (Yates et al. 2006). Researchers in Sacramento solicited input from stakeholders to develop a list of current water management decisions that may be sensitive to climate. They then applied several criteria to the list to narrow it down to a reasonable number of decision making processes amenable to climate change assessment (Yates et al. 2006). One of the criteria ensured that some segment of the stakeholder community had expressed a concern about the potential impact of climate change on the project (Yates et al. 2006).

3.2.3 Engaging Stakeholder Communities

All teams presented their proposals to stakeholder groups at the onset of these projects. These meetings were well attended; however, researchers from at least two of the case studies reported that attendees were not very responsive or specific when asked what information stakeholders themselves could provide to the study or what information or tools would be valuable for the research effort to produce. For the most part, the general public and laypeople who attended the initial meetings perceived their role as passive rather than participatory; their interests were primarily in hearing what researchers themselves were doing, not in playing an active role in study development.

Teams found it challenging to determine when to involve stakeholders in the assessment process after the kick-off meeting. The teams recognized that it would be ideal to have regularly scheduled meetings/consultations, but technical and modeling challenges prevented regular production of results. Researchers were disinclined to hold meetings without results. On the other side, many of the stakeholders seemed to lack both an understanding of whether and how study findings would be useful to them and a commitment to use the findings.

The Maryland case study team was able to develop an interactive relationship with the Montgomery County Department of Environmental Protection (MCDEP) that led to an exchange of data and some collaboration regarding desirable study products. Collaborative interactions with MCDEP were mostly limited to the land use components of the study, since they were less interested in the climate change components (Palmer et al. pers. comm.)⁴.

The San Pedro team's association with USPP and SAHRA allowed them access to an existing stakeholder process to which they could contribute research, planning, and management information. These stakeholders were not actively engaged in the research planning or implementation, but study results will be made available to them.

The Sacramento study team convened a technical advisory panel (TAP) and met with them at the beginning, middle, and end of the investigation to receive technical as well as stakeholder input to the analysis. The team engaged other stakeholders via *ad hoc* meetings with several high level decision making organizations. They found that the key to establishing working relationships

⁴ Subsequent citations of personal communication with the Maryland team refer to the interview at the conclusion of the case studies. Team members present were Margaret Palmer, Jim Pizzuto, Karen Nelson, Nancy Bockstael, and Glenn Moglen.

with the targeted stakeholders was to demonstrate that their work was relevant to the decisions at hand, scientifically credible, and legitimate as an approach to climate change analysis—three concepts that guided their stakeholder meetings. The Sacramento team also stressed the importance of finding an advocate among the participating stakeholders. One person who acts as a champion for collaborating with researchers and participating in the assessment process can help sustain and facilitate the relationship (Purkey and Yates pers. comm.).

3.2.4 Establishing Credibility

The Sacramento team noted that climate change may be viewed as a less important or non-vital concern to stakeholders. Climate change is not considered in most water resources planning efforts in California because there is a general perception that significant changes will not occur within the typical 20 to 30 year planning horizon used in most NEPA and CEQA studies (Yates et al. 2006). This view is widespread and presents a particular challenge for teams seeking to establish relevance.

The Sacramento team found that continuous input from stakeholders enhanced the relevance and credibility of results (Yates et al. 2006). They also concluded that it is important to spend time interfacing with stakeholders throughout the process to make them more comfortable with the assessment process.

3.2.5 Communicating Results

All of the case study teams have used scientific publications (e.g., peer-reviewed journals, books) as a primary means of dissemination, but many stakeholders do not find these types of publications to be particularly accessible, user-friendly, or succinct sources of information. Further, results presented in scientific publications may not be directly applicable to decision making.

Case study teams have found that one-on-one interaction with decision makers or stakeholder meetings to share decision-relevant results is an effective means of communicating with stakeholders. The Maryland team worked closely with the Montgomery County officials throughout the process and shared findings as they became available. The San Pedro team shared results with water resource managers and the Bureau of Land Management. The Sacramento case study group is participating in a multi-stakeholder state-wide planning process to project water resource supplies and needs for the State over the next 50 years.

The Sacramento and San Pedro case studies both noted the importance of using the concept of “ecosystem services” to enable individuals of different backgrounds to speak in a common language about the values they hold for ecological processes and functions (Yates et al. 2006). All three of the teams noted that, in principal, communicating decision-relevant results to decision makers in terms that avoid excessive technical jargon facilitates a more effective use of scientific findings.

3.3 Relevance of Impacts and Adaptation to Decision Making

EPA’s third major goal in conducting the watershed case studies was to assess adaptation options to improve decision-makers’ ability to respond to global change. EPA recognizes, however, that it is often a challenge to move beyond impact assessments and address adaptation options. Only the Sacramento case study assessed adaptation options, due largely to a second round of funding. The Sacramento team relied on a directly decision-driven approach that resulted in findings

relevant to planning processes that were soon to be initiated or already underway. The different approaches taken by the study teams – based on the goals communicated by EPA, available funding, and their own needs and resources – offer valuable lessons for future watershed assessments. The comparison of the teams’ approaches that follows informs the later conclusions and recommendations for future GCRP efforts.

The Maryland and San Pedro teams focused primarily on conducting impact assessments—determining the effects of global change (including climate change, land use change) on water quantity and quality and the consequences for aquatic ecosystems. These assessments made significant contributions by linking multiple models to better understand stressor interactions and responses. The assessments were not conducted from an “information demand” or decision-driven perspective, and thus were not immediately and directly applicable to specific decisions. However, both the Maryland and San Pedro assessments ultimately supported subsequent decisions or provided corroborating evidence for proposed decisions.

The Maryland team found that decision makers at the county level (Montgomery County) were more interested in the land use change component of the case study than the climate change component. Montgomery County officials seemed to be less interested in possible future stresses and focused on problems they are facing in the immediate term. However, the Maryland team’s findings indicate that decision makers should be considering climate change. For example, stormwater management facilities are currently being retrofitted or built without accounting for potential changes in the intensity of future rainfall events that could affect the performance of these facilities. On the other hand, County decision makers took an interest in the findings regarding nutrient concentrations in various streams and were pleased to see evidence that riparian buffers have a definite impact on those concentrations. They have used the study findings to validate recommendations they had already made and research they already have in progress (Palmer et al. pers. comm.).

The San Pedro team’s findings were used by the Bureau of Land Management (BLM) and water resource managers. The latter have used some of the team’s models to assess flow rules for reservoir releases from a dam in the middle San Pedro area. The team’s results regarding loss of water in the system led to a BLM decision to reintroduce beaver in an attempt to impound and detain water rather than letting it flow downstream. In this case, decision makers used the study findings, but did not consult the study team on the proposed management solution (which researchers anticipate could cause changes in habitat, topography, ecology, and impacts to the gallery forest). The San Pedro team noted that the politics in this area are an obstacle for the incorporation of study findings into the decision making process. Resource managers also seem reluctant to make decisions based on climate change options due to the level of uncertainty and other factors that take precedence in management decisions (Galbraith et al. pers. comm.).

The Sacramento team took a different approach than the other two case studies — in the second phase of this project, they started by identifying key water-related decisions and then tailored their analytical work to meet the needs of decision makers. They consulted stakeholders to develop a list of ongoing decision making processes in the California water system that might be sensitive to climate change. The list was then narrowed to include only decision-making processes that met three criteria:

- The success of a project to be implemented would be strongly influenced by hydrologic variability;

- The investment in a project would be substantial enough to merit the consideration of climate change impacts; and
- Some segment of the stakeholder community was concerned about the potential impact of climate change on the project (Yates et al. 2006).

The shorthand for these criteria are Sensitivity, Significance, and Stakeholder support, abbreviated as the “3S standard” (Purkey et al. 2006).

The Sacramento team targeted assessment endpoints that were intrinsic to the decision making processes (e.g., water flow). The WEAP model itself is a management tool that was modified for this assessment to include climate change. The Sacramento team included in their scenarios adaptive measures to assess the ability to mitigate climate change impacts.

The Sacramento team was able to apply findings to decision making processes to a greater degree than the other teams because they received a second phase of funding. These decision making processes included: (1) the Integrated Regional Water Management Plan (IRWMP) for the Consumes, American, Bear, and Yuba (CABY) watersheds; (2) the California Department of Water Resources’ 5-year water planning process (Bulletin 160); (3) an assessment by several water utilities generating hydropower in the American river basin of how vulnerable they are to climate change and their ability to meet more stringent inflow water demands; and (4) the 2006 Climate Action Team Final Report to Governor Schwarzenegger and the California Legislature.

4. Conclusions and Recommendations for Future Watershed Assessments

4.1 Contributions to Body of Knowledge on Climate Change Impacts

As noted earlier, these case studies addressed many issues associated with climate change and land use change and their impacts on the environment. These studies contributed both methodological advances and key results to this body of knowledge. The place-based approach used to generate climate impacts information was a key factor in ensuring its usefulness to specific decision makers, and the lessons learned and results may benefit or be applied to other assessment teams and geographic regions. This section discusses the methods and key results developed by the studies.

4.1.1 Methodology Development

The most significant methodological advance across the three case studies has been the integration of interdisciplinary models. The Sacramento team integrated a climate and hydrologic model within the water planning environment -- other water planning models typically hold hydrology as unchanging from the historic record -- and conceptually linked it to an ecological model. The San Pedro case study team integrated hydrologic, vegetation, habitat and climate change models, and the Maryland case study team integrated a hydrologic, geomorphologic, and ecological model using driver data from climate models. Each of the teams recognized the value of linking these types of models and expressed an interest in integrating additional models to add more dimensions to the studies.

This methodological advance was significant from both the scientific and decision support points of view. Scientifically, modeling system behavior reduces uncertainties associated with ignoring system interactions that cannot be modeled without an integrated approach. Similarly, integrated modeling reduces uncertainty for decision makers in terms of forecasting effects and providing new information about a whole suite of components quickly. In this way, integrated models make it easier and quicker to address decision-relevant questions using scientific models of system behavior. This approach also makes it easier to analyze multiple scenarios.

The Sacramento case study team's assessment framework helps decision makers evaluate possible adaptation strategies and identify tradeoffs among important ecosystem services. This framework, known as WEAP21, is able to provide integrated water resource management support to other regions as well. The decision-relevant approach taken by the team and the subsequent direct applicability of the results to decision making processes provides an excellent model for future GCRP watershed analyses (Yates et al. 2006).

The San Pedro team had several ideas for how to improve the methodological approach in the future. First, the models should incorporate a greater degree of complexity with respect to habitat responses to ecosystem changes. This would require observations to be done of subtle changes in the ecosystem to detect modifications of habitat. Their sense is that small changes in the ecological matrix can cause large swings in the wildlife community. Second, more knowledge is needed about the life history of species in the system to avoid only looking at conditions in an equilibrium situation. Third, the assessment should be expanded beyond the riparian area to look at climate change impacts on the entire system, including vegetation in the uplands or the recharge processes involved in mountainous areas (Galbraith et al. pers. comm.).

The methods developed in the Maryland and San Pedro case studies are transferable to regions with similar conditions, although the input data would have to be modified accordingly. For example, the Maryland models could be applicable in the North Carolina Piedmont and other areas that have similar ecosystems. The San Pedro model, although it is specific to riparian systems in the Southwestern U.S., could also be applied to other similar ecosystems, and is currently being used in the Rio Grande and Kern watersheds in California. In addition, the RIPET submodel could also be transferable to specific types of wetlands, such as the Everglades. The most transferable modeling system may be the WEAP model. Since the intrinsic logic behind WEAP is universal, it could be produced for other locations with site specific data over a relatively short time frame.

4.1.2 Key Results

The Maryland team separately quantified the effects of land use change and climate change, but determined that it was unclear which stressor had a larger impact; they found that each contributes to the same impacts but in slightly different proportions. Land use change provides more sediment due to increased construction and increased impervious surface, and climate change causes more increased storm flow, disturbances to the streambed, and variability in conditions than land use. Effects on ecological processes are thus generally negatively influenced by the projected climate and land use changes, and when the stressors are combined, predominantly negative effects emerge. (Moglen et al. 2006).

The Sacramento and San Pedro teams did not separate the effects of land use change and climate change, but expressed interest in evaluating these stressors independently in the future. Sacramento researchers noted that they would like to systematically separate ecosystem stressors given their particular challenge of moving water out of irrigation and into the urban environment (Purkey and Yates pers. comm.). The San Pedro team noted that climate change is not as significant a stressor as aquifer depletion; however, when both stressors are applied together, there is a synergistic effect. The team also acknowledged that isolating the effects of land use change and climate change in the future could provide information about runoff and surface flow (Galbraith et al. pers. comm.).

The Maryland team found that up to three-quarters of the fish species would be highly stressed under the combined effects of land use change and climate change and that this outcome could be mitigated by maintaining riparian buffers and decreasing urbanization. The team also concluded that all ecological processes were not negatively influenced by projected climate change and land use change; however, when they are combined, predominantly negative effects emerge. In addition, low flow modeling indicates that future precipitation trends will influence hydrologic and ecological processes more than future temperature trends, and the frequency of low flow events of a given magnitude will increase under future climate and land use changes (Moglen et al. 2006).

The San Pedro team found that among their five climate scenarios, the warmer drier scenario could exacerbate current water use conflicts between the human and natural ecosystems of the upper San Pedro basin and could accelerate the decline of cottonwood-willow gallery forests. A wetter future could partially mitigate the impacts of human water use (Dixon et al. 2006).

In one analysis, the Sacramento team addressed the issue of adapting to climate change by looking at three future alternatives including a simulation without adaptation, a simulation with increases in irrigation efficiency, and a simulation with improved irrigation efficiency and shifts

in cropping patterns related to the simulated status of available water supplies. The results showed that improvements in irrigation efficiency led to a decline in supply requirements. When coupled, the effect of improved irrigation efficiency and a dynamic crop pattern was a decrease in water supply requirements. In addition, the study showed that the management structures and practices that adversely affected the fish populations historically may provide an opportunity to alleviate some of the future impacts of climate change. More ‘natural’ and unmanaged systems may provide fewer opportunities for salmonid conservation (Yates et al. 2006).

All three of these place-based assessments provided impacts information that will be useful to specific decision makers as they develop management responses. Each case study team was able to examine the interaction of climate change with other stressors already present, particularly land use change, and was able to conclude that climate change will exacerbate those effects. Where stressors were examined separately by the Maryland case study, results revealed that the interactive effects were strongly negative and more apparent than when the stressors were considered separately.

4.2 Assessment Process

As noted earlier, a “portfolio approach” was used to select case studies and commission assessments in three distinctly different watersheds with differing ecosystem services, scales, and decision-making processes. One benefit of this approach is that although the study sites differ from each other hydrologically and bioclimatically, they are representative of a broader array of conditions within larger regions of the United States. Another benefit of this approach is that it demonstrates the diversity of methods, results, and processes over a range of settings. Even though there are many distinctions and differences in the assessment processes used in the case studies, associated with their unique objectives and endpoints, several cross-cutting findings emerged that can be extrapolated to other watersheds and regions and that can shape GCRP’s and other research institutions’ strategies for designing the process for similar assessments. The three main ways that results are more broadly useful are:

1. Extrapolation of the results themselves: individual results can be extrapolated for each watershed to similar systems. For example, San Pedro can be extrapolated to other arid systems relying on groundwater; Maryland results can be extrapolated to other Piedmont rivers; the interactive effects of climate and land use change can be generalized to other watersheds, and the results that climate will exacerbate existing effects of stressors
2. The methods used to link process models across disciplines may be used by other assessment teams and in other geographic regions of the country.
3. The insights gained about the assessment process, such as the standardization of methods for climate scenarios, stakeholder processes, and other topics described below, will be helpful to any research institution seeking to produce useful climate impacts information for decision makers.

4.2.1 Provide Keystone Capabilities and Tools to Assessment Teams

As noted earlier, there were several areas where all three teams expended considerable effort on similar tasks. It is reasonable to expect that other watershed-level assessments would need to undergo a similar process; when conducting similar assessments in the future, several keystone capabilities and tools might be useful:

- 1 • *Tools for converting GCM output to watershed modeling input.* The teams all had an
2 initial focus on reviewing and interpreting GCM runs to develop their climate scenarios.
3 GCMs analyze temperature and precipitation on short time steps ranging from 15 minutes
4 to half a day. These results are often stored as averages over longer time scales of (often
5 monthly) averages, however, because of data storage constraints. Most hydrologic
6 processes require daily (or even hourly) inputs over a finer geographic scale, and need to
7 be downscaled on both a temporal and geographic basis. GCM runs are also available for
8 many different combinations of emission scenarios and climate sensitivities, and it can be
9 daunting to choose among the scenarios. The lesson learned from these case studies is to
10 provide expertise to future assessment teams to aid in selecting, interpreting, and
11 downscaling GCM output. Future assessments could attempt to establish a tool or
12 methodology for handling climate information and explicitly implementing (and
13 evaluating) those practices.
- 14 • *Tools to develop or apply trend analysis of precipitation and hydrology to complement*
15 *GCM output.* Downscaled GCM outputs have a high level of uncertainty associated with
16 them and therefore may attract scientific controversy. A simple trend analysis of climate
17 variables may be a complementary approach to create future scenarios (Denault et al.
18 2006). However, conventional precipitation and hydrology analyses of intensity,
19 duration, and frequency are based on the assumption that there is no underlying trend in
20 the record, i.e., that a record from 100 years ago has equal relevance to predicting
21 tomorrow's conditions as a record from 100 days ago. Several powerful statistical
22 techniques have been developed to evaluate trends, and could be made available to
23 watershed researchers to complement GCM output (Denault et al. 2006).
- 24 • *Consulting services in keystone skills.* Assessment teams could benefit from having
25 access to consulting help in key areas such as climate scenario development and habitat
26 suitability analysis. To the extent that many of the assessments begin with the same
27 inputs and end with habitat-related outputs, it may streamline the assessment process to
28 provide access to experts.
- 29 • *Techniques for expressing uncertainty.* As noted earlier, the assessment teams generally
30 found it difficult to express uncertainty, and several noted that it would be helpful to have
31 guidance on how to characterize and communicate uncertainty results. In addition,
32 several noted that it would be useful to be able to compare climate change-related
33 uncertainty to uncertainty from other, more familiar sources relevant to long-term water
34 resource decision making, (e.g., population, land use change, per capita water demand).

35 For all of these keystone capabilities and tools, the benefit of providing them to the watershed
36 teams would have to be balanced against the objective of building broad-based technical capacity
37 and testing alternative approaches, which argues for less, rather than more, concentration and
38 standardization of expertise.

4.2.2 Emphasize Model Linkages

Given the multidisciplinary nature of these projects and the need for assessment teams to develop new modeling capabilities to analyze climate change impacts or opportunities for decision support, one of the key challenges is to facilitate smooth links between submodels. This was one of the most difficult challenges for the teams to overcome.

Although the disciplines that were well-represented among the teams (e.g., ecology, hydrology, geomorphology) tend to espouse “systems thinking,” many of the details involved in assuring seamless integration of models are viewed most effectively from an information technology perspective. There are trade-offs between setting up an IT-intensive interface for linked models versus a “hand-crafted” solution, and the different teams dealt with the trade-offs in different ways. In retrospect, however, it appears that in several cases the teams would have benefited from more design work up front in clearly defining inputs, outputs, and interactions among submodels.

4.2.3 Change Selection Criteria for Assessments

One of the recurring themes in this report is that the case studies were quite thorough and innovative in assessing climate change impacts, but did not necessarily attain the objective of providing decision support. This may be due, in part, to the emphasis on selecting case studies where there was a good foundation of existing data and models so that impacts could be assessed as efficiently as possible. For future watershed assessments, it may be useful to modify the selection criteria to emphasize case studies where it is clear that (1) decisions are being made that are sensitive to climate change, and (2) where there are existing relationships with decision makers that would enable the project team to provide relevant decision support products.

Another factor that should be re-evaluated in terms of selection criteria and study design relates to scale. The research teams noted that there were some mismatches between available data versus the scale of data needed to support assessment and decision making. All three teams were able to bridge the gaps. Nevertheless, in developing a strategy for future work, it would be useful to consider the scale at which GCM and watershed-level information is available, the scale at which key endpoints are assessed, and the uncertainty introduced by bridging the gap, to assure that it will be feasible to produce good science and sound decision support.

4.2.4 Establish Forum for Researchers to Compare Notes

The mid-project review meeting was very productive in terms of providing an opportunity for cross-fertilization among the project teams. It not only encouraged technology transfer on an inter-team basis, but it also provided an impetus for intra-team coordination, which was a continuing challenge within the teams. Preparation for the review meeting encouraged attention to several cross-cutting issues and envisioning likely results, and thus facilitated several adjustments and improvements to the methods. It also provided an opportunity for the GCRP to reiterate and clarify its desired outputs. If similar case studies are done simultaneously in the future, a mid-project forum should be convened to enable investigators to share notes on progress and to make mid-course corrections in project goals and methods.

4.2.5 Require an Uncertainty Analysis Plan

In addition to the earlier recommendation to develop a set of tools or methods for analyzing uncertainty in assessments and decision support, future assessments should include a requirement to address uncertainty more comprehensively, and, where possible and appropriate,

quantitatively. This would be helpful both from a perspective of scientific rigor and from a perspective of decision relevance. It should be made clear that a comprehensive uncertainty analysis is a key output of the study, and that resources need to be reserved to produce this output.

It would be useful to set out an uncertainty analysis plan as one of the initial deliverables in the process, and to design the plan to reflect feedback from decision makers on what types of uncertainty analysis would be most relevant to decision making. This feedback would help determine whether the plan should focus on developing several alternative scenarios, or a risk analytic approach that explicitly assigns probabilities to various components, or some other qualitative or quantitative characterization of uncertainty.

Many of the elements of uncertainty in watershed assessments like those described in this report are unknown or extremely difficult to quantify or parameterize, making it difficult to express uncertainty in terms of probabilities. Moreover, there is a growing literature that argues that it is not necessary to fully characterize probabilities of climate change to develop climate adaptation policy, but rather to focus on developing strategies of resilience and adaptive environmental management that enhances coping capacity across a broad range of climate outcomes (Yates pers. comm.)⁵. Nevertheless, regardless of the specific approach to analyze uncertainty, future watershed assessments should make a plan to conduct this analysis and then execute the plan.

4.3 Stakeholder Process

Streamlining and focusing stakeholder-related efforts is necessary and desirable. The lessons learned from this portfolio of case studies have led to an evolution in our view of effective stakeholder interaction. Our goal to produce case study outputs which directly impact the policies that avert potentially negative changes in areas sensitive to land use change or climate change may require more guidance to study investigators in the selection of priority stakeholders and managing the process to ensure useful outcomes. The case studies showed that stakeholder relationships may not need to extend to all potentially interested members of the lay public; instead, they should target specific decision makers who have an identifiable stake in the study's goals. The broad definition of stakeholders that GCRP initially embraced and the associated challenges that arose may have additionally hampered attainment of the objective to provide decision support. The recommendations that follow stem from these lessons learned in an effort to improve the stakeholder process.

4.3.1 Focus on Decision Makers

Decision makers are the most important stakeholders to engage during the assessment process. Study teams should focus on engaging decision makers early and interacting with them throughout the assessment. Collaborating with decision makers will ensure that case study findings are decision relevant and immediately applicable. Working closely with decision makers to supply information based upon their needs and demands will also help facilitate later transferability of case study results and processes. Decision-driven research tends to be more transferable, since it seeks to answer questions that decision makers elsewhere are likely to face. Also, where possible, focus on developing collaborative working partnerships with members of

⁵ E-mail from David Yates to Randall Freed, July 31, 2006.

the decision making body to gain their interest and trust in the assessment results. A working partnership builds technical capacity within the decision making body that increases the likelihood of climate change impacts being considered beyond the particular assessment.

4.3.2 Build on Existing Stakeholder Relationships

Research teams already work with stakeholders in many areas and have developed long-standing relationships with decision makers. Research teams should build on these existing relationships when seeking input from stakeholders. Strengthening existing relationships will take less time and resources than trying to establish new relationships with numerous stakeholders. Further, existing relationships can open doors to meeting and collaborating with new stakeholders who may be similarly interested in study findings. In much the same way that the selection criteria for this set of projects involved availability of existing data, future projects may also benefit from a selection criterion to evaluate availability of existing relationships.

4.3.3 Facilitate Interaction of Researchers and Decision Makers

Researchers and decision makers often speak in different languages or use different terminology. Focusing on ecosystem services helps to bridge the gaps (see Section 4.3.5, Communicate Results using Common Language below), but interactions may need further facilitation. Researchers may be preoccupied with the technical aspects of the work and professionally ill-equipped to manage external interests. One possible solution suggested at the expert workshop was to establish a separate office (within EPA or at the university where the study is being led) to manage public inputs to the study itself, rather than relying on the assessment team alone. Other means for facilitation should be considered to help foster open communication between researchers and decision makers.

4.3.4 Establish Credibility with Decision Makers

Establishing credibility and providing relevant findings takes time and commitment on the part of researchers. Study teams must set aside time to interface with decision makers to make them more comfortable with the assessment process and findings and how they fit into ongoing decision processes. Finding one or more champions amongst the participating stakeholders can help keep the lines of communication open between researchers and decision makers.

4.3.5 Communicate Results using Common Language

The concept of “ecosystem services” provides an excellent means for communicating scientific results to a wide variety of stakeholders. It allows researchers and stakeholders to speak in a common language that is not overly reliant on technical or industry-specific jargon. Distilling study results down to the findings that are decision relevant also goes a long way to bridging the gap that so often forms between researchers and decision makers.

Table 3: Summary of Recommendations for Future Watershed Assessments

Assessment Process	Stakeholder Process
<ul style="list-style-type: none"> • Provide Keystone Capabilities and Tools to Assessment Teams 	<ul style="list-style-type: none"> • Focus on Decision Makers
<ul style="list-style-type: none"> • Emphasize Model Linkages 	<ul style="list-style-type: none"> • Build on Existing Stakeholder Relationships
<ul style="list-style-type: none"> • Change Selection Criteria for Assessments 	<ul style="list-style-type: none"> • Facilitate Interaction of Researchers and Decision Makers
<ul style="list-style-type: none"> • Establish Forum for Researchers to Compare Notes 	<ul style="list-style-type: none"> • Establish Credibility with Decision Makers
<ul style="list-style-type: none"> • Require a Comprehensive, Quantitative Uncertainty Analysis 	<ul style="list-style-type: none"> • Communicate Results using Common Language

4.4 Final Thoughts and Future Directions for GCRP

The case study approach yields richness of detail in terms of methods and results, and propels the research team well up the learning curve on climate change issues. It has proven extremely effective in pushing forward the state of the art in impact assessment and characterizing the potential effects of climate change and land use change on ecosystem services, which is an essential foundation for adaptation.

It is important to ensure that capacity for doing assessments is in place before the project starts. As discussed at the beginning of the section on cross-cutting findings (see Section 3), there are a number of critical success factors for the case studies, including: good data, good models, clear goals, public awareness of the issue, etc. Identifying that these critical success factors are in place before launching an assessment will help determine if there is sufficient capacity to undertake such an assessment.

It is not enough to test ecological models; there is a clear need to also support decisions. Decision-relevant approaches need to be developed and employed. A need for transferability of assessment methodologies and model results arises out of the need to support decisions. If goals are defined upfront and the assessment approach is decision-relevant, different regions and watersheds with the same goals will be more likely to produce transferable methodologies and results. Approaching assessments with a focus on ecosystem services works well, but it is important that decisions drive the selection of which ecosystem services to focus on.

Moving forward, it may be constructive for study teams to develop a framework for assuring that research is decision-driven, not necessarily by early and frequent exposure to a broad set of stakeholders, but instead by a focus on a narrow set of decisions and stakeholders where the information will be most useful. The GCRP is developing a decision-driven approach through some of our other activities. For example, the GCRP is conducting a pilot study to inventory and analyze climate-sensitive decisions, and has developed a research design on which future assessments may be modeled. This project may provide the foundation data and analysis to aid in

1 developing a long-term strategy for providing effective decision support to the relevant decision
2 makers.

3 An effective way to establish adaptation priorities is to classify decisions into three categories:

- 4 (1) decisions unlikely to be affected by climate change
- 5 (2) decisions probably affected by climate change that could benefit from adaptive
6 decision support in the short term
- 7 (3) decisions that will probably be affected but where adaptive actions can (and often
8 should) be addressed later.

9 Decisions that fall into category (2) present opportunities for immediate decision support in the
10 form of scientific findings or other support products. Decisions in category (3) would benefit
11 from adaptive management approach. Ongoing research and assessments that are directly
12 decision relevant would thus be particularly useful for decisions that fall into this category.
13 Decision support products for decisions in categories (2) and (3) should be designed to be
14 compatible with any pre-existing decision frameworks.

15 This classification framework and the decision-driven approach will motivate future assessments
16 and other project activities that aim to build capacity to assess and respond to global change
17 impacts on water quality and aquatic ecosystems, but there is still much work to be done to
18 understand how best to implement such a decision-driven approach. It is our hope to learn more
19 about this approach through our future projects.

Literature Cited

- California Research Bureau. A Statistical Tour of California's Great Central Valley. CRB. 1997. Sacramento, CA.
- Denault, C., R.G. Millar, and B.J. Lence. 2006. Assessment of Possible Impacts of Climate Change in an Urban Catchment. *Journal of the American Resources Association*. **42**:685-697.
- Dixon, M. D., J. C. Stromberg, J. T. Price et al. 2006. Potential Effects of Climate Change on the Upper San Pedro Riparian Ecosystem: Boon or Bane?
- Karl, T. R. and R. W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological Society*, **79**:231-241.
- Moglen, Glenn E., Palmer, Margaret A., Bockstael, Nancy E., Pizzuto, James E. Jointly Changing Climate and Land Use in the Mid-Atlantic: Modeling Drivers and Consequences in Economics, Hydrology, Geomorphology, and Ecology. Final Report to U.S. EPA. 2006.
- Nelson, K. C. and M. A. Palmer. 2006. Stream Temperature Surges under Urbanization and Climate Change: Data, Models, and Responses. *Journal of the American Water Resources Association*.
- Nelson, Karen C., Palmer, Margaret A., Angermeier, Paul L., Pizzuto, James E., Moglen, Glenn E., Dettinger, Michael, and Hayhoe, Katharine. 2006. Modeling the vulnerability of stream-fish assemblages to urbanization and climate change. To submit to *Ecological Modelling*.
- Odgaard, A. Jacob. 1989. River-Meander Model: I. Development. *Journal of Hydraulic Engineering*, **115**(11):1433-1450.
- Peterson, S. and Richmond, B., 1996. STELLA and STELLA Research Software: Technical Documentation. High Performance Systems, Inc., Hanover.
- Pizzuto, J. E., G. E. Moglen, M. A. Palmer, and K. C. Nelson. 2006. Two model scenarios illustrating the effects of land use and climate change on gravel riverbeds of suburban Maryland, U.S.A.
- Price, Jeff T., Galbraith, Hector, Dixon, Mark D., Stromberg, Juliet C., Root, Terry, MacMykowski, Dena, Maddock, Tom, and Baird, Kate. Potential Impacts of Climate Change on Ecological Resources and Biodiversity in the San Pedro Riparian National Conservation Area, Arizona. Final Report to U.S. EPA. 2005.
- Purkey, David R., Huber-Lee, Annette, Yates, David, Hanemann, M., and Julius, Susan H. Integrating a Climate Change Assessment Tool into Stakeholder-Driven Water Management Decision-Making Processes in California. To appear in a special issue of *Water Resources Management*, entitled WARM/ Advances in Global Change Research. 2006.
- SRAG (Southwest Regional Assessment Group). 2000. *Preparing for a changing climate: the potential consequences of climate variability and change*.
<http://www.ispe.arizona.edu/research/swassess/pdf/complete.pdf>
- Srinivasan, R.S., Arnold, J.G., and Jones, C.A. 1998. Hydrologic modeling of the United States with the soil and water assessment tool. *Water Resources Development* **14**(3):315-325.

- 1 US EPA, GCRP. Problem Formulation Report for the Assessment of the Consequences of
2 Global Change for Aquatic Ecosystems. 2003. Washington, DC, EPA\ORD\NCEA.
- 3 Webler, T. and S. Tuler. 1999. Integrating Technical Analysis with Deliberation in Regional
4 Watershed Management Planning: Applying the National Research Council Approach. Policy
5 Studies Journal, **27**:530-543.
- 6 Wilby, R. L., Charlies, S. P., Zorita, E., Timbal, B., Whetton, P., and Mearns, L. O. Guidelines
7 for use of climate scenarios developed from statistical downsacaling methods. 1-27. 2004.
8 United Kingdom, Environment Agency of England and Wales.
- 9 Yates, David, Sieber, Jack, Purkey, David, and Huber-Lee, Annette. 2005. WEAP21- A
10 Demand-, Priority-, and Preference-Driven Water Planning Model, Part I: Model Characteristics.
11 Water International 30(4):487-500.
- 12 Yates, David, Purkey, David, Galbraith, Hector, Huber-Lee, Annette, Sieber, Jack, and Joyce,
13 Brian. Global Change Impacts on Freshwater Ecosystem Services of the Sacramento Watershed,
14 California USA. 3-136. Final Report to U.S. EPA. 2006.