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A Framework to Assess the Relative Vulnerability of Aquatic Ecosystem Services to Global Stressors

Prepared for:

Susan Herrod-Julius
U.S. Environmental
Protection Agency
Global Change Research Program

Prepared by:

Elizabeth Strange
Josh Lipton
Margaret Lefer
Jim Henderson
Jennifer Hazen
Stratus Consulting Inc.
PO Box 4059
Boulder, CO 80306-4059
(303) 381-8000

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Acronyms

DAPTF	Declining Amphibian Populations Task Force
DOI	U.S. Department of the Interior
EPA	U.S. Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
IWI	Index of Watershed Indicators
NASQAN	National Stream Quality Accounting Network
NAWQA	National Water Quality Assessment
NLFWS	National Listing of Fish and Wildlife Advisories
NOAA	National Oceanographic and Atmospheric Administration
NRDA	natural resource damage assessment
NWI	National Wetlands Inventory
UV	ultraviolet

1. Background

Over the next several years, the U.S. Environmental Protection Agency's (EPA's) Global Change Research Program will conduct a series of case studies in different regions of the United States to evaluate potential changes in aquatic ecosystems as a result of global stressors (U.S. EPA, 2000c). Aquatic ecosystems include inland surface waters (lakes, rivers, and streams); wetlands; near-coastal waters (tidal rivers, estuaries, and near-shore waters); and coral reefs. Global stressors of concern include climate change and climate variability, ultraviolet (UV) radiation, and the development of land and water resources.

A primary interest of the case studies planned by EPA is to understand effects of global stressors on the ecosystem services provided by aquatic resources and their supporting habitats. Ecosystem services are the physical and biological functions performed by natural resources and the human benefits derived from those functions. Examples of the services provided by aquatic ecosystems include biodiversity, energy and biogeochemical cycling, food (for organisms and humans), water storage and delivery, water purification, and the provision of recreational opportunities that help promote human well-being (Cowling et al., 1997; Daily, 1997; Daily et al., 1997; Ewel, 1997; Postel and Carpenter, 1997; Costanza, 1999; Ewel et al., 1999; Holmlund and Hammer, 1999; Moberg and Folke, 1999; Roennbaeck, 1999; Guo et al., 2000).

There are several advantages of focusing EPA's aquatic case studies on ecosystem services. First, by explicitly considering ecosystem services, EPA will ensure that case study analyses do not become focused solely on investigators' personal research interests without consideration of the broader ecological and sociological context. Further, ecosystem services are "cross-cutting" indicators of ecological conditions that can be readily communicated to diverse stakeholders (Rapport et al., 1998; Norberg, 1999). A focus on services also makes it possible to concentrate a large amount of ecological data into a limited number of variables that are directly relevant to environmental decision-making (de Groot, 1992). In addition, ecosystem service endpoints can be directly linked to studies of societal preferences and values (Prugh et al., 1995; Simpson and Christensen, 1997; Turner et al., 1998; Wilson and Carpenter, 1999; King et al., 2000; Loomis et al., 2000).

This report describes an assessment framework designed to help case study researchers collect, organize, analyze and communicate to diverse stakeholders relevant ecological information on the effects of global stressors on aquatic ecosystem services. The framework is intended to ensure that the case studies conducted for EPA's Global Change Research Program provide a comprehensive evaluation of the potential consequences of global stressors for both aquatic resources and the services they provide. The following sections provide an overview of existing frameworks that can be adapted for global change research, describe the proposed framework for evaluating effects of global stressors on aquatic ecosystem services, and outline steps in the proposed assessment process.

2. Existing Frameworks for Related Assessments

Elements of two existing environmental assessment approaches have been adapted and combined to develop the process proposed herein for evaluating the potential effects of global stressors on aquatic ecosystem services. The two approaches are the EPA ecological risk assessment framework and the natural resource damage assessment (NRDA) process of the U.S. Department of the Interior (DOI) and the National Oceanographic and Atmospheric Administration (NOAA). These approaches are outlined briefly below.

2.1 Ecological Risk Assessment

EPA's ecological risk assessment framework presents a logical and systematic process for collecting, organizing, and analyzing ecological data for the purpose of evaluating the risks posed to natural resources by environmental stressors (U.S. EPA, 1998). The process involves three main phases: problem formulation, analysis, and risk characterization. In addition to its logical and coherent organizational structure, this framework has the advantage of focusing analysis on the assessment of risk rather than exact prediction, in recognition of the uncertainty and variability that characterize natural systems.

In addition, the framework is readily adapted to watershed-scale, multiple stressor assessments (Serveiss, 2002). A regional scale perspective is important given the connections among processes in different catchments and at different scales (Boughton et al., 1999; Garnier and Mouchel, 2000; Kling et al., 2000) that influence how global stressors will influence service flows (Bhat et al., 1998; Hurd et al., 1999; Winter, 2000).

2.2 Natural Resource Damage Assessment

The DOI and NOAA have developed approaches and promulgated regulations for conducting an NRDA. Although the NRDA process is designed to provide for compensation for losses of natural resources, it provides an interesting potential template for global change case studies because it involves explicit evaluation and quantification of ecosystem services (43 CFR Part 11, 15 CFR Part 990). The injury determination phase of an NRDA includes characterization of the pathways by which resources have been exposed to stressors, while the quantification phase establishes the extent of the injury in terms of the loss of services provided by the injured resources.

3. Proposed Assessment Framework

The assessment framework proposed here combines the organizational structure and emphasis on risk characterization of EPA's ecological risk assessment framework with the NRDA focus on ecosystem services (Figure 1). The following sections outline each phase of the assessment process, including some simplified examples for illustrative purposes. As indicated in Figure 1, the assessment process should involve ongoing dialogue between researchers and stakeholders. Communication with stakeholders is essential to ensure that researchers and decision-makers understand what issues are of greatest concern to stakeholders, and that stakeholders understand the scientific basis for planning decisions. Interaction with stakeholders will ensure that useful information is developed, relevant stressors and effects are identified and investigated, and policy-relevant results are communicated effectively.

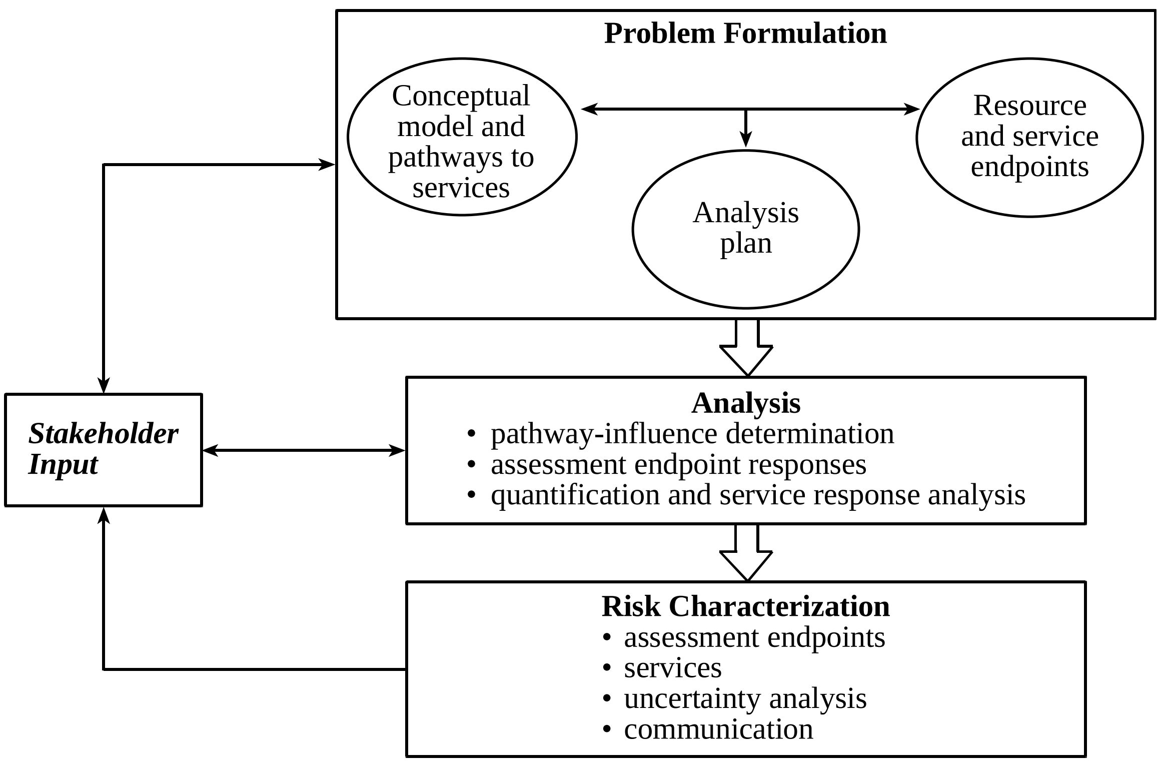

Figure 1. Proposed assessment framework.

Steps in the three phases of the proposed assessment process are outlined in Figure 2 and described below.

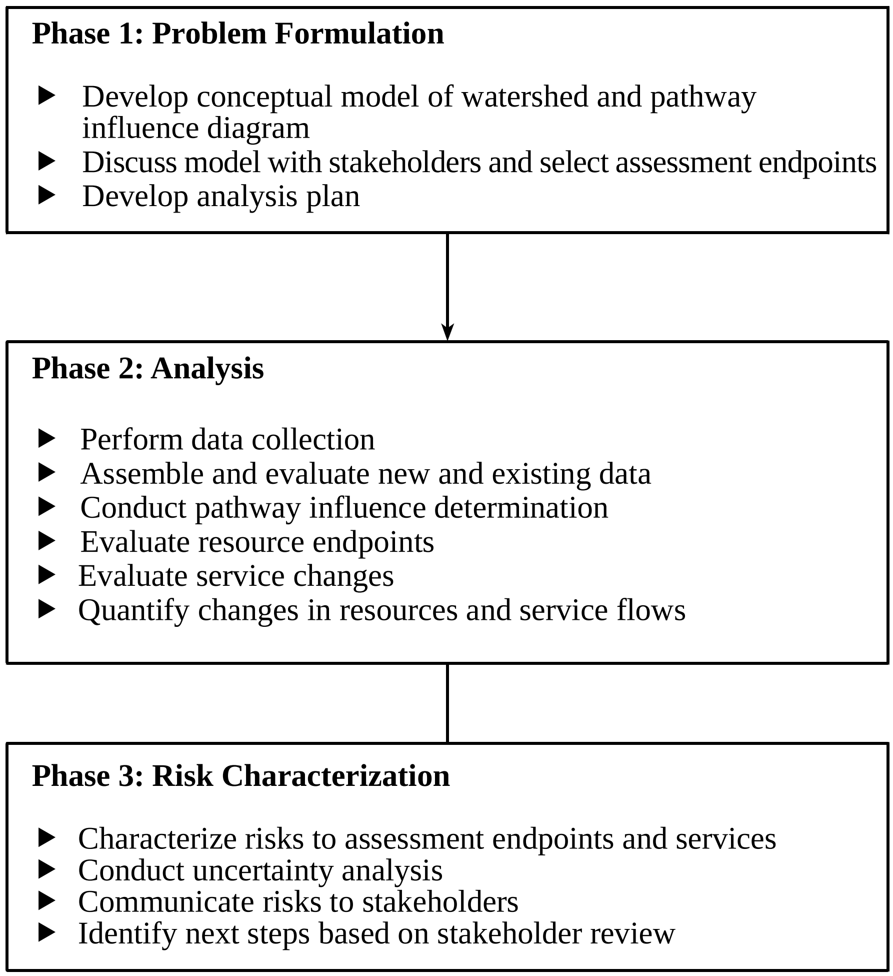

Figure 2. Outline of steps in the proposed assessment process.

Phase 1: Problem Formulation

In this initial phase of the assessment process, information on global stressors, physical, chemical, and biological conditions in the watershed, natural resources potentially at risk, and ecosystem service responses is integrated to develop a conceptual model of the watershed under study. The objectives of this phase of the analysis are to:

1) **develop a conceptual model** of the watershed and a **pathway influence diagram** to provide a systematic examination of the links among stressors of concern, watershed resources, and ecosystem services

2) **discuss model with stakeholders** and **select assessment endpoints,** including the natural resources and associated ecosystem services that are potentially at risk

3) **develop an analysis plan** that provides stakeholders with a transparent identification of the assessment endpoints that will be evaluated, the measures of change that will be considered, and the metrics for quantification of resource and service changes.

(1) Develop conceptual model

In this step, investigators will develop a conceptual model of the watershed focusing on the pathways that generate ecosystem services. Development of a conceptual model will ensure that a systematic consideration of watershed structures, functions, and services is undertaken before selecting assessment endpoints and approaches. Specific activities that should be undertaken in the development of the conceptual model include (but are not necessarily limited to) the following:

Describe watershed attributes. The specific attributes of the watershed being studied should be described in order to develop a coherent picture of the relationships between stressors and receptors. Box 1 provides a simplified example of a watershed description for a typical urbanized river, the South Platte River Basin in Colorado. Watershed attribute information should include the following:

- The geographic and human setting of the watershed, including information on climate, landform and cover types, ecological region, human land uses, and general economic and socioeconomic conditions and uses in the watershed.

Box 1. Simplified illustration of watershed description, South Platte River Basin

The South Platte River Basin in Colorado is typical of urbanized watersheds throughout the arid and semi-arid regions of the United States. In these watersheds, climate-induced reductions in precipitation combined with increased land and water use are expected to alter hydrologic conditions that help generate aquatic ecosystem services (Strange et al., 1999). The potential effects of global stressors will vary depending on current conditions in different parts of the basin. The upper South Platte River Basin provides services typical of forested uplands, including habitat for native biota and numerous recreational opportunities. The middle river, which includes the Denver metropolitan area, is a major source of water for municipal and industrial uses, while the lower river is used to irrigate agriculture. Global stressors have the potential to reduce the quantity and quality of water for all of these uses.

- The hydrological regime, including precipitation, water recharge and flow patterns, the timing and magnitude of flows in the basin, the watershed's drainage network, and water uses. The illustrative example provided in Figure 3 depicts the hydrologic regime and associated ecosystem services of the upper, middle, and lower South Platte River as a series of input-output relationships. Inflows are the inputs to the system and flow-related ecosystem services are the outputs. Separate representations are given for native inflows, imported inflows (transbasin diversions), municipal treatment plant discharges, and agricultural return flows. Ecosystem services provided by the river (represented with rectangles, circles, and triangles) include riparian habitat, birds and fish, instream recreation, flatwater (reservoir) recreation, dilution of contaminant concentrations, hydropower, agricultural use, and municipal use.

- Biological attributes of the watershed, including a description of representative habitats; taxa (including aquatic, semi-aquatic, and riparian taxa); general food-webs; threatened, endangered, and other special status species; and commercially/recreationally important species.

- General nutrient flows and biogeochemical cycling (e.g., relative importance of *in situ* primary production versus allocthonous carbon inputs).

Develop a pathway influence diagram. The purpose of this step is to conceptually and visually describe relationships among watershed structures and processes so that potential receptors can be linked causally to the stressors under consideration. This involves development of a pathway influence diagram that outlines links among sources, stressors, resources at risk, and associated services. This should include consideration of the complete "chain of events" that is hypothesized to occur when considering multiple stressor-response relationships. This will help identify potential feedback loops that can result in "risk cascades" (Lipton et al., 1993). The concept of risk cascades refers to ecological effects that represent a source of risk for other system components.

It is also important to recognize that although many aquatic ecosystems are resilient and quickly respond to changing environments, the intensity, frequency, and locations of impacts within a given watershed may create time lags in ecosystem responses that result in long-term cumulative effects (Stevens and Cummins 1999; Dube and Munkittrick, 2001; Schindler, 2001). The accumulation of these direct and indirect effects may be considerable, but difficult to identify, document, or integrate into the assessment. Although it is important to recognize complexities such as risk cascades and cumulative effects, it is also important to make sure that the pathway influence diagram is not so complex that response "signals" will be difficult to detect.

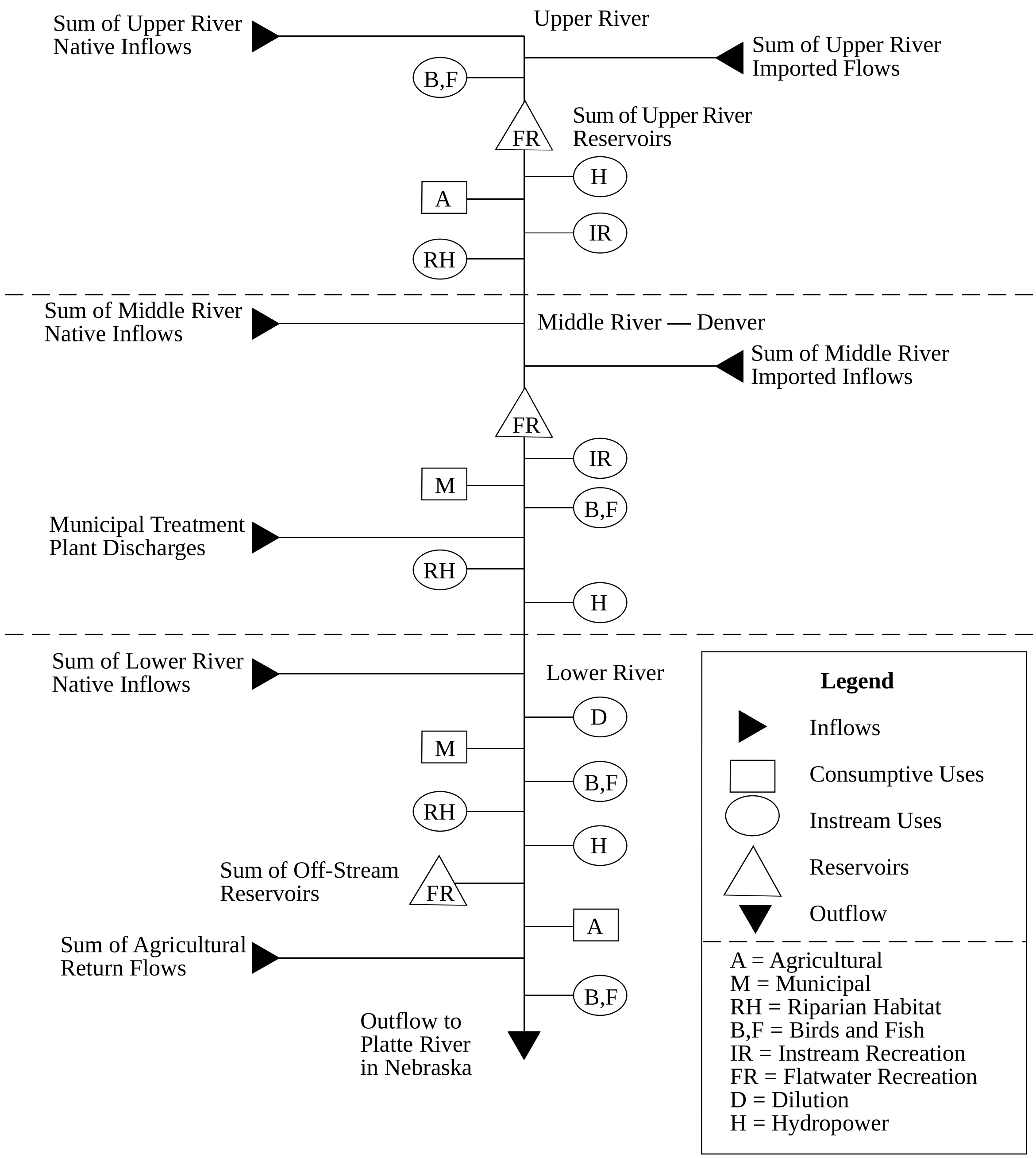

Figure 3. Illustrative geographical representation of South Platte River hydrology and associated ecosystem services. Representations of the interactions between basin hydrology, biological resources, and human interactions can aid investigators in development of site conceptual models.

At a minimum, the development of a pathway influence diagram will involve the following steps:

- **Identify and define the sources and stressors to be assessed.** Investigators should clearly identify the human activities and stressors to be assessed. Global change stressors (e.g., land use, water development, climate change, climate variability, UV) are, by definition, broad and subject to confusion among stakeholders. For stakeholders to evaluate the analysis plan, it is important that the stressors of interest be clearly presented and described. It also should be recognized that multiple and interacting stressors may influence ecosystem services. To the extent feasible (and without rendering the assessment hopelessly complex), investigators should therefore consider both multiple stressors and interactions among them.

- **Identify natural resources of concern.** Investigators should clearly identify natural resources (both abiotic and biotic) that are potentially at risk.

- **Identify services associated with resources of concern.** After identifying the stressors and resources of concern, investigators should explicitly describe the ecological and human services provided by the resources (see example, Box 2). This will provide stakeholders with a clear description of the types of services associated with the stressors being evaluated.

- **Identify stressor-resource-service response relationships.** In this step, investigators should outline relationships among stressors and the potentially affected services (as mediated by changes in resource receptors) (see example, Box 3). This defines the pathways by which stressors are likely to impact potential assessment endpoints.

Box 2. Illustration of service relationship: Water supply for human uses

Water development and other human activities affect the quantity and quality of water available for a variety of ecological and human uses. For example, in the South Platte River Basin, increases in return flows from irrigated farm lands, combined with increases in stream diversions, have raised salinity concentrations in the lower South Platte River (Dennehy et al., 1993). Elevated salinity can impair domestic water supplies and the quality of irrigation water, reducing crop production, as well as causing toxicity to aquatic biota and altering community composition.

Box 3. Simplified illustration of stressor-resource-service response relationships

Water development activities (e.g., diversions, channelization, impoundments, groundwater pumping) are stressors that can alter the frequency, duration, timing, and magnitude of surface water flows. Flow alteration can affect numerous aquatic resources, including instream and riparian habitat and biota. In turn, the impairment of aquatic structures and functions affects numerous services, including water storage and delivery, nutrient cycling, provision of habitat for aquatic biota, and recreational opportunities.

Figure 4 provides an illustrative example of a simple pathway influence diagram outlining some of the relationships among water development activities, flow alteration, and changes in riparian and stream resources and services in the South Platte River Basin. In the South Platte Basin, native riparian trees such as cottonwood (*Populus angustifolia)* require a bare, moist substrate produced by spring floods for seedling germination, followed by a period free from disturbance for seedling establishment (Johnson, 1994; Shafroth et al., 1995; Friedman et al., 1997). Flow alteration through various water development activities has decreased snowmelt peaks in the South Platte River Basin, slowed the rate of peak flow recession, and increased summer base flows. All of these changes have reduced recruitment of native cottonwood, resulting in less habitat for native cavity-nesting birds (Knopf and Olson, 1984). Reduction of spring peak flows has also allowed vegetation to establish on stream bars, reducing nesting habitat for special status species such as the sandhill crane (*Grus canadensis*) (Johnson, 1994). In turn, the loss of riparian avifauna reduces services such as bird watching. The loss of peak flows, combined with periods of stream dewatering, also reduces instream habitat for fish as well as flows for recreational activities such as swimming and boating. Differences in the services provided by native and non-native species can have important economic as well as ecological consequences (e.g., Cowling et al., 1997; Wilcox and Harte, 1997; Brismar, 2002).

(2) Meet with stakeholders to discuss model and select assessment endpoints

In this step, researchers should meet with stakeholders to present the conceptual model and discuss potential assessment endpoints. Assessment endpoints are the natural resources and ecosystem services that are hypothesized to be at risk and are of concern to stakeholders.

(3) Develop analysis plan

The purpose of this step is to develop a clearly articulated analysis plan that will provide stakeholders with a transparent identification of the endpoints of the assessment, the measures of change to be used in evaluating those endpoints, available data, and metrics to be used to quantify changes in watershed resources and services. Specific elements of the analysis plan include the following:

- **Select assessment endpoints**. Based on the conceptual model, pathway influence diagram, and stakeholder input, the specific endpoints to be examined in the assessment should be specified. Assessment endpoints should include both resource endpoints (e.g., flow regime) and service endpoints (e.g., agricultural water use). Selection of assessment endpoints is based on considerations such as susceptibility to global stressors, relevance to stakeholder priorities, and ecological importance. Selection of assessment endpoints also should entail explicit discussion of the scale of ecological organization being evaluated (e.g., species, community, habitat, landscape). To the extent feasible,

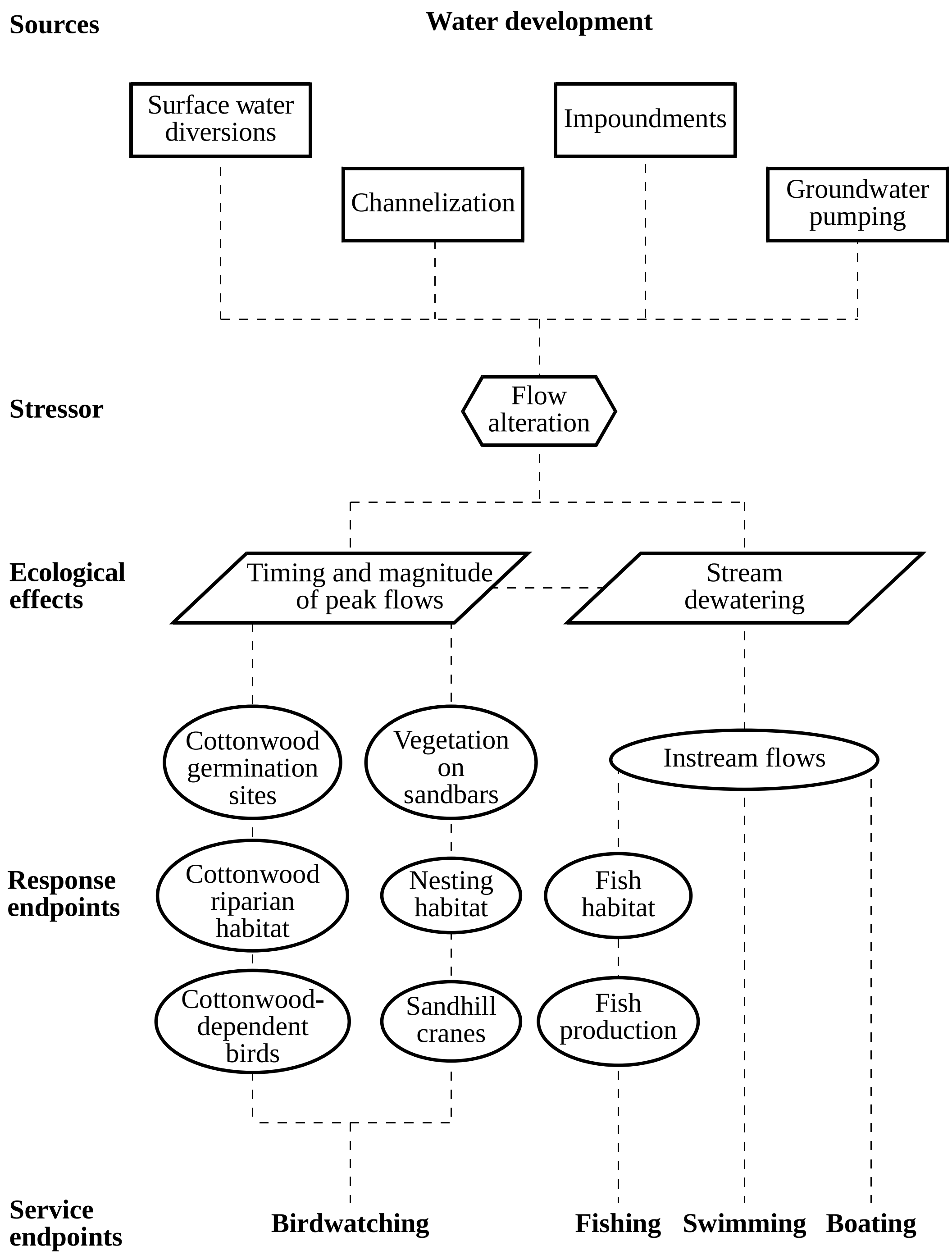

Figure 4. Example of a simple pathway influence diagram of relationships among water development activities, flow alteration, and changes in riparian and stream resources and services in the South Platte River Basin.

investigators should endeavor to consider multiple organizational scales, as well as functional connectivity within the ecosystem being assessed (e.g., migration corridors, energy transport and biogeochemical fluxes within systems, interactions between aquatic and terrestrial habitats).

- **Select measures of change.** The investigators should identify and describe those specific measures of change that will be used to evaluate assessment endpoints. For example, changes in the timing or magnitude of peak flows might be used to evaluate the flow regime as an assessment endpoint. In certain cases, it may be appropriate for investigators to identify specific numerical measures that may be used (e.g., number of days on which water temperature exceeds a lethal threshold for rainbow trout), or specific statistical measures that may be employed in evaluating potential changes in the assessment endpoint (e.g., 20% decrease in base flow) (e.g., Richter et al., 1996).

- **Describe time horizon of assessment.** Global change stressors may influence ecosystem services over lengthy time horizons. Investigators should describe the time horizon being considered in the analysis, as well as, to the extent feasible, the anticipated relationship between the time horizon over which ecological responses might manifest themselves relative to the temporal sequence of the stressor.

- **Select quantification metrics.** In this portion of the analysis plan, the investigators should identify the metrics that will be used to quantify changes in both resource receptors and the services provided by the resource. This quantification step is important because stakeholder interpretation of study results should be informed through an understanding of the potential magnitude and extent of change rather than simply a determination that some change may occur. Quantification metrics to be considered by investigators might include defining the *degree* of potential impacts; the *areal* (e.g., stream miles, number of affected acres), *geographic* (e.g., geographic area), and *temporal* (duration, frequency, seasonality, etc.) extent of potential impacts; and the *probability* of potential effects (described quantitatively or qualitatively in terms of level of certainty).

  In some cases, ecological indicators can be useful measures of stressors and effects. EPA's Office of Research and Development defines an ecological indicator as "a measure, an index of measures, or a model that characterizes an ecosystem or one of its critical components" (U.S. EPA, 2000a). Considerable effort has been devoted to developing indicators of aquatic ecosystem status and trends (U.S. EPA, 1990, 2000b; NRC, 2000), and some studies have explicitly evaluated indicators of aquatic ecosystem services (OECD, 1993, 1997; Cole et al., 1996; Revenga et al., 1998, 2000; Heinz Center, 1999; King et al., 2000; Burke et al., 2001). Indicators can be used to characterize the current level of an ecosystem service within a watershed and to predict potential changes in service levels in response to particular global change scenarios. Appendix A provides a matrix of indicators that may prove useful in evaluating service pathways.

- **Identify available data, models, data/model gaps.** The analysis plan should provide an overview of available data for the watershed study and existing models that will be used to evaluate changes, and identify data/model gaps. The plan should then describe how data/model gaps will be filled (e.g., collection of new data, construction of new models, reliance on certain assumptions). Appendix B lists some existing watershed databases.

- **Present research plan.** Finally, the analysis plan should include a defined research plan that describes the methodological approaches to be used by the investigator. The plan should be submitted to stakeholders for review and revised as appropriate based on stakeholder input.

Phase 2: Analysis

In the analysis phase, the research and analysis outlined in the analysis plan are conducted. The nature of the analysis undertaken by an investigator is necessarily case-specific and investigators must retain the flexibility to apply a wide variety of analysis methods and approaches. Notwithstanding this latitude, the analysis should include the following components:

- **Perform data collection.** Based on the analysis plan, researchers should identify existing data sources and collect new data, if required, to fully specify the stressor-resource-service pathways of interest.

- **Assemble and evaluate new and existing data.** The selection of study methods and the degree of analytical sophistication will depend on the data to be evaluated.

- **Conduct pathway influence determination.** In this step, the investigators should present information that provides formal consideration of whether the pathway-influence relationships postulated in the problem formulation phase are supported and the nature of those pathway influences.

- **Evaluate resource endpoints.** In this step, the investigators should determine whether resources of concern are likely to be affected by the stressors under consideration. Investigators should evaluate selected measures of change and describe, based on their analysis, whether the responses in the measures of change will be linked quantitatively to changes in the resource endpoints.

- **Evaluate service changes.** In this step, the investigators should provide an evaluation of which services might be affected as a result of changes in resource endpoints. The determination of service change should be relative to a baseline condition that reflects those future conditions that would be expected in the absence of the global stressor being evaluated.

- **Quantify changes in resources and service flows.** To the extent possible, this step should include quantitative evaluation of changes in assessment endpoints, including the degree of change, the probability of change, and the areal, geographic, and temporal extent of change. This quantification of change should be relative to a "future baseline" condition. Investigators may wish to present this quantification of changes in service flows under alternative states of nature (e.g., hypothesizing alternative future conditions), or under alternative regulatory, mitigation, or adaptation scenarios as a means of evaluating the relationship between service modifications and future human activities.

Phase 3: Risk Characterization

This final phase of the assessment involves the following steps:

- **Characterize risks to assessment endpoints and services based on the results of the analysis.** Characterization of risks (described quantitatively or qualitatively) should consider the nature of changes in assessment endpoints, including the degree of change, the probability of change, and the spatial and temporal extent of change. In addition, the risk characterization should describe the temporal horizon of the analysis and discuss the sensitivity of the risk predictions relative to selection of the time horizon. The characterization should also include, if possible, identification of potential "hot spots" within the watershed.

  EPA's Guidelines for Ecological Risk Assessment discuss in detail the components of risk characterization, including the estimation of risk, the interpretation of the significance of effects, and the analysis of uncertainties, assumptions, and qualifiers in the risk assessment (U.S. EPA, 1998). Risk estimates can be developed using a variety of techniques, including quantitative field or laboratory studies, qualitative rankings, and mathematical models of ecological processes. The significance of risk estimates is evaluated by considering the multiple lines of evidence obtained from such assessment techniques.

- **Conduct uncertainty analysis.** Sources of uncertainty should be described and quantified where possible. Uncertainties result from various sources, including natural variability, imprecision in underlying data, lack of complete information, or lack of confidence in modeling assumptions (Finkel, 1990; Morgan and Henrion, 1990; Lipton and Gillett, 1992; Hoffman and Hammonds, 1994; Rowe, 1994). To the extent feasible, investigators may wish to include formal sensitivity analysis, error, or simulation analysis into an evaluation of the uncertainties inherent in the assessment. In addition, investigators should attempt to describe the degree of uncertainty in the "direction" of the anticipated response, the degree of the response, and the geographic or temporal sensitivity of the response. Finally, it may be beneficial to stakeholders to perform such uncertainty analyses for both the assessment endpoints and the potentially affected services (for example, the degree of uncertainty regarding the risk to a specific assessment endpoint or species may be different than for an aggregated service).

- **Communicate risks to stakeholders.** Once risks are fully characterized, results need to be communicated to stakeholders. The methods, format, and timing of communication should be responsive to the specific needs of stakeholders and therefore may vary from project to project depending on expressed needs. Communication may include development of a "report card" summarizing current risks to key services (e.g., Harwell et al., 1999).

Table 1 presents one simplified example of a risk summary based on a simple stressor-response matrix. The column headings display stressor categories and the row headings display ecosystem service categories. Each stressor-response interaction is assigned a risk value (high, moderate, low) based on case study results. Reading across the matrix provides an indication of the relative risk posed by the various stressors to each ecosystem service. Reading the matrix vertically provides an indication of the relative risk posed to the various services by a given stressor.

Table 1. Example summary of risk characterization.

	Stressors		
	Riparian development	**Flow alteration**	**Sedimentation**
Services			
Fishing	*Moderate*	*High*	*High*
Flood control	*High*		
Boating	*Low*		

Note: The table indicates the relative vulnerability in qualitative terms (low, moderate, high) of different services to various stressors.

Such a summary can help indicate which services are most vulnerable at a given case study site and which risks are most serious. Summaries of this type are useful communication tools for presenting assessment results and have been used in many related applications (Harwell et al., 1999; Revenga et al., 2000; U.S. EPA, 2000c; Burke et al., 2001; IPCC, 2001).

- **Discuss next steps.** Based on results of the risk analysis and stakeholder review, researchers and stakeholders should identify follow-up activities.

4. Conclusions

The assessment framework described in this report is intended to help case study researchers make explicit the potential effects of global stressors on aquatic resources and the services they provide. The framework is meant to be general enough to incorporate different types of data and methods, but also specific enough that risks to aquatic ecosystem services in different geographic areas can be compared or even aggregated across regions as appropriate.

The framework is readily adapted to watershed-scale, multiple stressor assessments. This makes it possible to explicitly recognize that different types of aquatic ecosystems (e.g., lakes, rivers, wetlands, riparian forests, and floodplains) are embedded within a landscape context that determines both the amount and type of materials imported and exported, as well as their connectivity to surrounding communities and food webs (Boughton et al., 1999; Kling et al., 2000; Winter, 2000).

Details for any particular assessment will depend on site-specific considerations. Each case study site will present unique features that will determine which assessment endpoints are most appropriate to evaluate given the stressor scenarios of interest, available data, and stakeholder priorities. As case study research proceeds, results will help guide further development of the assessment process outlined here.

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Appendix A — Potential Indicators

Table A-1 presents a categorization scheme for aquatic ecosystem services and ecological indicators that might be used to evaluate service pathways. Data sources for quantifying these indicators are provided in Appendix B. Note that the categorization scheme and potential indicators are examples only. Specific research questions will guide the selection of assessment and measurement endpoints, as discussed in the text.

Table A-1. Indicators that can be used to evaluate service pathways under particular global change scenarios.

	Ecosystem services												
Indicators	Water storage and delivery	Flood control	Transportation	Hydropower	Water-based recreation	Decomposition and assimilation of waste	Erosion control	Contaminant absorption and detoxification	Nutrient cycling	Maintenance of biodiversity	Provision of habitat	Production of food and raw materials	Nearshore recreation
Precipitation	X	X	X	X	X	X	X	X	X	X	X	X	X
Air Temperature	X	X	X	X	X	X	X	X	X	X	X	X	X
Slope	X	X	X	X	X	X	X	X	X	X	X	X	X
Aspect	X	X					X		X	X	X	X	X
Landscape Type	X	X	X	X	X	X	X	X	X	X	X	X	X
% Forest	X	X	X	X	X	X	X	X	X	X	X	X	X
% Agricultural	X	X	X	X	X	X	X	X	X	X	X	X	X
% Urban (level of development)	X	X	X	X	X	X	X	X	X	X	X	X	X
Landscape Patch Size	X	X	X	X	X	X	X	X	X	X	X	X	X
Bank Vegetation Cover & Type		X				X	X	X	X	X	X	X	X
Wetland Area / Extent	X	X		X	X	X	X	X	X	X	X	X	X
Hydrodevelopment (# of dams/mi)	X	X	X	X	X	X		X		X	X	X	
Channelization	X	X	X	X	X	X	X	X		X	X	X	X
Flood Control Structures	X	X	X	X	X	X	X	X		X	X	X	
Groundwater Depletion	X			X									
Annual Basin Withdrawls	X				X	X		X	X	X	X	X	X
Hydrologic Regime (Timing & Magnitude)	X	X	X	X	X	X	X	X	X	X	X	X	X
Runoff Rate	X	X	X	X	X	X	X	X	X	X	X	X	X
Infiltration	X	X	X	X	X	X	X	X	X	X	X	X	X
Water Temperature			X		X	X		X	X	X	X	X	X
Evapotranspiration	X	X	X	X	X	X	X	X	X	X	X	X	X
Sediment Transport	X		X	X	X	X	X	X	X	X	X	X	X
Soil Permeability	X	X	X	X	X	X	X	X	X	X	X	X	X
Nutrient Transport					X	X		X	X	X	X	X	X
Organic Matter Transport					X	X		X	X	X	X	X	X
Contaminant Transport					X	X		X		X	X	X	X
Water Levels	X	X	X	X	X		X		X	X	X	X	X
Water Flow (Dry Season)	X	X	X	X	X		X			X	X		X
Extent and Duration of Ice Cover	X	X	X	X					X	X	X	X	X
Water Volume (in relation to capacity)	X	X		X									

Table A-1. (cont.) Indicators that can be used to evaluate service pathways under particular global change scenarios.

	Ecosystem services												
Indicators	Water storage and delivery	Flood control	Transportation	Hydropower	Water-based recreation	Decomposition and assimilation of waste	Erosion control	Contaminant absorption and detoxification	Nutrient cycling	Maintenance of biodiversity	Provision of habitat	Production of food and raw materials	Nearshore recreation
Renewable Water Supply per Person	X												
Residence Time of Water in Basin	X	X											
Volume of Water in Aquifer Storage	X												
Saltwater Intrusion in Aquifer	X					X		X					
Sediment Deposition	X		X				X			X	X		
Sediment Suspension			X		X	X	X	X		X	X		
Dredging Expenses			X										
Contaminant Concentrations					X	X		X		X	X		X
Nutrient Concentrations					X	X		X	X	X	X		X
Suspended Solids (Secchi depth)					X	X		X		X	X		X
pH					X	X		X		X	X		X
Dissolved Oxygen (hypoxia)						X		X		X	X		X
Biochemical Oxygen Demand (BOD)						X		X		X	X		X
Eutrophic Condition (Chlorophyll a, etc.)					X	X		X		X	X		X
Wastewater Assimilative Capacity						X		X					
Biological Productivity									X	X	X		X
Species Diversity										X	X		X
Species Richness										X	X		X
Threatened & Endangered Species										X	X		X
Endemic Species / Non-Native Species										X	X		X
Presence of Rare Species										X	X		X
Biological Distinctiveness Index										X	X		X
Index of Biotic Integrity										X	X		X
Community Index										X	X		X
Water Quality Standard Violations					X	X		X		X	X		X
Fish Consumption Advisories					X	X		X				X	X
Fisheries Catch Composition												X	
Fisheries Catch Per Unit Effort													
Beach Closures					X								X

Notes: Ecosystem services are indicated across the top of the table. Indicator variables are listed in the far lefthand column. Indicator variables associated with each service are indicated by X's in the columns.

Appendix B — Data Sources

Land cover

National Wetlands Inventory (NWI).

Water quantity

USGS gauging stations and regional hydrologic models for specific river basins provide estimates of changes in runoff patterns (volume, timing, rates).

Water quality

EMAP (http://www.epa.gov/emap/). Data on biota (plankton, benthos, fish) and environmental stressors (water quality, sediment quality, tissue accumulation). Among the resource groups monitored by EMAP are estuaries, inland surface waters, and wetlands. EMAP scientists use monitoring data to determine if statistical associations exist between **condition indicators** (characteristics of the environment that provide quantitative estimates of the state of ecological resources) and **stressor indicators** (characteristics of the environment that are thought to produce changes in ecological resources).

USGS National Stream Quality Accounting Network (NASQAN) (http://water.usgs.gov/osw/) — water chemistry and sediment data for the four largest U.S. river systems (Colorado, Columbia, Rio Grande, and Mississippi, including the Ohio and Missouri) and the National Water Quality Assessment (NAWQA) — detailed studies of 60 smaller U.S. river basins.

U.S. EPA Index of Watershed Indicators (IWI) includes 15 indicators of watershed condition and vulnerability as reflected in overall water quality based on available data on fish consumption advisories, sediment contamination, and other variables.

EPA Great Waters Program (http://www.epa.gov/oar/oaqps/gr8waters/) — research and reporting on deposition of hazardous air pollutants to Great Lakes, Lake Champlain, Chesapeake Bay, and certain other coastal waters).

NOAA National Estuarine Eutrophication Assessment. CWA 303(d) lists of impaired waters stored in EPA’s TMDL Tracking Program (http://www.epa/gov/owow/tmdl/).
305b state assessments stored in EPA’s National Assessment Database.

National Listing of Fish and Wildlife Advisories (NLFWA). Website: http://www.epa.gov/OST/fish.

Status of Shellfish Growing Waters. Website: http://sposerver.nos.noaa.gov/projects/95register.

National Coastal Research and Monitoring Strategy. Website: http://cleanwater.gov/coastalresearch.

EPA's National Coastal Assessment (EMAP Estuary Assessments). Website: http://www.epa.gov/emap/nca.

PrimeNet, the EPA/NPS UV monitoring network. Website: http://www.epa.gov/uvnet.

Habitat and biota

North American Breeding Bird Survey by Patuxent Environmental Science Center. Website: http://www.mbr.nbs.gov/bbs.

DAPTF (Declining Amphibian Populations Task Force). Website: http://www.open.ac.uk/daptf/. DAPTF is a network of more than 3,000 scientists working in 90 countries.

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DIAS (Database on Introduction of Aquatic Species). Available on-line at: http://www.fao.org/fi/statist/fisoft/dias/index.htm.

USGS Non-indigenous Aquatic Species information resource.

Food production — Fisheries

FAO (Food and Agriculture Organization of the United Nations). 2000. *The State of World Fisheries and Aquaculture*. FAO. Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). 1999. Projection of World Fishery Production in 2010. Available on-line at: http://www.fao.org/fi/highligh/2010.asp.