Identification and Preliminary Characterization of Global Water Resource Issues Which May Be Affected by CO₂- Induced Climate Change

J. M. Callaway
M. L. Cohen
J. W. Currie

April 1984

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IDENTIFICATION AND PRELIMINARY
CHARACTERIZATION OF GLOBAL
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Richland, Washington 99352

SUMMARY

This research was performed by the Pacific Northwest Laboratory (PNL) for the Division of Carbon Dioxide Research, U.S. Department of Energy (DOE). It was undertaken as a part of the CO₂ Indirect Effects Research Program to assist DOE in achieving the following two objectives:

- Identify, characterize, and define existing or projected regional and global water resource management issues which may be affected by CO₂-induced climate changes.
- Develop research priorities for acquiring additional information about the potential effects of a CO₂-induced climate change on the availability and allocation of freshwater supplies.

To achieve these objectives PNL has broken down its research into four work elements: (1) identification of water resource management issues on a global and regional basis; (2) identification of a subset of generic CO₂-related water resource management issues believed to have the highest probability of being affected, beneficially or adversely, by a CO₂-induced climate change; (3) selection of specific sites for examining the potential effect of a CO₂-induced climate change on these issues; and (4) conducting detailed case studies at these sites, the results from which will be used to identify future research and data needs in the area of water resources. This report summarizes the research related to the first three work elements.

IDENTIFICATION OF GLOBAL AND REGIONAL WATER RESOURCE MANAGEMENT ISSUES

A basic working hypothesis that underlies this research is that CO₂ build-up is unlikely to create any entirely new water resource issues. Instead, it is assumed that the general impacts of CO₂ on the world water resources situation will be reflected either by changes in the magnitude of current issues where they now exist and/or by some geographic redistribution of these issues. Given this hypothesis, a literature search of relevant water resources planning and research publications was undertaken to identify current water resource

management issues, worldwide, and representative locations where these issues are now present. In all, twenty-six different water resource management issues were identified at roughly 90 locations around the world.

The results of this information search are shown in the "Specific" World Water Supply/Allocation Matrix contained in Appendix A. Each issue in this matrix is accompanied by at least three locational references. The following information is displayed for each locational reference: (1) the magnitude of the impacts associated with the relevant issue; (2) the probable future trend of these impacts in the absence of climate change; (3) those factors, unrelated to climate, which influence the magnitude of these impacts; (4) the potential sensitivity of the issue to increases in precipitation and temperature; and (5) the agency or agencies charged with responsibility for managing each issue.

The information in this matrix has been further condensed into a series of short issue summaries designed to give the reader general background information regarding the nature of each issue, the magnitude of the impacts related to it, its pervasiveness over space and likely persistence over time, as well as its potential sensitivity to climate change.

IDENTIFICATION OF GENERIC ISSUES

A set of criteria was selected for screening the twenty-six specific water resource issues in order to determine which of them appeared to have the greatest potential for being affected, beneficially or adversely, by a CO₂-induced climate change, 50 to 100 years in the future. These criteria included: (1) climate sensitivity, (2) persistence over time, (3) pervasiveness over space, and (4) magnitude of societal impact. Each of the issues was scored along all four of these dimensions and, after comparing the results of these scores using several sets of decision rules to discriminate between the scores, nine issues were identified under the generic category. These include:

- flooding
- droughts
- inadequate surface water supply/storage
- groundwater mining
- sedimentation of rivers

- salinity problems
- conflicts in use
- water losses from storage systems
- aquatic vegetation

SITE-CASE STUDY SELECTION

Three methods were identified for characterizing the effects of a CO₂-induced climate change on individual generic issues in the context of site-specific case studies. These included: (1) selecting key parameters of climate change and speculating on the effects of changes in these parameters on individual generic issues; (2) applying empirical methods to determine how extreme climatic fluctuations and anomalies contained within the historical record have affected individual generic issues at the selected site as a basis for studying the impacts of projected climate changes; and (3) using systems-based, watershed models in connection with projections of key climate parameters to characterize the effects of these changes on individual, generic issues.

After reviewing the strengths and weaknesses of these three approaches, it was decided to use the first approach to develop working hypotheses regarding the possible effects of changes in key climate parameters on the magnitude of individual, generic issues. Since the state of the art in hydrologic analysis and modeling is such that neither of the remaining two approaches has been clearly identified as the best one for characterizing the effects of climate change on water resources, it was decided to compare the performance of these two approaches at a single site.

The site selected for this comparative analysis was the Salt River Basin in central Arizona. This site was chosen based on the application of a set of eight criteria which were developed specifically for this purpose. The site selection process used to arrive at the Salt River was iterative in the sense that specific criteria were applied sequentially to narrow the geographic scope of the search, first to a site in the United States, then to four large, water resource planning regions located either in the Great Plains or the West, to a single region, the lower Colorado River, and finally to a site within that region, namely the Salt River.

In the final phase of this research, the Salt River will be studied intensively, using both empirical and watershed models, to attempt to characterize the potential effects of a CO₂-induced climate change on the magnitude of individual generic issues. The extent to which the findings from this research can be generalized to other river basins in both the United States and the rest of the world will be addressed. In spite of the extreme variety and variability across space that characterizes the interaction between climate and the hydrologic systems of individual river basins, it seems likely that some of the findings on six of the issues will be transferable to other sites, particularly in arid regions of the world. These issues include: 1) droughts, 2) inadequate surface water supply/storage, 3) groundwater mining, 4) conflicts in use, 5) water losses from storage systems and 6) aquatic vegetation.

Finally, the results of the research on the Salt River will serve as a basis for outlining both future research in the area of CO₂ and water resources and the data required from the climate program to support this research.

CONTENTS

SUMMARY.....	iii
1.0 INTRODUCTION.....	1.1
CO ₂ AND WATER RESOURCES.....	1.1
OBJECTIVES AND SCOPE OF PNL RESEARCH.....	1.2
Task 1. Development of "Specific" World Water Supply/Allocation Matrix.....	1.3
Task 2. Development of "Generic" CO ₂ -Water Supply Issues.....	1.3
Task 3. Region/Site Specific Analyses.....	1.3
SCOPE AND ORGANIZATION OF THIS REPORT.....	1.3
REFERENCES.....	1.5
2.0 CONCLUSIONS AND RECOMMENDATIONS.....	2.1
CONCLUSIONS.....	2.1
Identification of Generic Issues	2.1
Choice of Case Study Method.....	2.2
Site Selection.....	2.3
RECOMMENDATIONS.....	2.4
3.0 IDENTIFICATION OF SPECIFIC ISSUES.....	3.1
RESEARCH STEPS.....	3.1
DESCRIPTION OF THE "SPECIFIC" WORLD WATER SUPPLY/ALLOCATION MATRIX.....	3.2
HOW TO READ THE MATRIX.....	3.3
CURRENT MAGNITUDE OF THE ISSUE.....	3.5
Issue Trend.....	3.5
Nonclimatic Determinants.....	3.5
Sensitivity of Issue to Increases in Precipitation and Temperature.....	3.6

Institutional Responsibility.....	3.7
EXAMPLES.....	3.7
Upper Mississippi Floods (Page A.1).....	3.7
Conveyance Losses in Australia (Page A.15).....	3.9
DISCUSSION OF RESULTS.....	3.9
Location of Specific Issues.....	3.10
Current Magnitude of Issues.....	3.10
Future Trends.....	3.11
Climate Sensitivity.....	3.12
Water Resources Agencies.....	3.23
REFERENCES.....	3.24
4.0 IDENTIFICATION OF GENERIC ISSUES.....	4.1
RESEARCH STEPS.....	4.1
Development of Criteria.....	4.1
Application of Criteria.....	4.2
DISCUSSION OF RESULTS.....	4.5
Climate Sensitivity.....	4.5
Persistence Over Time.....	4.9
REFERENCES.....	4.17
5.0 CASE STUDY-SITE SELECTION.....	5.1
METHODS FOR CHARACTERIZING THE IMPACTS OF CLIMATE CHANGE ON WATER RESOURCE SYSTEMS.....	5.1
The Speculative Approach.....	5.2
The Empirical Approach.....	5.3
The Systems-Based Approach.....	5.9

RESEARCH STRATEGY.....	5.15
Choice of Method.....	5.15
Choice of the Number of Sites.....	5.18
SITE SELECTION.....	5.19
Site Selection Criteria.....	5.19
Selection of National Scope.....	5.21
Selection of Alternative Regions.....	5.21
Selection of Target Region.....	5.28
River Basin Selection.....	5.32
TRANSFERABILITY OF CASE STUDY FINDINGS.....	5.35
Flooding.....	5.36
Drought.....	5.37
Inadequate Storage/Supply.....	5.37
Groundwater Mining.....	5.37
Sedimentation of Rivers.....	5.38
Conflicts in Use.....	5.39
Salinity Problems.....	5.39
Water Losses From Storage Systems.....	5.40
Aquatic Vegetation.....	5.40
REFERENCES.....	5.41
APPENDIX A - "SPECIFIC" WORLD WATER SUPPLY/ALLOCATION IMPACT MATRIX.....	A.1
APPENDIX A - DEFINITIONS OF WATER RESOURCE ISSUES GENERATED IN TASK 1.....	B.1
APPENDIX C - SPECIFIC ISSUE PROFILE FORM.....	C.1
APPENDIX D - SPECIFIC ISSUE SUMMARIES.....	D.1

FIGURES

3.1	Flow Diagram of the Hydrologic System.....	3.13
5.1	Impacts of Changes in Precipitation and Evapotranspiration (ETP) on Runoff for the Peace River at Vernon, Texas (Source: Nemec and Shaake 1982).....	5.11
5.2	Impacts of Changes in Precipitation and Evapotranspiration (ETP) on Runoff for the Leaf River near Collins, Mississippi. (Source: Nemec and Shaake 1982).....	5.12
5.3	Flow Diagram for Research Phases of Site Specific Case Study.....	5.17
5.4	Location of Selected Water Resource Regions in the Western United States.....	5.22
5.5	Distribution of Climate Types in the United States in (a) the Wet Year (1915) and (b) the Drought Year (1934).....	5.24

TABLES

3.1	Specific Water Resource Issues and Categories.....	3.4
3.2	Sensitivity of Hydrologic System to Climate Change/Variation.....	3.16
3.3	Sensitivity of Specific Issues to Hydrologic Processes.....	3.20
4.1	Criteria Rankings for Specific Water Resource Issues.....	4.3
4.2	Potential Effects of CO ₂ -Induced Climate Change on Specific Water Resource Issues According to Decision Rule.....	4.6
4.3	Potential Effects from CO ₂ -Induced Climate Change on Specific Water Resource Issues.....	4.7
4.4A	Climate Sensitivity of Generic Issues to Changes in Climate Parameters - Precipitation.....	4.11
4.4B	Climate Sensitivity of Generic Issues to Changes in Climate Parameters - Temperature.....	4.13
5.1	Summary of Approaches for Characterizing the Potential Effects of Climate Change on Individual Generic Issues by Level of Analysis.....	5.16
5.2	Selected Climate Types Based on the Thornthwaite Moisture Index (I _m).....	5.23
5.3	Distribution of Generic Issues by Climate Type.....	5.26
5.4	Distribution of Generic CO ₂ -Water Resource Issues in Selected Water Resource Regions.....	5.29

1.0 INTRODUCTION

This research was performed by the Pacific Northwest Laboratory (PNL) for the Division of Carbon Dioxide Research, U.S. Department of Energy (DOE). It was undertaken as a part of the CO₂ Indirect Effects Research Program to assist DOE in achieving the following two objectives:

- Identify, characterize and define the probable scope of the indirect effects, detrimental and beneficial, of increased atmospheric CO₂ on human health and welfare.
- Identify, characterize and define specific data and information requirements regarding climate (atmosphere and ocean) and vegetation effects to advance indirect effects research beyond the definition step.

CO₂ AND WATER RESOURCES

Atmospheric CO₂ has increased steadily over the last 150 or so years from about 280 parts per million by volume (ppmv) to a current level of about 340 ppmv. At this rate, the ambient concentration of CO₂ could reach 630 ppmv by 2030, depending on the rate of growth of fossil fuel consumption. Increases of atmospheric CO₂ of this magnitude can be expected to alter global mean temperatures through the so-called "greenhouse effect." Scientists estimate that a doubling of CO₂ could result in an average increase in global temperature on the order of 2° to 3°C. This potential increase is expected to be much greater at the poles, perhaps as much as 11°C, and far less at the equator, perhaps as little as 2°C. This fact is important because it is the polar/equatorial differential in temperature which plays a significant role in driving the world climate system. As a result, future weather patterns could be altered fairly dramatically by a twofold increase in atmospheric CO₂.

The effect of changes in the ambient concentration of CO₂ on the world climate system is not well understood at this time. However, climate experiments conducted with numerical general circulation models have shown that increases in atmospheric CO₂ could lead to changes in the magnitude and

seasonal variation of temperature, precipitation, soil moisture, and snow mass (Manabe and Wetherald 1980; Washington et al. 1980; Washington and Meehl 1982).

These meteorological phenomena play an important role in determining the availability and timing of both surface and subsurface supplies of freshwater through the action of the hydrologic cycle. Thus, changes in the ambient concentration of CO₂ can be expected to exert some influence on the amount of freshwater that will be available in the future to satisfy a wide variety of societal needs. In addition, many different types of demands for freshwater are sensitive to changes in climate. This is particularly true of changes in temperature which can directly affect the amount of water needed for drinking and sanitation purposes, growing crops, generating electricity and for satisfying a wide variety of recreational uses. Thus, the ultimate impacts of CO₂-induced climate change on water resources, whatever they may be, will depend on the interaction between man and his environment, and not just on the effects of changes in climate on natural hydrologic systems.

OBJECTIVES AND SCOPE OF PNL RESEARCH

Consistent with both the importance of adequate supplies of freshwater for the future health and welfare of mankind and the potential sensitivity of natural and manmade water resource systems for CO₂ buildup, DOE has identified water resources as one of the four broad issue areas to be investigated under the CO₂ Indirect Effects Research Program. The objectives of the research which PNL is conducting for DOE in this area are as follows:

- Identify, characterize, and define existing or projected regional and global water resource management issues which may be affected by CO₂-induced climate changes.
- Develop research priorities for acquiring additional information about the potential effects of a CO₂-induced climate change on the availability and allocation of freshwater supplies.

In order to achieve these objectives PNL has broken down its research along the following task lines:

Task 1. Development of "Specific" World Water Supply/Allocation Matrix

This task will consist of providing DOE with a comprehensive list of water supply/demand management issues on a worldwide basis. Issues will be further identified with respect to the time frame in which they are expected to become critical (if they are not already so). The nature of the issue and its timing will be related to changes in the magnitude and timing of temperature and precipitation by type. With this information, hypotheses will be developed to show how CO₂-induced changes in these parameters could affect each issue and its timing.

Task 2. Development of "Generic" CO₂-Water Supply Issues

Criteria will be developed to screen the issues generated in Task 1 in order to identify those issues which have the highest probability of being impacted by a CO₂-induced climate change. These criteria will be used to relate the generic impacts associated with each kind of climate change to the type of impacts that might actually occur within specific climate zones. Criteria will then be developed and used to select specific regions/sites for detailed analyses.

Task 3. Region/Site Specific Analyses

Detailed analysis of several regions/sites will be done in a qualitative and quantitative manner to illustrate the potential impacts from CO₂-induced climate changes. Issues which need research to lessen the critical uncertainties will be outlined and prioritized. Data/information requirements from direct effects program elements will be defined.

SCOPE AND ORGANIZATION OF THIS REPORT

This report summarizes the research results of Tasks 1 and 2, as previously outlined. The report is organized into five sections. The Introduction in this section is followed by Section 2.0 which contains the major conclusions and recommendations of this research. Section 3.0 outlines the research steps followed in constructing the Task 1 World Water Supply/Allocation Matrix, explains how to read the matrix, and discusses the major

problems encountered in developing this matrix. Section 4.0 outlines the procedures used to identify those water resource issues which appear most likely to be affected by an increase in the ambient concentration of CO₂ (e.g., the generic issues), and discusses the results obtained from this research. Section 5.0 focuses on the case study selection process. It also identifies the criteria used to select specific sites for further research and provides a general statement of the research objectives and methods that will be pursued in connection with these case studies. The Task 1 matrix is presented in Appendix A. Appendix B contains a brief set of definitions for the water resource issues identified in Appendix A. This is followed by Appendix C which presents a copy of the standard form used to gather information about specific water resource issues. Finally, Appendix D contains a set of short, summary statements about each of the 26 specific issues highlighted in Appendix A.

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- Washington, W. M. et al. 1980. "A General Circulation Experiment with a Coupled Atmosphere, Ocean and Sea Ice Model." Journal of Physical Oceanography, 10(4):1887-1908.
- Washington, W. M. and G. A. Meehl. 1982. General Circulation Model Experiments on the Climatic Effects Due to a Doubling and Quadrupling of Carbon Dioxide Concentration. NCAR/0306/81-2(E), National Center for Atmospheric Research, Boulder, Colorado.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations contained within this report are limited in scope. This is due, by and large, to the fact that the research performed to date has focused primarily on identifying water resource management issues believed to be directly relevant to CO₂ buildup and on selecting the appropriate methods and locations for conducting site-specific case studies. As such, major conclusions and recommendations regarding a) the potential effects of a CO₂-induced climate change on water resources, b) the additional research required to resolve the uncertainties surrounding these impacts, and c) the data required to do so cannot be advanced until the final, case study phase of this research has been completed.

CONCLUSIONS

The major conclusions contained in this report relate broadly to the following topics:

- Identification of generic issues,
- The choice of method for characterizing the potential impacts of a CO₂-induced climate change, and
- The selection of individual sites for in-depth analysis.

Identification of Generic Issues

This research suggests that virtually all of the major water resource management issues which impact directly on human health and welfare can be categorized under one or more of the twenty six issues which are shown in Table 3.1 in the text. Of these issues, nine of them appear to be most directly relevant to CO₂ buildup. Based largely on their climate sensitivity and persistence over time, the following issues appear to have the highest probability of being affected, beneficially or adversely, by a CO₂-induced climate change in the next 50 to 100 years:

- flooding
- drought

- inadequate surface water supply/storage
- groundwater mining
- river sedimentation
- salinity problems
- conflicts in use
- water losses from storage systems
- aquatic vegetation

Choice of Case Study Method

Based on the limited research conducted in the area of climatic change and water resources, three different approaches were identified as having the greatest promise for characterizing the effects of a CO₂-induced climate change on the magnitude of individual generic issues. These include:

- Speculative Approach - which involves identifying the relevant climate parameters to which generic water resource issues may be responsive and then speculating upon the effects that changes in these parameters will have upon the magnitude of the impacts associated with these issues.
- Empirical Approach - which consists of using existing climate and hydrologic records and, given sufficient variability in the former, determining the effects which analogous climate changes may have on the generic water resource issues, both on the basis of the short term response of these issues to historical climate fluctuations and on the basis of questioning water managers in the area.
- Systems-Based Approach - which involves projecting the magnitude and trend of relevant climate parameters, and using this information to drive hydrologic models to determine how these changes may affect snowmelt, runoff, infiltration and other hydrologic processes; then, on the basis of analyzing these data with area water managers, characterize the potential impacts which changes in the relevant hydrologic processes would have upon the generic water resource issues.

After reviewing each of these different approaches it was decided that the best role for the speculative approach lies in the area of formulating working hypotheses about the effects of changes in key climate parameters on the magnitude of individual, generic issues. However well suited this method may be in that role, it lacks the quantitative dimension necessary to actually test these hypotheses. Therefore, other methods must be used in the hypothesis testing phase of the case study research. Based on a review of the analytical potential of the other two approaches, it was concluded that there is no clear consensus among hydrologists regarding which approach is best suited for examining the impacts of climatic change and/or variation on the hydrologic system. In the absence of unanimity on this score, it was concluded that both approaches should be applied to a single site, in a comparative framework.

Site Selection

The site selection process used in this study involved the development of criteria that were used, on an iterative basis, to narrow the geographic scope of the search from the global down to the individual river basin level. Non-U.S. sites were eliminated based on three broad considerations:

- The U.S. is subject to substantial climate variability insofar as this phenomenon affects both the geographic distribution and severity of individual, generic issues;
- The U.S. experiences all of the generic issues that occur in other nations of the world, the only major differences being institutional and cultural in nature; and
- The relatively high quality and availability of U.S. water resources data, coupled with the substantially higher costs of conducting research on non-U.S. sites.

After narrowing down the scope of the search within the U.S. to four water resource planning regions in the Great Plains and the western U.S. and then to a single region, the lower Colorado River, the site selected for the comparative case study was the Salt River Basin in central Arizona. This site was selected based on the following general conclusions:

- It is subject to extensive climate variability;
- It experiences all of the generic issues with a moderate to high degree of severity;
- Snowmelt is an important source of runoff;
- The drainage area of the salt is characterized by substantial climatic and physical variety;
- The major sources of runoff in the basin are small watersheds;
- The placement of manmade controls along the Salt is such that man's operation of the system does not obscure the effect of climate on the hydrologic system; and
- The availability of data from the Salt River Project and the water management expertise lodged within this institution.

RECOMMENDATIONS

Because of the particular scope of this research, the only recommendations that are warranted regard the methods to be used and the sites to be studied in the case study analysis phase of this research. Based on the conclusions contained in the first portion of this section, the following two recommendations are advanced:

- The empirical and systems-based approaches should be used in a comparative framework to try to characterize the effects of a CO₂-induced climate on the magnitude of individual generic issues at a single site
- This research should be performed using the Salt River Basin, including the drainage areas of the Salt and Verde Rivers, as the selected site.

3.0 IDENTIFICATION OF SPECIFIC ISSUES

A major premise that underlies this research is that CO₂ buildup is unlikely to create any entirely new water resource issues. Instead, we assume that the general impacts of CO₂ on the world water resources situation will be reflected either by changes in the magnitude of current issues where they now exist and/or by some geographic redistribution of these issues. In that general framework, the purpose of constructing the "Specific" World Water Supply/Allocation Matrix displayed in Appendix A is twofold, namely: to identify and locate the most important water resource issues currently facing mankind and to collect enough information about these issues to develop hypotheses regarding how they may be influenced by CO₂ buildup in the future.

RESEARCH STEPS

The development of the preliminary "Specific" World Water Supply/Allocation Matrix was undertaken in four steps. The first step involved identifying the relevant types of sources that could be searched to locate as many different specific water resources issues as possible. For efficiency, an initial decision was made to focus the brunt of the collection effort on published planning documents prepared by public and private organizations that have historically been involved in water resources research, planning and development, either in the U.S. or on an international basis. This information was then supplemented by published periodical literature, monographs and other types of sources uncovered through a subsequent literature search and through contacts with knowledgeable water resources experts.

The second phase of the research consisted of identifying and acquiring the relevant literature available from the types of sources pinpointed in the previous phase of the research. This was accomplished through computer-aided searches (by organization and issue) of water resources information files, telephone contacts with water resources experts, offsite meetings by PNL staff members with representatives of various water resources organizations in Washington, D.C. and New York City, and library searches conducted at the University of Washington and the United Nations Headquarters in New York City.

The third step of the research involved distilling the information gathered in the previous phase of the research into a format that would (a) facilitate grouping the specific water resource issues located in the literature into a series of more general categories and (b) provide some systematic basis for developing criteria to screen these issues in order to identify those which have the highest probability of being impacted by a CO₂-induced climate change in 50 to 100 years from now. This was accomplished through the use of a standard form which was filled out for each issue identified in the literature. In addition to identifying the issue and its geographic location, this form contained questions relating broadly to the cause of the issue and its current magnitude, the projected trend of the problem and the time frame in which it was expected to become serious, the sensitivity of the issue to changes in precipitation and temperature, and the institutional responsibility for managing this issue. A copy of this form is contained in Appendix C.

The final step of the research involved constructing the "specific" world water supply/allocation impact matrix from the information collected about specific water resources issues. Subsequently, this information was synthesized into a set of issue summaries designed to give the reader a better general grasp of each of the 26 issues that appear in Appendix A. These summaries are contained in Appendix D.

The next section of this report outlines the organization of this matrix; defines the row and column headings; and provides examples to assist the reader in understanding its content.

DESCRIPTION OF THE "SPECIFIC" WORLD WATER SUPPLY/ALLOCATION MATRIX

The specific issues shown in the "Specific" World Water Supply/Allocation Matrix (hereafter referred to as the matrix) are grouped under three, generally recognized categories. These categories include:

- supply
- distribution
- use and reuse.

The supply category is further broken down into issues related to surface water and groundwater, respectively. The remaining two categories are separated into issues related to either water quantity or quality.

A complete listing of the water resources issues identified in the course of this research is shown by category and subcategory in Table 3.1. Definitions for each of the specific issues shown in Table 3.1 are contained at the end of this report in Appendix B.

The water resource issues appearing in the matrix are classified according to the component of the water resource system (e.g., supply, distribution, use and reuse) that is impacted most directly by each specific issue. Thus, while groundwater mining might be viewed as an issue related to water use, it is more directly related to the availability of groundwater. As such, it is classified as a groundwater supply issue in Table 3.1. It is also important to note that some issues may fall under more than one category. For example, eutrophication directly affects both water availability and water supply; however, it is shown in the matrix as a supply issue. In cases such as this one, the issue appears only in a single category.

HOW TO READ THE MATRIX

The first column, at the far left of the matrix, identifies specific issues (i.e., groundwater mining, eutrophication, etc.) according to the water resource category in which it falls. At least three locational references are provided for each specific issue. Where possible, an effort was made to select locational references based on the relative severity of the water resource issue in question. However, in many cases, the data necessary to arrive at consistent rankings regarding the relative magnitude of an issue at different locations could not be identified. When this problem was encountered, locational references were selected to illustrate the geographic distribution of the issue where it currently occurs with severity.

Each locational reference contains information on five issue descriptors which are identified by the following column headings, reading from left to right:

TABLE 3.1. Specific Water Resource Issues and Categories

<u>SUPPLY ISSUES</u>	
<u>Surface Water</u>	<u>Groundwater</u>
<ol style="list-style-type: none"> 1. Flooding 2. Drought 3. Reservoir Sedimentation 4. Aquatic Vegetation 5. Water Losses from Storage Systems 6. Eutrophication 7. Effects of Land-Use Changes on Basin Hydrology 8. Inadequate Storage/Supply 	<ol style="list-style-type: none"> 1. Groundwater Mining (Groundwater Overdraft)
<u>DISTRIBUTION ISSUES</u>	
<u>Quantity</u>	<u>Quality</u>
<ol style="list-style-type: none"> 1. River Sedimentation 2. Conveyance Losses 3. Availability of Potable Water 	<ol style="list-style-type: none"> 1. Channel Scour/Channel Erosion
<u>USE AND REUSE ISSUES</u>	
<u>Quantity</u>	<u>Quality</u>
<ol style="list-style-type: none"> 1. Inefficient Irrigation Practices/Management 2. Waterlogging (of Soils) 3. Groundwater Infiltration of Municipal Sewer Systems 4. Effect of Changing Water Levels on Aquatic Ecosystems 5. Navigation Problems 6. Conflicts in Use <ol style="list-style-type: none"> (a) between instream uses (b) between offstream uses (c) between instream and off-stream uses 	<ol style="list-style-type: none"> 1. Saline Intrusion of Aquifers 2. Salinity Problems 3. Waterborne Diseases 4. Groundwater Contamination 5. Surface Water Contamination 6. Acidification of Lakes 7. Inadequate Water Treatment Facilities

- current magnitude of the issue
- issue trend
- nonclimatic determinants
- sensitivity of the issue to increases in precipitation and temperature
- institutional responsibility.

A brief explanation of each of these column headings is provided below. Discussion of the problems associated with applying these descriptors to each of the locational references in Appendix A will be deferred, for the moment, to a later portion of this section.

CURRENT MAGNITUDE OF THE ISSUE

This column provides a quantitative assessment and, where possible, a projection of the magnitude of the issue and its associated impacts for the corresponding locational reference. If quantitative information was inaccessible or did not exist, the current magnitude of the issue was described qualitatively using available information.

Issue Trend

This column indicates whether the issue is increasing or decreasing in severity. This assessment is based on current or expected changes in those factors which are generally recognized as having an influence on the magnitude of the issue. The assessment does not take into account the possible effects which projected CO₂-induced climatic changes may have upon the magnitude of the issue. Thus, for the example of drought in Australia, while there has been no observed change in the climatic conditions that produce droughts on that continent, nonstructural measures are being implemented which are expected to reduce the adverse impacts of droughts. Consequently, the severity of the issue is viewed as decreasing.

Nonclimatic Determinants

This column identifies those nonclimatic factors which are generally regarded as the major determinants influencing the magnitude of a specific

water resource issue where it currently occurs. In most cases, the information contained in this column provides a basis for determining the issue trend in the previous column. Thus, for the case of droughts in Australia, the decrease in the severity of the impacts caused by this phenomenon can be explained in terms of the institution of a "drought watch" information service, the issuance of drought bonds for insurance purposes, and improved farm management practices.

Sensitivity of Issue to Increases in Precipitation and Temperature

This column is intended to provide a rough estimate of the directional influence which an increase in average annual precipitation (holding temperature constant) or temperature (holding precipitation constant) will have upon the magnitude of a specific water resource issue.

In most cases, the indication of the sensitivity of a specific issue to changes in temperature and precipitation was based on the conservation of mass principle. According to this principle, the rate of inflow to a river basin in the form of precipitation minus the rate of outflow in the form of evapotranspiration, consumptive uses of water by man and animals, and basin discharge is equal to the rate of change of storage of water in the contiguous stream, soil and groundwater systems. The relationship between precipitation, evapotranspiration and runoff is known as the annual water balance. Given a basic understanding of this principle, the general relationships between temperature and potential evapotranspiration and between precipitation and runoff, and a basic knowledge of how these changes can affect different consumptive uses of water by man, it was possible to draw some very general conclusions about the climate sensitivity of many of the specific issues.

The notation used to indicate the direction of the response is as follows:

- $I_p \uparrow$ or $I_t \uparrow$ indicates that an increase in average annual precipitation or temperature, respectively, exacerbates the problem, and consequently the magnitude and impacts of the issue may increase.

- I_p+ or I_t+ indicates that an increase in average annual precipitation or temperature acts as a mitigating factor, and consequently the magnitude and impacts of the issue may decrease.
- I_p0 or I_t0 indicates that there is no immediate, significant effect associated with an increase in average annual temperature or precipitation.
- $I_p\updownarrow$ or $I_t\updownarrow$ indicates that the issue may be sensitive to an increase in these climatic parameters, but that more than one effect is possible and thus the net outcome is uncertain.

The approach used to determine the climate sensitivity of specific issues is limited insofar as it considers only the impact of changes in average annual precipitation or temperature on the severity of these issues. A more complete discussion of the water balance approach and the problems associated with viewing climatic change from the perspective of changes in average annual precipitation and temperature is contained in the discussion of the Task 1 matrix at the end of this section.

Institutional Responsibility

This column identifies the relevant governmental agency responsible for addressing the issue and its impacts. Since water resources management and planning often cuts across institutional lines, it was not always possible to list all of the agencies involved in a given issue. In some cases, there is more than one specific agency within a particular department or ministry that is responsible for a specific issue, and only the relevant department or ministry is listed.

EXAMPLES

The following two examples are presented to show how to read the Task 1 matrix contained in Appendix A.

Upper Mississippi Floods (Page A.1)

The first issue appearing in the matrix is floods. The top of page A.1 indicates that all issues appearing on that page are problems of water supply, and the top of the left-hand column identifies them as surface water issues.

The first locational example for floods is the Upper Mississippi Region, listed as 1.a. Column two, labeled "Current Magnitude of Issue," indicates the nature of the regional flood problem: current average annual damages (\$235 million/yr). The next column--"Issue Trend"--indicates that although there is no observed change in the underlying frequency distribution of flood events, damages from floods are increasing.

A look at column four shows that although the trend is toward increasing damages due primarily to inflation, such factors as regulation of flood plain development and the implementation of structural controls may act to lessen the extent of the increase in damages by the year 2000. Thus, although the impacts are increasing, there are several nonclimatic determinants of the rate of increase.

The next column indicates the sensitivity of the regional flood problem to changes in temperature and precipitation. It is fairly clear that increased precipitation concentrated in the spring and early summer will increase runoff, streamflows, and the potential for floods, and this is represented by $I_p \uparrow$. However, the timing and duration of precipitation events are critical in determining the occurrence and magnitude of floods. The effect of increased temperature on floods is less clear. Warmer winters might reduce the amount of moisture stored in the form of ice and snow, which would then result in reduced flows generated by spring snowmelt. Conversely, if snow and ice do hold significant amounts of moisture, a rapid spring warming could aggravate flood problems. Thus, $I_t \updownarrow$ indicates that more than one effect could occur, and the net direction of the outcome is uncertain. However, it is evident that the flood problem is sensitive to changes in temperature.

Finally, the last column, labeled "Institutional Responsibility," identifies the U.S. Army Corps of Engineers and the Soil Conservation Service of the U.S. Department of Agriculture as having primary responsibility for the regional flood problem.

Conveyance Losses in Australia (Page A.15)

The top of page A.15 indicates that it contains water distribution issues, and the top of the left-hand column further identifies the issues on this page as water quantity issues.

The problem of water losses from conveyance systems in Australia appears on this page as number 2.b. The current magnitude of the issue is given in column two as a loss of 41.4% of the water entering conveyance systems. This is attributed to seepage and operational inefficiencies.

Column three indicates that the magnitude of the issue and impacts is increasing. Column four identifies several factors, including growth in irrigated agriculture and population, which are expected to amplify the impacts of water loss and result in action to reduce conveyance losses.

In column five, $I_p \uparrow$ indicates that increased precipitation would reduce the magnitude of the impacts by increasing water availability and thus decreasing the relative importance of the amount of water lost through conveyance. $I_t \uparrow$ shows that warmer temperatures may, through evaporation, decrease available supplies, thereby magnifying the impact of any water losses, including those from conveyance systems. Finally, the Australian Department of Natural Resources is identified in the last column as the responsible government agency.

DISCUSSION OF RESULTS

As mentioned earlier, the specific water resources issues matrix shown in Appendix A was the product of a fairly extensive information search focused upon the most readily available kinds of sources which, it was believed, would yield the greatest amount of information over a relatively short period of time. While the selective nature of this information search can certainly be faulted, it should be kept in mind that the objective of this task was not to compile a definitive list of all the world's water resources problems, but rather to collect enough information about these problems to characterize the possible scope of the indirect impacts of CO₂-induced climate on these issues.

Problems encountered in conducting this initial characterization were related to:

- locating the issues;
- describing the current magnitudes of the issues;
- determining the future trends of the issues;
- assessing the climate sensitivity of the issues; and
- identifying the agencies responsible for managing the issues.

Location of Specific Issues

An important aspect of characterizing the potential impacts of CO₂ buildup on the world water resources situation involves determining the expected geographic scope of these impacts. While the current geographic distribution of a water resources issue may well differ from its distribution in the future (irrespective of CO₂ buildup), an indication of how widespread an issue is in current terms provides a starting point for the examination of changes which may occur in the future.

Defining the location of specific problems proved to be a problem for at least two reasons. First, the selective nature of the information search conducted in the preliminary phase of Task 1 yielded literature that was not representative of the world. For example, the search did not produce a great deal of information about water resources problems in Europe, while India and Egypt - which admittedly experience a number of severe problems - were perhaps over-represented in the literature uncovered. Second, some of the issues identified in Appendix A which were found to exist in a number of nations are locally isolated phenomena. For example, saltwater intrusion of aquifers, which is a problem in many regions of the world, occurs only in coastal areas with specific geologic features. Where problems like this were discussed in the literature, the references often tended to be general rather than specific.

Current Magnitude of Issues

Perhaps the most difficult information to obtain about water resources issues from the sources reviewed for Task 1 was an indication of the magnitude of specific issues. There are a couple of reasons for this. First of all, water resources planning documents are, in most cases, summary statements of much more detailed research about specific issues. Very often, the results

of the background research relating to the magnitude of specific issues are presented in very general, qualitative terms - a concession made in view of the audience for which these documents are intended. A second problem is that, in severe cases, it is very difficult to determine the magnitude of a specific issue, for example: the amount of water lost due to seepage in irrigation canals; the value of agricultural income lost due to inefficient application of water, poor management of irrigation systems, and the "stealing" of water; or the number of lives lost due to unsanitary drinking water. Many of the world's water resources problems can only be measured in terms of these kinds of "opportunity costs" which are difficult to obtain except through detailed site-specific research. In many instances, this type of detailed information was not available for specific sites. Somewhat more information about the magnitude of specific issues was available on a national level, and where possible these figures are included in the specific issues summaries in Appendix D. However, these estimates are often very rough and, even though they represent the best data currently available on the magnitude of many specific issues, they should still be viewed with some caution.

Future Trends

How will the current magnitude of an issue change over time in the absence of a CO₂-induced climate change? In some cases, this question is fairly simple to answer. For example, in the United States, it is unlikely that flooding will become a more serious issue (as long as climate is stable) because: (a) most of the major control projects in the U.S. that can be justified on economic grounds have already been constructed or are nearing completion and (b) flood plain development is regulated by Federal and state laws and by local zoning ordinances. However, the same thing cannot be said about flooding problems in those nations of the world where: (a) extensive deforestation, urbanization and other anthropogenic impacts are changing the runoff characteristics of watersheds and (b) human settlement and economic activity continue to encroach upon floodplains susceptible to severe and moderate flooding. The point of the above comparison is that predicting the future trend in the magnitude of current issues in many cases must also involve predicting the long term behavior of man and his impact on the environment.

A second problem associated with predicting the future magnitude of many of the specific issues involves the rate at which non-institutional, technological solutions will be developed and adapted for the solution of certain issues. In many cases, there currently exist a number of water resource issues which have technical solutions. Relevant examples include the control of aquatic vegetation, methods for reducing evaporation from lakes and reservoirs and structural methods for controlling saltwater intrusion in coastal aquifers. The relatively low adoption rates associated with these, and many other, technological solutions for existing water resource problems can be explained by the fact that they are too costly to implement. In time, some water resource problems may become so severe that it will become economically feasible to solve them using existing technology. In that case, the magnitude of the adverse impacts associated with an issue would stabilize. Alternatively, and in some cases coincidentally, technological breakthroughs may occur which will substantially reduce the costs of solving some water resource problems, in which case these problems might even become less serious in the future than they are today. Unfortunately both of these kinds of changes are extremely difficult to predict and the best we can do is acknowledge the difficulty they present in trying to determine the future trend of specific issues.

Climate Sensitivity

To understand how specific water resource issues may be sensitive to climate change, it will prove useful to review the basic workings of the hydrologic system. Figure 3.1 is a flow diagram of the hydrologic system. Precipitation enters the system from clouds. A portion of this precipitation is intercepted by trees, plants and manmade structures from which it is evaporated. The remainder reaches the soil surface either as rainfall or snow. Rainfall then takes one of three paths: either it can be stored in depressions on the land surface (where it is subject to evaporation); it can be carried to streams in the form of surface runoff; or it can infiltrate the soil in some cases as seepage from lakes and reservoirs. Snowfall, on the other hand, is usually stored for some period of time. The portion of snowpack that does not evaporate (or remain in storage permanently) eventually melts and

SOURCE: HUBER et al., 1976

FIGURE 3.1. Flow Diagram of the Hydrologic System

follows the same paths as does rainfall, albeit with time lags. Water that is retained as surface storage or soil moisture can be depleted by evaporation into the atmosphere or transpiration by plants. The remaining soil moisture either flows to streams as subsurface runoff (sometimes known as interflow) or else it percolates into groundwater storage. In many watersheds, the groundwater and stream channel storage systems are joined through an interface whereby they draw upon each other's reserves depending on seasonal streamflow conditions. Finally, Figure 3.1 shows that both storage systems are subject to losses through consumptive use by man and/or evapotranspiration, as well as to inflows and outflows.

The hydrologic system, as shown above, is a dynamic system consisting of three basic components: the media acted upon (water in its various physical states), a set of constraints applied by the physical nature of the watershed, and the driving forces supplied by direct solar energy, gravity, and capillary potential fields (Huber et al. 1976). The component processes of the hydrologic system are interrelated by the continuity of mass. The continuity of mass in this case can be described by the following equation of hydrologic equilibrium (Todd 1964):

$$\begin{array}{l}
 \text{Surface inflow} \\
 + \\
 \text{Subsurface inflow} \\
 + \\
 \text{Precipitation} \\
 + \\
 \text{Decrease in surface storage} \\
 + \\
 \text{Decrease in soil storage} \\
 + \\
 \text{Decrease in groundwater storage}
 \end{array}
 =
 \begin{array}{l}
 \text{Surface outflow} \\
 + \\
 \text{Subsurface outflow} \\
 + \\
 \text{Consumptive use} \\
 + \\
 \text{Evapotranspiration} \\
 + \\
 \text{Increase in surface storage} \\
 + \\
 \text{Increase in soil storage} \\
 + \\
 \text{Increase in groundwater storage}
 \end{array}$$

The hydrologic balance is essentially an accounting system which can be used to predict the movement of water within a system at specific points in time and space. However, the hydrologic balance, by itself, is insufficient even as a purely conceptual tool for characterizing the effects of climate change on specific water resources issues. To do this, at any level of

abstraction, requires that we understand, first of all, how the component processes of the hydrologic system respond to changes in climate parameters and, secondly, how changes in hydrologic process can affect the magnitude of individual issues.

The hydrologic processes shown in Figure 3.1 can be distinguished on the basis of whether they are directly or indirectly sensitive to climate change or climate variability. Since the relationships embedded in the hydrologic system are characterized by a substantial degree of recursivity and in some uses simultaneity, most (if not all) hydrologic processes that are not directly affected by climate variability and/or change are indirectly influenced by those which are. For example, deep percolation is not directly climate sensitive, but from an accounting standpoint the amount of water available for percolation is affected by both surface runoff and evapotranspiration, which are both highly climate sensitive. We concentrate, therefore, on those processes which are directly sensitive to climate.

Table 3.2 shows the effects of different climatic factors on the five most directly climate sensitive, hydrologic process namely: surface runoff, evaporation, transpiration, infiltration and snowmelt. Because the relationships which define the primary moisture and energy couplings between the atmosphere and the land are extremely complex, a change in a single atmospheric state variable may directly and indirectly influence a number of other atmospheric and hydrologic state variables. The effects described in Table 3.2 do not, in many cases, reflect this fact. Nevertheless, they do illustrate the fact that, even at a fairly simple level of analysis, it is extremely difficult to make a priori statements about the sensitivity of individual water resource issues to climate change. A second lesson to be drawn from this compilation is that, in most cases, it is extremely difficult to assess the sensitivity of these processes to climate using information about average annual changes in temperature and precipitation. This is a fairly obvious point to a trained hydrologist who understands the complexity of the interface between climate and the hydrologic system. However, this point needs to be stressed in view of the fact that much of the information currently being provided by General Circulation Models (GCMs) of the global climate system is not adequate for taking into account many of the effects shown in Table 3.2. Thus, an important question that will have to be addressed in future research is how much and at what

TABLE 3.2. Sensitivity of Hydrologic System to Climate Change/Variation

<u>Process</u>	<u>Climate Sensitivity</u>
Surface Runoff	<u>Precipitation</u>
	Type - runoff response to rainfall is immediate; runoff response to snowfall occurs with time lags.
	Intensity - surface runoff increases with rainfall intensity once infiltration capacity of soil is reached.
	Duration - after initial, critical period runoff increases with duration of rainfall.
	Distribution - runoff increases with the spatial variation of rainfall in a watershed.
	Orientation of Storm Movement to Direction of Streamflow - peak flows downstream increase when direction of storm movement coincides with direction of streamflow.
	Timing of Events - surface runoff increases with soil moisture content prior to individual precipitation events.
Evaporation	<u>Temperature</u>
	Frost - runoff is greater from frozen soils due to low infiltration capacity of soil when the ground is frozen.
	<u>Temperature</u>
	Magnitude - evaporation is proportional to vapor pressure <u>difference</u> between air and water.
	Seasonal Variation - time lags in the response of water surface temperature to seasonal variation in air temperature affects the timing of evaporation losses in lakes.
	<u>Wind</u>
	Velocity - higher velocities will increase evaporation up to a point.

TABLE 3.2. (contd)

Process	Climate Sensitivity
Evaporation (contd)	<p>Temperature - higher temperature increases energy for evaporation; cool winds may cause condensation.</p> <p><u>Sunlight</u></p> <p>Cloud cover - increased cloud cover reduces incoming solar radiation which is the primary energy source for evaporation.</p> <p>Seasonality - insolation, and thus evaporation is highest in summer months.</p>
Transpiration	<p><u>Temperature</u></p> <p>Magnitude - Since leaf temperature in sunlight is greater than air temperature, transpiration increases with temperature.</p> <p><u>Sunlight</u></p> <p>Cloud Cover - increased cloud cover reduces incoming solar radiation required for transpiration.</p> <p>Seasonality - insolation and, thus, transpiration is highest in summer months.</p> <p><u>Wind</u></p> <p>Velocity - gentle winds remove water molecules from leaf surface while higher velocities can reduce transpiration.</p> <p><u>Precipitation</u></p> <p>Type and Intensity - intense rains or hail may injure leaf surfaces causing reduced transpiration.</p> <p>Effect on Soil Moisture - when soil moisture is limiting wilting occurs and transpiration declines sharply.</p>

TABLE 3.2. (contd)

Process	Climate Sensitivity
Infiltration	<u>Precipitation</u>
	Effect on Soil Moisture - if antecedent soil moisture is low prior to rainfall, infiltration is higher.
	Intensity - soil compaction occurs more rapidly as intensity increases, reducing infiltration capacity of soil.
	<u>Temperature</u>
Snowmelt	Timing - infiltration capacity is lowest in colder seasons due to higher viscosity.
	Freezing - freezing of soil moisture reduces infiltration capacity of soil.
	<u>Sunlight</u>
	Cloud Cover - reduces incoming solar radiation required for snowmelt, but also holds in terrestrial radiation, causing warmer temperatures.
	<u>Temperature</u>
	Magnitude - increased temperature causes more rapid melting; snowline may rise, as well.
	Timing - antecedent soil temperature prior to snowfall and accumulation of snowpack affect melting due to heat conduction from soil.
	<u>Precipitation</u>
	Temperature - snowmelt increases with temperature of rainfall.
	Duration and Intensity - holding amount constant, long duration rainfall events have a greater impact on snowmelt than short duration events, up to a point.

level of temporal and spatial detail must information about a CO₂-induced climate change be provided to adequately assess the impacts on specific water resource issues? This question will be addressed in somewhat more detail in Section 5.0.

Assessing the sensitivity of specific water resource issues to changes in average annual temperature and precipitation, despite its limitations, can nevertheless be defended as a primary screening tool for comparing a fairly large number of specific issues and eventually screening them to a manageable subset of generic issues at a later stage of the analysis. However, examining the sensitivity of individual hydrologic processes to climate represents only the first step in determining how the magnitude of specific issues will be affected by a CO₂-induced climate change. In order to complete such an assessment it is also necessary to determine the sensitivity of individual issues to the component processes of the hydrologic system, particularly those processes that are most sensitive to climate.

Table 3.3 provides a very basic indication of the responsiveness of each of the specific issues to increases in the amount of water per unit of time carried through or out of the hydrologic system by those hydrologic processes to which each issue is most sensitive. (See Figure 3.1 and ensuing discussion on the hydrologic processes shown in Table 3.3.) Potential changes in the severity of each issue are indicated as either increasing (+), decreasing (-), or mixed (+/-), meaning that even when all other hydrologic processes are held constant it is not possible to determine the direction of the impact. If there is an NA (not applicable) entry associated with a hydrologic process this means that the relationship between the relevant issue and that process is either indirect or, if direct, of secondary importance.

Table 3.3 shows that there is a substantial amount of variability in both the nature of the relationship between individual hydrologic processes and specific water resource issues and between the number of hydrologic processes that directly affect individual issues. Some examples may help to illustrate this. The first issue is flooding. Other things being equal, increases in runoff and snowmelt (which is converted into runoff) will increase flood flows. Increases in evaporation and transpiration will have an opposite effect

TABLE 3.3. Sensitivity of Specific Issues to Hydrologic Processes

Issue							
	Runoff	Snow-melt	Evap-oration	Trans-piration	Infil-tration	Percolation	Stream-Groundwater Interface
Flooding	+	+	-	-	-	NA	NA
Drought	-	-	+	+	-	NA	NA
Reservoir Sedimentation	+	NA	-	-	NA	NA	NA
Aquatic Vegetation	-	NA	+	+	-	NA	NA
Water Losses from Storage Systems	-	NA	+	+	+	NA	NA
Eutrophication	+/-	NA	+	+	NA	NA	NA
Effects of Land-Use Changes on Basin Hydrology*	+	NA	+/-	-	-	-	-
3.20 Inadequate Storage/Supply	-	-	+	+	NA	NA	NA
Groundwater Mining	NA	NA	+	+	-	-	-
River Sedimentation	+	NA	-	-	NA	NA	NA
Conveyance Losses	NA	NA	+	+	+	+	NA
Availability of Potable Water	-	NA	+	NA	NA	NA	NA
Channel Scour/Channel Erosion	+	NA	NA	NA	NA	NA	NA
Inefficient Irrigation Practices/Management	-	NA	+	+	NA	NA	NA

TABLE 3.3. (contd)

Issue	Stream-Groundwater Interface						
	Runoff	Snow-melt	Evap-oration	Trans-piration	Infil-tration	Percolation	
Waterlogging (of soils)	NA	NA	+/-	+/-	+	+	NA
Groundwater Infiltration of Municipal Sewer Systems	NA	NA	NA	NA	NA	+	+
Effects of Changing Water Levels on Aquatic Ecosystems	-	NA	+	NA	NA	NA	NA
Navigation Problems	-	-	NA	NA	NA	NA	NA
Conflicts in Use	-	-	+	+	-	-	+
Saline Intrusion of Aquifers	NA	NA	NA	NA	NA	+	+
3.21 Salinity Problems	-	NA	+	NA	+/-	NA	+
Waterborne Diseases	+/-	NA	+/-	NA	NA	NA	NA
Groundwater Contamination	NA	NA	NA	NA	+	+	+
Surface Water Contamination	+/-	NA	+	NA	NA	NA	+
Acidification of Lakes	+	NA	NA	NA	NA	NA	NA
Inadequate Water Treatment Facilities	+/-	NA	NA	NA	NA	NA	NA

* Land use practices are not directly affected by climate; cell entries indicated processes directly affected by land use changes and direction of effect of land use changes on relevant processes.

since these processes remove water from the hydrologic system that might otherwise run off into streams. Finally, flood flows are affected by increases in the infiltration capacity of the soil, since only a portion of the precipitation that infiltrates the soil runs off into stream channels through interflow.

Waterlogging is an example of an issue whose sensitivity to individual hydrologic processes is more difficult to describe. Waterlogging occurs when the root zones of plants become saturated with water. Thus, as more water infiltrates the soil the danger of waterlogging increases. If the resultant soil moisture exceeds field capacity for a long period of time plant growth will be affected adversely. Waterlogging can also be caused by a rise in the level of a "perched" water table, hence an increase in the amount of water that percolates into a high water table increases the chances of waterlogging. The relationship between evapotranspiration and waterlogging is less clear-cut. Increases in evaporation mean that less water is available for soil moisture and percolation, while increases in the transpiration of water by plants will effectively increase the rate at which soil moisture is depleted. However, if soils and/or irrigation water are saline, then a rise in evaporation will increase the concentration of salts in the soil, and an increase in transpiration will require more intensive irrigation to meet plant water demands. Thus, more irrigation water will have to be applied to the soil to satisfy these demands and/or leach salts from the soils. This may cause a rise in the water table up toward the root zone and, in the presence of high salinity, lead to further reductions in plant growth.

By putting the information contained in Tables 3.2 and 3.3 together it was possible to advance some initial hypotheses about the climate sensitivity of the twenty-six specific issues to changes in average annual temperature and precipitation. In some cases, it was possible to speculate further about the impacts of changes in other parameters of the annual and seasonal distributions of temperature and precipitation. However, this was not done on a systematic basis because of the lack of detailed climate and hydrologic information about the regions in which specific, and fairly severe, problems currently are occurring and because of the extreme variety, variability and complexity of the

various physical, and institutional processes that affect, or are contained within, the hydrologic system in different watersheds and river basins.

Ultimately, of course, methods which can take into account the impact of a wider variety of climatic changes on the magnitude of specific water resources must be employed in order to assess the potential responsiveness of these issues to a CO₂-induced climate change. However the purpose of this research is not to provide definitive statements about the potential impacts of CO₂ buildup on regional water resources. Rather, it is to identify a set of water resource issues which, after preliminary screening, appear to have the greatest potential for being affected by a CO₂-induced climate change and to select specific sites for conducting case studies of these issues.

Water Resources Agencies

In general, planning documents do contain a great deal of information about the institutional responsibilities for specific water resources issues. However, because water resources management, development and planning has historically been the object of institutional proliferation in many nations of the world, it is often difficult to determine how multi-agency responsibilities relate to a simple problem in a specific location. The problem of defining the agency responsibility for specific water resources issues is further complicated in those countries where water resources management is either highly decentralized or else split between the private and public sectors.

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4.0 IDENTIFICATION OF GENERIC ISSUES

Given the twenty-six specific water resource issues identified in Table 1.1, it was necessary to ask the question: which of these issues appears to have the greatest likelihood of being adversely or beneficially affected by a CO₂-induced climate change over the next 50 to 100 years? A thorough review of the information collected on each of the issues revealed substantial differences along all of the dimensions that could be used to compare them (e.g. geographic distribution, climate sensitivity, magnitude, and projected trend) and, as such, did not provide very many obvious candidates for inclusion in a list of generic, CO₂-related water resource issues. Therefore, it was necessary to devise an efficient procedure for systematically answering the above question.

In that general framework, the purpose of this section of the report is to outline the procedures used to identify a subset of generic, CO₂-related water resource issues and, as a preliminary to the final section of this report, to outline some of the more basic issues associated with characterizing the impacts of a CO₂-induced climate change on the climate sensitivity and persistence of these generic issues.

RESEARCH STEPS

Identifying the generic CO₂-related water resource issues (hereafter referred to simply as generic issues) involved two separate steps, namely:

- Developing criteria to screen the 26 specific issues.
- Applying these criteria to select a subset of generic issues.

Development of Criteria

Four criteria were used to screen the initial list of specific issues. These criteria included:

- Climate Sensitivity - Is the magnitude of the issue sensitive to changes in temperature or precipitation (irrespective of the source of these changes)?

- Persistence Over Time - Does it appear that the problems that give rise to the issue can be eliminated or significantly reduced within the next 50 to 100 years or more?
- Pervasiveness Over Space - Does the issue currently exist in a number of countries around the world or does it have the potential to become widespread, due to CO₂ or other causes, in the next 50 to 100 or more years?
- Societal Impact - Does this issue have the potential to significantly impact the health and/or economic well-being of mankind in those areas where it occurs or could occur?

Application of Criteria

Given the criteria shown above, it was necessary to develop a method for systematically applying these criteria to the specific issues identified in the previous research phase. The preferred methods for selecting generic issues based on the above criteria involve the application of the, so called, "Nominal Group Technique" (Delbecq and Gustafson 1975) and Delphi Method (Linstone and Turoff 1975), both of which consist of structuring the group communication processes to arrive at a consensus about complex problems. However, both of these methods were rejected, after initial consideration, due to time and resource constraints connected with this research. The method finally chosen for screening the specific issues was selected in part because of its efficiency and because more complicated and costly methods, such as those described above, could not be justified in view of the limited objectives of this phase of the research.

The method involved two separate steps. First, each of the criteria was applied to an individual issue (i.e., flooding, drought, etc.) and then given a score of 1, 2, or 3 to indicate whether the criterion was highly relevant, moderately relevant, or relatively unimportant, respectively, in relation to the issue. The issues and the individual criterion scores given to each issue are shown below in Table 4.1.

TABLE 4.1. Criteria Rankings for Specific Water Resource Issues

Issue	Climate Sensitivity	Persistence (Time)	Pervasiveness (Space)	Societal Impact
Flooding	1	1	1	1
Drought	1	1	1	1
Inadequate Supply/ Storage	1	1	1	2
Groundwater Mining	1	1	1	2
River Sedimentation	1	1	1	2
Conflicts in Use	1	1	1	2
Salinity Problems	1	1	1	2
Aquatic Vegetation	1	1	2	2
Water Losses from Storage Systems	1	1	2	2
Waterlogging (of soils)	1	2	2	2
Saline Intrusion of Aquifers	2	1	1	2
Surface Water Con- tamination	2	1	1	2
Effects of Land-Use Changes on Basin Hydrology	2	1	1	2
Acidification of Lakes	1	2	2	2
Waterborne Diseases	2	2	2	1
Eutrophication	2	1	1	3
Inefficient Irrigation Practices/Management	2	2	2	2
Navigation Problems	2	2	2	2
Reservoir Sedimentation	1	2	2	3
Groundwater Contamination	3	1	2	2
Effect of Changing Water Levels	1	1	3	3
Conveyance Losses	3	2	1	2
Availability of Potable Water	3	2	2	1
Inadequate Water Treatment Facilities	3	2	2	1
Channel Scour/Channel Erosion	2	3	2	3
Groundwater Infiltration of Municipal Sewer Systems	3	2	2	3

Given the limited amount of information contained in Table 4.1 for selecting generic issues, it was decided to adopt a series of decision rules for determining the potential of each issue to be affected by a CO₂-induced climate change. All of the decision rules used in this step of the analysis involved classifying specific issues on the basis of a high, moderate, or low potential for being affected by a CO₂-induced climate change. The basis for arriving at this determination in each of the three decision rule applications is as follows:

Decision Rule 1

Issues were ranked according to the total score received from adding the row entries in Table 4.1. The range of total scores computed from this table lies between 4 and 10. Issues which received a score of 4 or 5 were placed in the high potential category; issues receiving scores of 6 or 7 were placed in the moderate potential category; and issues with a score of 8 or more were placed in the low potential category.

Decision Rule 2

Issues were ranked purely on the basis of their climate sensitivity and persistence over time. Issues which received a score of 1 on both climate sensitivity and persistence over time were considered to have a high potential for being affected by a CO₂-induced climate change. Issues which were given a score of 3 on either climate sensitivity or persistence over time were considered to have a low potential for being impacted by a CO₂-induced climate change. The remaining issues were then placed in a moderate potential category.

Decision Rule 3

The third set of decision rules was fairly close, conceptually, to the second set of decision rules in emphasizing climate sensitivity and persistence as important factors in determining the potential effect of a CO₂-induced climate change on each of the specific issues. However, more weight was attached, specifically, to low criteria rankings (i.e., 3) from Table 4.1 than in the other two sets of decision rules. An issue which received a score of 1 on both

climate sensitivity and persistence was assigned to the high potential category, provided that the issue did not receive a score of 3 on pervasiveness and societal impact. An issue which received a score of 3 on any of the four criteria shown in Table 4.1 was placed in the low potential category and the remaining issues were assigned to the medium potential category.

The results obtained by applying each of these three sets of decision rules to the specific water resource issues in Table 4.1 are shown in Table 4.2. In general, the three sets of decision rules generated fairly consistent results. Of the 26 specific issues to which the decision rules were applied there was complete agreement on 19 of them. In the 7 cases where there was some inconsistency in the classifications, the discrepancies were not large in the sense that 2 of the 3 sets of decision rules produced similar results. Accordingly, it was decided to resolve any differences in the classifications on the basis of "majority rule."

Table 4.3 shows the final classification of the potential effects of a CO₂-induced climate change on the original 26 specific water resource issues. For the purposes of this report and the research remaining to be conducted on the potential impacts of a CO₂-induced climate on global freshwater resources, those issues in the high potential category will be viewed as generic issues.

DISCUSSION OF RESULTS

The generic issues shown in Table 4.3 share in common two attributes: we hypothesize that they are highly climate sensitive and that they will be extremely persistent over time. The remainder of this section of the report addresses some of the conceptual issues related specifically to characterizing the impacts of a CO₂-induced climate change on the climate sensitivity and persistence of these generic issues.

Climate Sensitivity

One of the most basic problems that is likely to be encountered in characterizing and, later, actually assessing the impact of CO₂-induced climatic changes on the generic issues identified above is that the workings of the

TABLE 4.2. Potential Effects of CO₂-Induced Climate Change on Specific Water Resource Issues According to Decision Rule

Issue	Potential Effect of Climate Change		
	Rule 1	Rule 2	Rule 3
Flooding	High	High	High
Drought	High	High	High
Inadequate Storage/Supply	High	High	High
Groundwater Mining	High	High	High
River Sedimentation	High	High	High
Conflicts in Use	High	High	High
Salinity Problems	High	High	High
Aquatic Vegetation	Moderate	High	High
Water Losses From Storage Systems	Moderate	High	High
Waterlogging (of soils)	Moderate	Moderate	Moderate
Saline Intrusion of Aquifers	Moderate	Moderate	Moderate
Surface Water Contamination	Moderate	Moderate	Moderate
Effects of Land-Use Changes on Basin Hydrology	Moderate	Moderate	Moderate
Acidification of Lakes	Moderate	Moderate	Moderate
Waterborne Diseases	Moderate	Moderate	Moderate
Eutrophication	Moderate	Moderate	Low
Inefficient Irrigation Practices	Low	Moderate	Moderate
Navigation Problems	Low	Moderate	Moderate
Reservoir Sedimentation	Low	Moderate	Low
Groundwater Contamination	Low	Low	Low
Effect of Changing Water Levels	Low	High	Low
Conveyance Losses	Low	Low	Low
Availability of Potable Water	Low	Low	Low
Inadequate Water Treatment Facilities	Low	Low	Low
Groundwater Infiltration of Municipal Sewer Systems	Low	Low	Low
Channel Scour/Channel Erosion	Low	Low	Low

TABLE 4.3. Potential Effects from CO₂-Induced Climate Change on Specific Water Resource Issues

<u>Issue</u>	<u>Potential Effect from CO₂-Induced Climate Change</u>
Flooding	HIGH
Drought	
Inadequate Supply/Storage	
Groundwater Mining	
River Sedimentation	
Conflicts in Use	
Salinity Problems	
Water Losses from Storage Systems	MODERATE
Aquatic Vegetation	
Waterlogging of Soils	
Saline Intrusion of Aquifers	
Surface Water Contamination	
Effects of Land-Use Changes on Basin Hydrology	
Acidification of Lakes	
Waterborne Diseases	
Eutrophication	
Inefficient Irrigation Practices/ Management	
Navigation Problems	LOW
Reservoir Sedimentation	
Groundwater Contamination	
Effect of Changing Water Levels on Aquatic Ecosystems	
Conveyance Losses	
Availability of Potable Water	
Inadequate Water Treatment Facilities	
Channel Scour/Channel Erosion	
Groundwater Infiltration of Municipal Sewer Systems	

hydrologic system are governed directly by weather and not climate. For example, while it is certainly true that the amount of runoff reaching a stream in a particular watershed can be measured on an annual basis and then averaged over a period of historical record, the mechanisms that govern runoff directly and indirectly are affected by changes in precipitation and temperature that occur continuously, or in very small increments, over time. Given that this is true, not only of runoff, but of all of the processes that constitute the hydrologic system in a watershed, the question which we must then ask is: at what level of temporal resolution must data on temperature or precipitation be made available to detect the impacts of a CO₂-induced climate change in a particular watershed?

The answer to this question is not at all clear-cut, since the amount of data required to predict, say, the relationship between changes in precipitation and the magnitude and frequency of floods will vary tremendously by watershed (Dalrymple 1964). As a purely statistical exercise, it is probably safe to say that the phenomena of flooding can be completely eliminated in most "small" watersheds^(a) by simply altering the daily and, in some cases, the hourly distribution of precipitation. However, simply because floods can be made to disappear, statistically, in this fashion does not mean that we must always, or even usually, have monthly or hourly data to determine how changes in climate will affect this, or other generic issues.

Continuing with the example of flooding, one usually finds that the flood period of rivers and streams on which there are major flood hazards is usually concentrated in two to three months of the year and that the time during which the flood period does occur can be related, observably, to seasonal and not daily variations in climate (Jarvis et al. 1936). This suggests that, in the case of flooding, at least, information about seasonal changes in climate conditions, while it may be insufficient for predicting the magnitude of specific

(a) A small watershed is one in which overland flows rather than channel flow is the dominant factor affecting runoff.

flood events, or their recurrence intervals^(a) over time, may be sufficient for determining changes in flood impacts on man that are associated with changes in the timing and length of flood periods.

Flooding is just one example that can be used to show some of the problems that may be encountered in relating changes in climate to a hydrologic system that is essentially driven by weather. In order to deal with this problem on a somewhat more systematic basis Tables 4.4A and 4.4B present a series of working hypotheses about the sensitivity of the generic issues to changes in climate parameters including: (1) the annual mean values, (2) the variance in the annual mean values, and (3) the seasonal distribution of precipitation and temperature, respectively. Since these tables by no means exhaust the number of climate parameters to which the generic issues may be responsive, they can best be viewed as a preliminary effort (which will be expanded in the case study phase of this research) to make the concept of climate change more directly relevant to the generic issues.

Persistence Over Time

The purpose of applying this criterion was to try to determine which of the specific issues shown in Appendix A were most likely to continue as problems over the next 50 to 100 or more years from now, when CO₂ buildup may become a problem for man. Hence, any issue which appeared to have a technological or institutional "fix" could be quickly eliminated. Unfortunately, the history of water resources development in the United States has demonstrated that many of the supposed technological fixes to water resources issues were either not as permanent as first believed (for example, building more water storage facilities in the arid southwest) or else were too costly to implement (for example, massive interbasin transfers of water such as the North American Water Power Alliance System) (Howe and Easter 1971).

(a) The recurrence interval of a flood relates its magnitude in terms of peak discharge to the number of years in which that flood will occur, on average, over a 100 year period.

TABLE 4.4A. Climate Sensitivity of Generic Issues to Changes in Climate Parameters - Precipitation

Issue	Climate Parameters		
	Mean Annual Precipitation	Variance of Mean Annual Precipitation	Seasonal Distribution
Flooding	Holding other factors constant, proportional increases in this parameter will have a larger impact on the frequency and magnitude of existing floods than will a decrease, owing to changes in the infiltration capacity of the soil	Primary effect will be on recurrence intervals of floods; holding mean annual precip. constant, an increase in the variance will increase the probability of severe floods	Potentially severe effects will occur if more precipitation is concentrated in current flood period; otherwise the frequency and perhaps the magnitude of floods will be reduced
Drought	Effects will depend on current climate orientation; small increases/decreases in arid regions may be sufficient to reduce/increase the incidence of drought	Increases in variance will, by definition, increase drought incidence; dry and subhumid regions will be most sensitive	In regions with pronounced annual wet-dry cycles an increase in the amount of concentration of precip. in dry months, on average, may reduce susceptibility to drought, while a small decrease in wet months may produce a drought
Inadequate Supply/Storage	Some effects, but water supply systems are most sensitive to changes in the seasonal distribution of precip.	Increases in variance will reduce the reliability of existing supply systems; while a decrease will mean more dependable supplies	Effects will be most severe if precip. declines in wet seasons when storage accumulates; effects will also depend on time distribution of water demand, by region
Groundwater Mining	Depends on source and rate of recharge; some formations will be extremely sensitive to long-run increases/decreases in mean precip.	Increases in the incidence of wet years may help to increase recharge, while increases in the incidence of dry years may reduce recharge	Primary impacts will depend on time distribution of water demands in relation to seasonal recharge; decreased precip. in seasons of high demand will put more strain on ground water resources
River Sedimentation	Effects depend on existing means; between 0-12 in. erosion will increase with precip.; between 12-45 in. erosion will decline with more precip; above 45 in., no increase in erosion with precip.	Large amounts of sediment are transported by flood events; an increase in the probability of flooding should increase sediment loads.	Primary effect will occur through impacts on flooding and soil loss associated with inundation of flood plains
Conflicts in Use	Increases in precip. may reduce competition for water, but problems are more directly related to the time distribution of precip. changes	Increasing the probability of dry years will generally raise the level of conflict; while decreases should have the opposite effect	Conflicts will generally increase if differences between the seasonal distribution of water supply and demand become more pronounced
Salinity Problems	Will depend on effect of precip. changes on streamflow as agent for diluting dissolved solids; sustained decreases in runoff and streamflow over many years may increase soil salinization	Little if any significance	Deposition of salinity in soil and transport to streams could be affected by changes in the seasonal concentration of runoff, particularly if sharp increases/decreases in precip. occur in either wet or dry seasons
Water Losses from Storage Systems	Little if any direct significance	Primary effect is through change in drought incidence	Effects are indirect on seasonal replenishment of storage and on seasonal water demands
Aquatic Vegetation	Little if any direct significance	Primary effect is through change in drought incidence	Effects are indirect on seasonal replenishment of storage and on seasonal water demands

TABLE 4.4B. Climate Sensitivity of Generic Issues to Changes in Climate Parameters - Temperature

Issue	Climate Parameters		
	Mean Annual Temperature	Variance of Mean Annual Temperature	Seasonal Distribution
Flooding	Proportional changes in temp. may effect frequency of snowfall and duration of storage as snowpack; potential impacts will be most pronounced in temperate and cold climates	Primary impacts will occur in extreme years due to more/less snowfall and snowmelt	Small increases/decreases in seasonal distribution of temperatures will affect snow lines, extent of snowpack and rate of snowmelt
Drought	Drought temperatures tend to be significantly higher than average due to the feedback effect of dry soil on air temperature.	Increases in variance may increase the probability of drought, although drought temperatures may not be significantly greater than in normal years	In regions with pronounced, wet-dry cycles increases/decreases in temperature in dry months may aggravate/reduce drought impacts
Inadequate Supply/Storage	Some effects, but changes must be great to increase or reduce problems since water supply systems are most sensitive to seasonal climate changes	Increases in the variance will increase the probability of dry years and put additional pressure on existing supplies	Increased temperatures in periods of peak water demands, usually summer, will cause most severe problems due to increases in evapotranspiration and consumptive uses associated with higher temperatures
Groundwater Mining	Slight effect if temperature changes affect evapotranspiration year-round	Little if any significance	Primary effect is through the impact of seasonal changes on water demand
River Sedimentation	In transitional climate regions, temperature changes may effect vegetative cover which influences soil loss	Little if any significance	Little if any significance
Conflicts in Use	Warmer temperatures on average may increase level of conflict, but problems are more directly related to the seasonal distribution of temperatures	Increasing the probability of hot years will generally intensify conflicts; while an increase in the number of cool years will probably have no effect as long as precip. is held constant	Increased temperature in periods of peak water demands usually summer, will intensify conflicts due to higher evapotranspiration and consumptive uses associated with higher temperatures
Salinity Problems	In dry regions, sustained increases in temperature, on average, may increase soil salinity through increased evaporation of surface storage; the impacts of decreased temperature and evaporation on soil salinity problems in dry regions may be slight	Little if any significance	Increases in summer temperatures in particular will aggravate soil salinity problems due to increased irrigation water demands, while increased leaching of salts from the soil may also increase surface water salinity
Water Losses from Storage Systems	Little if any significance	Little if any significance	Water losses due to evaporation depend primarily on temperature variability and water depth; however the relationship is complex
Aquatic Vegetation	Increases in temperature, on average, may increase transpiration and increase water losses; changes in mean temperature can also affect the range of aquatic weeds	Little if any significance	Changes in the seasonal distribution of temperatures may affect plant growth and development; increased summer temperatures will increase transpiration and thus increase water losses caused by aquatic vegetation

Institutional fixes of a lasting nature are equally rare in the U.S. For example, conjunctive use problems on the South Platte River in Colorado and other locations of the arid southwest have persisted for many years despite repeated attempts to resolve the basic legal issues surrounding inadequately defined property rights that lie at the heart of this problem. Elsewhere in the world there have been notable advances in water management, for example, Taiwan (Abel 1976) and Western Europe (Sand 1973; UNDP 1976); however, among developing nations economic growth has tended to increase rather than lessen many of the institutional problems in water management (Easter and Martin 1977; Coward 1980).

There are, however, two factors that are more basic to the persistence of water resources issues over time than the ability to devise technological or institutional fixes for them. They are the long-term impacts which population growth and economic development will have on:

- the physical characteristics of river basins; and
- the demand for freshwater as it relates to a specific issue.

Over long enough periods of time, population growth and economic development can affect the annual water balance in a river basin. For example, land use changes, drainage practices, and the construction of dams and reservoirs directly affect basin runoff and streamflow. Water losses in a basin can be affected by the clearing of forests and vegetation which influence interception and transpiration and by the construction of buildings which affects interception. Finally, man can influence the infiltration of precipitation into the soil due to soil compaction by farm machinery and livestock, by the removal of vegetation and by urban development which increases the amount of area in a basin that is impervious to infiltration.

Thus, even if one chooses to characterize the impact of a CO₂-induced climate change on the world's water supply, ignoring issues of water demand for the sake of expediency, it may still be necessary to try to take into account the impact which both population growth and economic development could have over the next 50 to 100 or more years on the hydrology of individual river basins around the world. The problems with doing this are twofold; first,

long term predictions of population growth and economic development are generally not very accurate, and secondly, there is very little hard empirical data currently available which can be used to quantify the physical relationships between man's historical impact on the physical environment and the effect which this has on basin hydrology.

In view of the impact which urban and suburban development in the U.S. has had on small watersheds located in these areas, the lack of data for modeling the impact of man on the hydrologic system may seem surprising at first. On reflection, however, this situation is a good example of man's traditional ignorance about the latent consequences of many of his actions on the environment. In time, however, this type of data should become more readily available based on the experience of the developing and lesser developing nations.

Finally, the persistence of many of the specific, as well as generic water resource issues uncovered in the course of this research, will depend directly on future changes in the magnitude and structure of the demand for consumptive uses of water by man, on a regional basis. These changes will occur, first of all, due to population growth and economic development that would have occurred anyway in the absence of CO₂ buildup, and secondly due to the impacts of CO₂ buildup on the use of water by plants and by man.

The basic problem with projecting both of these types of changes in the demand for water is that, over long periods of time, changes in technology and the preferences of consumers for different types of goods and services can occur which have the effect of altering the underlying structure of the economy. It is largely because of the potential for these structural changes to occur in the future that it is difficult to assess the persistence of individual water resource issues.

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5.0 CASE STUDY-SITE SELECTION

The two major objectives of the site-specific case study phase of this research are, first of all, to examine if it is possible to tell whether or not individual generic issues will be affected by a CO₂-induced climate change and, if this is possible, to try to gauge the direction and the potential magnitude of these impacts. In that context, the purpose of this section of the report is to provide answers to the following questions:

- What types of approaches can be used to detect and/or characterize the effects of a CO₂-induced climate change on individual, generic issues?
- Which of these approaches appears to be best suited to achieve the above two study objectives?
- How many sites should be studied?
- Which specific sites should be selected for closer study?

METHODS FOR CHARACTERIZING THE IMPACTS OF CLIMATE CHANGE ON WATER RESOURCE SYSTEMS

Generally speaking, the scientific community has not focused a great deal of attention on the potential effects of CO₂ buildup on natural and manmade water resource systems. In fact, a fairly thorough search of the relevant literature revealed only two citations (Schwarz 1977; Nemec and Shaake 1982) on this subject in the open literature and a single Master's thesis (Maristany 1979). As such, there is not yet a formal consensus regarding the best approach for characterizing the impacts of climate change in specific watersheds or larger regions.

Focusing on the analysis of specific watersheds, we follow Schwarz and Nemec and Shaake in identifying three different approaches that can be used to characterize the impacts of future climate changes on the hydrologic system in different watersheds of the world. In the absence of well-developed terminology for identifying these approaches, we label them according to whether the

results obtained from each are based primarily on: (1) speculative relationships between climate and the hydrologic system; (2) the observed response of the hydrologic system to existing climate fluctuations and anomalies; or (3) the application of a systems-based, hydrologic model. These three approaches can be defined, briefly, as follows:

- Speculative Approach - which involves identifying the relevant climate parameters to which generic water resource issues may be responsive and then speculating upon the effects that changes in these parameters will have upon the magnitude of the impacts associated with these issues.
- Empirical Approach - which consists of using existing climate and hydrologic records and, given variability in the former, determining the effects which analogous climate changes may have on the generic water resource issues, both on the basis of the short term response of these issues to historical climate fluctuations and on the basis of questioning water managers in the area.
- Systems-Based Approach - which involves projecting the magnitude and trend of relevant climate parameters, and using this information to drive hydrologic models to determine how these changes may affect snowmelt, runoff, infiltration and other hydrologic processes; then, on the basis of analyzing these data with area water managers, characterize the potential impacts which changes in the relevant hydrologic processes would have upon the generic water resource issues.

The Speculative Approach

This approach was used by Schwarz in a somewhat different framework to speculate about the impacts which climate-induced changes in streamflow parameters (i.e., mean, variance, skewness, etc.) might have upon certain broad attributes of water supply systems, such as yield from unregulated streams, yield from groundwater and system reliability, in the northeastern United States. We have used a somewhat similar approach in this research, first to characterize the climate sensitivity of specific water resource issues and

then to speculate on the effects which changes in the annual means, variances and seasonal distribution of precipitation and temperature might have on the generic water resource issues.

The primary advantage associated with this approach is that it is a relatively efficient tool, first of all, for identifying water resource issues that may be highly climate sensitive and, secondly, for generating a series of working hypotheses about how individual water resource issues or, as in the case of Schwarz, the attributes of water supply systems, may respond in broad terms to changes in specific climate parameters. This method could also be used in a site-specific framework to develop a set of more sharply focused hypotheses about the responsiveness of local generic water resource issues to climate change. However, this approach is not well-suited for hypothesis testing and, thus, cannot be regarded as a substitute for the other two approaches, nor have any such claims been advanced within the literature (as limited as it is) in this regard.

The Empirical Approach

The second approach, which was suggested by Schwarz, has never been tested in the context of a specific site except in a superficial fashion.^(a) A more systematic approach was undertaken by Maristany who examined the impact of changes in average annual temperature and precipitation on average annual runoff in the U.S. using standard multivariable regression in conjunction with cross-sectional data for 100 climate subregions and 8400 gaging stations. On the basis of his research, Maristany concluded that for a 12% increase in precipitation (which is consistent, he argues with a 2°C increase in temperature) wet season average annual runoff would increase by about 31% and dry season runoff by only 10%. Interestingly, Maristany's research also showed that the effect of a one percent increase in precipitation on the percentage change in runoff was not statistically different between eastern and western regions. However, this last finding is probably more a result of data aggregation than it is a reflection on physical processes.

(a) See Schwarz (1977), pp. 113-115.

While Maristany's approach is empirical in terms of method, due to his use of regression analysis, it is not site-specific. Therefore, his research does not provide a great deal of insight regarding the use of the empirical approach in a specific watershed or river basin.

The empirical approach, as conceived in this report, consists of the following elements: (1) a specific site (watershed or river basin) in which there is substantial year-to-year and seasonal climate variability; (2) a data base consisting of meteorological, hydrologic and other types of records which reflect this variability as well as its impact both on the hydrologic system and on the magnitude of individual, generic issues; (3) the application of statistical methods to these data to test hypotheses regarding the effects of climate variability on both the hydrologic system and on the magnitude of the generic issues at the site; and (4) local water managers with specific expertise regarding the operation of the water supply system and the relevant generic issues. A more detailed discussion of each of these elements follows.

Climate Variability

Regardless of the a priori information that may be available about expected changes in climate in the region where the case study is to be conducted, it is fundamentally important to select a site in which there is substantial variability in climate, both on an annual and seasonal basis. There are two reasons for this.

The first reason is general in the sense that it applies broadly to any approach used to characterize the effects of climate change on natural and man-made hydrologic systems. This reason relates to the way in which man responds to climate variability in the design and operation of water supply systems and his management of water resource problems. Other things being equal, if climate is more variable in a specific watershed or river basin, greater flexibility will have to be built into the water supply system to accommodate the impact of this variability on the hydrologic system. Flexibility in design, in turn, implies that there will be a wider range of operating rules that can be used to regulate flow within the system to meet specific conditions as they occur. Furthermore, since many local water resource issues may either result directly from, or be indirectly affected by, existing fluctuations in climate,

there is an implied need for flexible management strategies to deal with these issues. Given that man generally builds and operates water supply systems and manages the freshwater resource in an adaptive framework, selecting a site that is subject to a substantial amount of climate variability can provide valuable insights regarding the way in which man may respond to future climate changes.

The second reason for selecting a site that is subject to a fairly high degree of climate variability relates to the use of inferential statistical methods, such as multivariate regression analysis, to characterize the effects of climate variability on the hydrologic system and the relevant generic issues at the site. If extremes in the existing climate record are to be used as an analogy for climate change, then it is important to have a sufficient number of extreme data points, related to the relevant climate parameters, to accurately capture the effects of interest in the estimated coefficients of the regression equations.

This problem is routinely discussed under the topic of "outliers" in any standard text on regression analysis (Draper and Smith 1966). From an intuitive standpoint, the problem is that if the observations on two variables, say average annual runoff and average annual precipitation, are tightly clustered around a fairly narrow range of precipitation values, the presence of a few extreme observations (i.e., outliers) may unduly influence the regression line that is fitted to these data. Furthermore, the standard error associated with the predicted value of runoff for an extreme precipitation value would be quite high in such a case. On the other hand, if the observations on runoff are based on a precipitation record that is characterized by a wider range of values, then any outliers will have a smaller impact on the regression line and the standard error associated with runoff predictions within the range of precipitation variability will be smaller. Thus, one could feel more confident about the accuracy of runoff predictions made using the estimated regression coefficients.

Data

There are at least three different types of data, broadly speaking, that can be used in conjunction with the empirical approach. These data include meteorological data from the historical record on precipitation, temperature,

and, where possible, potential evapotranspiration (PET). Precipitation and temperature data are widely available from standard government sources and are often supplemented by observations from weather stations operated by local water resource management agencies. PET data are widely available in the arid and semiarid portions of the U.S. from the U.S. Bureau of Reclamation and local water resources management agencies who supply this information as a public service for irrigation scheduling purposes.

The second type of data that can be used in conjunction with the empirical approach is hydrologic data. These data include observations on runoff and streamflow as collected by the U.S. Geological Survey (U.S.G.S.) and also by local water resource management agencies. However, the hydrologic information that can be used profitably with the empirical approach are not limited to these traditional sources, but may also include unit hydrographs and flow duration curves that have been constructed in the basin, groundwater data sources including groundwater depletion and type curves, and storage-yield curves for relevant reservoirs in the water supply system. These and a wide variety of other hydrologic data sources, which describe the relationships between variations in climate parameters and the movement of water through the hydrologic system over time, can all be helpful in testing hypotheses about the effects of climate change on the hydrologic system and on site-specific generic issues at varying levels of methodological sophistication.

The third type of data that can be used with the empirical method includes observations on the key dimensions of site-specific generic issues. Some of these data can be obtained directly from previously mentioned sources such as peak discharges associated with specific flood events, the frequency and duration of droughts and the seasonal drawdown of aquifers due to groundwater pumping. In some other cases, water management records can be consulted directly to determine, for example, how sediment loads and surface water salinity have varied over time, although the availability and quality of these records will vary depending both upon the perceived severity of the issue and the resources the relevant water management agency is able to devote to such monitoring. In many other cases, however, data on the magnitude of the problems associated

with some issues will probably not be available on a systematic basis and will have to be pieced together from water management records and available secondary sources.

Methods

The extent to which it will be possible to relate (a) variations in climatic parameters over time and space to changes in key hydrologic variables such as streamflow, runoff and percolation and (b) changes in relevant hydrologic variables to changes in the magnitude of generic issues, using inferential statistical methods will depend on three factors. These include:

- The nature of the generic issue - does it lend itself to the use of these methods?
- The availability of data - are there a sufficient number of observations on the relevant variables at the above two levels of analysis to estimate the necessary regression coefficients used to project the effect of climate change on the magnitude of individual, generic issues?
- The consistency of the data - are the observations on the relevant variables consistent with respect to the dimensions of time and space over which they are recorded?

Provided that all three of these conditions are met, then it will be possible to formally test hypotheses regarding the effects of climate change on the magnitude of individual generic issues, using multivariate regression techniques.

These methods are widely used in hydrologic analysis at varying levels of complexity. Perhaps the simplest example is the, so called, "rational formula" (Chow 1964)

$$Q = rIA$$

which relates a single dependent variable, peak discharge in cfs (Q), to a compound, independent variable which is the product of rainfall intensity in inches per hour (I) and drainage area in acres (A) through a runoff coefficient

(r). Given a consistent set of observations on Q , I and A from a specific watershed, the value of the regression coefficient, r , can be estimated by the method of ordinary least squares. Specific values for I and A can then be substituted into the rational formula to predict Q . More complicated regression models that are used routinely in hydrologic analysis include models for estimating flood peaks on ungaged watersheds (Aron and Kibler 1981) and monthly streamflow models first developed by Thomas and Fiering (1962) and subsequently refined by Fiering (1967), Fiering and Jackson (1971) and others.

Regression models, sometimes referred to in the literature as transfer functions (Linsley 1982) or empirical models (Woolhiser 1971), are frequently criticized because individual regression coefficients often lack physical significance in terms of the basic principles of hydraulics (Huggins and Burney 1982). However, as Klemes (1982a) notes, as long as an empirical relationship is valid, a causal relationship cannot negate it.

There are, nevertheless, several practical problems associated with using empirical models to describe the impact of variations in climate on the hydrologic system and individual, generic issues. The first problem, already mentioned under the subject of outliers, is that the standard error for the predicted value of the dependent variable in a regression model increases as one uses more extreme values for the independent variables in the model as a basis for making projections. In other words, the predictions that can be made from these models become less accurate as one moves away from average climatic conditions. This is obviously a problem when using historical climate extremes as an analog for climate change.

The second problem is that because regression models in hydrology usually simplify the results of complex causal chains, variables not included in the model are assumed to remain constant over the range of the observations used to estimate the regression coefficients. This ceteris paribus assumption tends to narrow the range of climatic and hydrologic variability within which these models can be used to accurately assess the impact of changes in climate on the hydrologic system and individual, generic issues. Thus the flooding model, PSU-IV, developed by Aron and Kibler (1981) may be able to predict flood peaks

very accurately in ungaged watersheds in Pennsylvania, but would probably not be able to do so for ungaged watersheds in Arizona. In other words, the generality of these models over space and climatic conditions is usually limited.

Water Management Expertise

An important aspect of the empirical approach will involve questioning relevant water resource managers at the site regarding the operation of the water supply system under extreme climate, runoff and streamflow conditions and also about the management actions that might be taken under these same conditions to deal with the projected changes in the magnitude of individual, generic issues. This is an extremely important element of the research because it is far from certain that water managers will respond to climate change in the same way they have responded, historically, to climate variability. For example, Howe^(a) has shown that during the drought years of 1976-1978 most water management districts in Colorado did not change their reservoir operating procedures even when it became clear that the drought was likely to continue for a second year. In a somewhat related vein, Glantz (1982) found that Bureau of Reclamation overreacted to the 1977 drought in the Yakima river basin in central Washington and, based on an erroneous water supply forecast, allocated far less water to farmers than was actually available.

Would water managers in Colorado and Washington have acted differently if, instead of facing a transient drought problem, the climates in these two regions became persistently hotter and drier? Unless these questions are posed on a hypothetical basis to individual water managers, the results obtained from analyzing the historical record may be misleading and biased.

The Systems-Based Approach

The last of the three approaches to be reviewed in this report involves the use of watershed simulation models to project the effect which changes in climatic parameters will have upon the hydrologic system. To date, only two studies have been published using this approach. In the first of these

(a) Howe, C. W. et. al. 1980. "Drought Induced Problems and Responses of Small Towns and Rural Water Entities in Colorado," Colorado Water Resources Research Institute, Fort Collins, Colorado (Mimeo).

studies, Schwarz (1977) arbitrarily varied the parameters of a stochastic, streamflow model in order to generate a series of synthetic streamflows for the Potomac River. He used these data in conjunction with a reservoir storage model to determine the safe reservoir yield that could be developed from these hydrologic records. In Schwarz's own words, "The result of this analysis was generally disappointing to those who believe that climate change should radically alter the water-supply planning process." Under the most unfavorable streamflow regime tested, the reliability associated with an assured supply of 1400 cfs fell from 95% to 91%, a relatively minor difference.

In point of fact, Schwarz's study falls somewhere between the empirical and systems-based approach since neither of the two models which he used can really be considered a watershed simulation model in the strictest sense (Haan et al. 1982). The one study that clearly does fall under the heading of a systems-based approach is Nemec and Schaake's (1982) use of the Sacramento soil moisture accounting model (Burnash et al. 1973) to examine the impact of hypothetical changes in precipitation and temperature on the Peace River near Vernon, Texas, and the Leaf River near Collins, Mississippi. The results of their research showing the effect of percentage changes in precipitation and evapotranspiration^(a) on runoff at these two gaging stations are presented in Figures 5.1 and 5.2. On the basis of the information shown in these figures, the authors concluded that "precipitation is by far the most important factor affecting the change in runoff as a result of climate change." In addition, it can readily be seen from these two figures that runoff responds much more rapidly to changes in precipitation and temperature in the dry basin (e.g., the Peace River) than it does in the wet basin.

Systems-based watershed models have proved themselves to be extremely versatile tools in water management. Specific applications that reflect this versatility include the use of these models to examine irrigation scheduling practices (Kincaid and Heerman 1974) and drainage problems on agricultural land (Bhattacharya et al. 1977); to predict the effects of various land use changes, such as clearcutting of forests (Leaf and Brink 1973) and urban stormwater

(a) A 1°C change in temperature equals a 4% change in evapotranspiration (ETP).

Peace River at Vernon, Texas
 Drainage area = 9034 km²
 Mean precipitation base 540 mm
 Mean runoff base 11 mm

FIGURE 5.1. Impacts of Changes in Precipitation and Evapotranspiration (ETP) on Runoff for the Peace River at Vernon, Texas
 (Source: Nemec and Shaake 1982)

control alternatives (Huber and Heaney 1977) on runoff; and to analyze the effects of precipitation augmentation on streamflows and reservoir storage (Lumb and Linsley 1971). The apparent versatility of these models reflected in the above applications suggests that it is possible to use them to examine both

Leaf River near Collins, Mississippi
 Drainage area = 1949 km²
 Mean precipitation base = 1314 mm
 Mean runoff base = 409 mm

FIGURE 5.2. Impacts of Changes in Precipitation and Evapotranspiration (ETP) on Runoff for the Leaf River Near Collins, Mississippi. (Source: Némec and Shaake 1982)

the effect of climate change on the hydrologic system (for example, the effect of an increase in temperature on snowpack and snowmelt) and the influence of climate-induced changes in the hydrologic system on the magnitude of individual, generic issues (for example, the effect of more rapid snowmelt on flooding).

However, this is not usually the case because, in most water resource management applications, watershed models must be used in conjunction with other types of models and information to provide insights into management problems. For example, in the case of water supply problems, watershed models could be used to predict the effect of climate-induced changes in runoff on streamflow. However, to determine how streamflow variations will affect reservoir yields and drought requires the use of additional models and/or analytical techniques.

The systems-based approach, as envisioned in this report and as used by Nemec and Shaake, can be employed to examine how climate change affects various processes, particularly snowmelt, runoff, evapotranspiration and streamflow, in the hydrologic system. In that regard, this approach is not a complete substitute for the empirical method which can be used to analyze both levels of the causal chain between climate, the hydrologic system and individual, generic issues, although with somewhat less methodological rigour. Thus, there may be some benefit in comparing the value of these two approaches for determining how climate change in specific watersheds affects the hydrologic system - a subject that will be discussed in a later portion of this section.

The major problems associated with using empirical methods to assess the effect of climate change on the hydrologic system have already been discussed. Despite the attitude among many hydrologists that physically based systems models are preferable to empirical models in hydrologic analyses (Woolheiser 1971; Linsley 1982), the use of these models to assess the effects of climate changes on the hydrologic system can be questioned on at least two grounds, namely: (1) the specification of climate change within a watershed model, and (2) the validation of the results obtained from the model.

Specification of Climate Changes

Watershed models are structured in a manner to represent, at different levels of sophistication, the physical properties of the hydrologic system. Accordingly, most of these models run on very short time-steps and usually require hourly or daily information about relevant meteorological parameters, such as temperature and precipitation, to drive them. In short, these models are driven by weather, not climate. Since the ability to predict hourly and daily weather 50 to 100 years in advance has not yet been developed, how can we

use these models to predict the indirect effects of CO₂ buildup on the hydrologic system? Nemec and Shaake attempted to solve this problem by distributing changes in temperature and precipitation evenly over all days of the years and then comparing the simulated changes in monthly runoff with the monthly averages from the historical record. While the simulated monthly values for runoff were all significantly different from the historical series, the way in which climate change was specified in the model has been criticized by Klemes (1982b) because of its lack of realism.

However, the specification of climate change in a more realistic fashion does not necessarily solve the problem of whether models that are driven by hourly or daily weather can provide useful insights about the effects of climate change on the hydrologic system. What must be tested are not more realistic climate projections, per se, but rather the robustness of the hydrologic system to changes in weather within a given type of climate change. If it can be shown that small changes in weather (i.e., the frequency, duration and timing of individual precipitation events) about a fixed climate have a greater impact on, say, average monthly runoff than do changes in average monthly precipitation, then this will be an important finding. It will mean that, unless information about climate change is accompanied by information about changes in weather, the indirect effects of CO₂ buildup on the hydrologic system can only be characterized by a great deal of uncertainty at this time. On the other hand, if the hydrologic system is shown to be more robust to changes in weather than to changes in climate--that is if average monthly runoff is more responsive, say, to changes in monthly average precipitation than to changes in daily precipitation--then we may be able to characterize the effects of a CO₂-induced climate on the hydrologic system with existing climate information.

Validation of Results

In using a mathematical model to forecast future events one always runs the risk that the sensitivity of the forecasts to changes in the value of input variables will tell us more about how the model operates than about the future. This is a persistent problem in the use of hydrologic models. The problem is even more acute in the current context because it is often true that a water-

shed model that is calibrated under one set of climatic conditions, in a given area, will produce different results when it is calibrated under a set of different climatic conditions in the same watershed (Klemes 1982a). Hence, the generality of the results provided by these models may be as subject to question as the generality of the results obtained from regression models.

Whether this problem can be resolved or not is a serious question in the context of climate change. However Klemes^(a) has suggested several different approaches to this problem, some of which will be tested in the case study phase of the research. These methods include split sample and split station tests. Split sample tests involve calibrating a model, twice, at a single gaging using two different samples from the historical record and comparing the results for different types of climate change. Split station tests involve calibrating the model at two different homogenous locations in a watershed and comparing the results across locations for different types of climate change.

RESEARCH STRATEGY

Three different approaches have been identified for characterizing the potential effects of a CO₂-induced climate change on the hydrologic system and/or individual, generic issues. The questions that must now be answered are, given the objectives of this research and usual resource limitations, (1) what is the best approach to use to achieve these objectives, and (2) to how many different watersheds or river basins should the method, or methods, chosen be applied?

Choice of Method

Table 5.1 summarizes how the three different approaches can be used in a case study framework to examine, first, the potential effect of climate change on the hydrologic system and, second, the potential effect of changes in the hydrologic system on the magnitude of the problems associated with individual, generic issues.

(a) Klemes, V. 1982. "The Desirable Degree of Rigour in the Testing of Rainfall-Runoff Models," National Hydrology Research Institute, Environment Canada, Ottawa (Mimeo).

TABLE 5.1. Summary of Approaches for Characterizing the Potential Effects of Climate Change on Individual Generic Issues by Level of Analysis

Approach	Level of Analysis	
	Climate → Hydrology	Hydrology → Generic Issue
Speculative	Develop working hypotheses	Develop working hypotheses
Empirical	Develop and test hypotheses using empirical models in connection with climate analogs from historical records	Develop hypotheses using relevant published research on generic issues at site; test hypotheses using empirical models; question water managers about management response to climate changes
Systems-Based	Develop and test hypotheses using watershed models in connection with historical data (calibration) and climate projections (simulation)	Watershed models provide limited insights into management problems and must be used in conjunction with other models and analytical tools

Here it can be seen that the speculative approach is best suited to developing working hypotheses at both levels of analysis. The empirical approach can be used both to develop and test hypotheses regarding the interface between climate and the hydrologic system using empirical models in connection with climate analogs drawn from the historical record. It can also be used to develop hypotheses regarding the interface between the hydrologic system and the generic issues using general and site-specific research results on individual, generic issues. These hypotheses can then be tested using empirical models in conjunction with information obtained from water managers about how they might respond to a long-term change in climate. Finally, the systems-based approach can be used in conjunction with either historical data or climate projections to test hypotheses regarding the interface between climate and the hydrologic system using historical data. Hypothesis building and testing at the second level of analysis can be accomplished with the systems-based approach using other models and techniques, including regression models as well as more complex hydrologic and water allocation models.

Since neither the empirical or systems-based approaches have been proven superior in this specific research application, a comparative approach would

seem to represent the most sensible approach for determining (1) whether or not one can even determine if changes in climate will affect freshwater resources and (2) if so, what are some of the potential consequences for man? The comparative approach that is suggested for conducting the case study analysis phase of this research is shown in Figure 5.3.

The comparative research strategy shown in this figure is divided into four phases. In the first phase, part of which is completed, hypotheses will be advanced regarding both the sensitivity of the hydrologic system to changes in climate and the sensitivity of individual, generic issues to changes within the hydrologic system. In the next phase of the research the former set of hypotheses will be tested using both empirical and watershed models. Presumably this phase of the research will shed some light on whether it will even be possible to tell if a CO₂-induced climate change will affect the hydrologic system. If these impacts cannot be detected using current methods, then it may be possible to determine the magnitude of the climate changes that must occur before their impact on the hydrologic system can be detected using current analytical tools. In the third phase of the research the second set of hypotheses as well as any new hypotheses generated in the previous research phase will be tested using appropriate empirical and, to the extent possible, physical models in conjunction with the inputs of local water managers. Out of this

FIGURE 5.3. Flow Diagram for Research Phases of Site Specific Case Study

research, in the final phase, will come a set of findings regarding the potential effects of a CO₂-induced climate change on individual, generic issues.

Choice of the Number of Sites

Roughly speaking, there are three alternatives for selecting the number of sites to be studied. These are:

- Select several sites and study a small number of different issues at each site;
- Select several sites and study the same small set of issues at each site;
- Select a single site which experiences multiple issues and study these issues at that one site only.

The logic that underlies the selection of multiple sites for the first two alternatives is straightforward: because of the tremendous variability and variety in the hydrologic system over time and space, the effect of an identical climate change on any two basins, even if they appear to be superficially homogenous, will probably not be the same. While this is undeniably true to some degree, the extension of this argument to its logical consequence is that a very large number of sites must be studied before one can feel confident about characterizing the impacts of a CO₂-induced climate change on individual, generic issues.

Even though studying multiple sites will probably help to improve our understanding about the way in which changes in climate may affect the hydrologic system, the cost of collecting data, calibrating watershed models and conducting the necessary computer simulations for different sites must be weighed against the benefits of obtaining additional information about the effects of climate change. Given an identical budget, the analysis of multiple sites would necessarily have to be more superficial than the analysis of a single site. Moreover, by selecting a single site with a substantial amount of climatological and hydrologic variety over space, and by using different sampling, calibration and testing techniques, it may be possible to achieve some of the same benefits associated with studying multiple sites in a single river basin.

The question of whether it is better to study a number of different issues at different sites or the same issues at one or more sites is best viewed from the standpoint of how well these two choices lend themselves to the comparative methodological framework that will be adopted. Insofar as a comparative focus may be helpful in determining which of the two broad approaches (e.g., empirical and systems-based) is best suited for characterizing the effects of climate change on the hydrologic system, it would seem to make more sense to do this in the context of the same, rather than different generic issues.

Based on the above considerations, we conclude that the last alternative--studying a variety of issues at a single site using a comparative methodological framework--represents the most efficient combination of methods with number of sites for performing the case study phase of this research.

SITE SELECTION

The process used to select a specific site for the case study analysis was done on an iterative basis, by successively applying individual site selection criteria developed for this report to narrow the geographic focus of the search from the global, to the national, to the regional level and finally down to an individual river basin.

Site Selection Criteria

The criteria chosen for selecting a specific case study site represent a set of ideal characteristics, the presence of which at a particular site would greatly enhance the ability to achieve the stated objectives of the case study phase of this research. These site characteristics include:

- Extensive year-to-year and seasonal fluctuations in climate;
- A fairly large number of generic issues which have been identified as currently or potentially severe in nature;
- An hydrologic system in which small watersheds (in hydrologic terms) are a dominant feature;
- Snowmelt that is an important component of runoff and streamflow;

- Placement of manmade controls so that it does not confound or obscure the effect of climatic variation and/or change on the hydrologic system;
- Substantial physical and climatological variety across space within the basin;
- The availability of extensive high quality data bases relating to climate, the hydrologic system, and the operation of the system and use of water by man;
- The cooperation of an identifiable group of water managers and water resource experts familiar with the operation of the water supply system and local water resource issues.

Most of these characteristics have either been discussed previously in this section, or else their importance is fairly straightforward. Three of them that appear to require more elaboration relate to the hydrologic and physical characteristics of the basin. These include: 1) the importance of small watersheds in the basin; 2) the placement of manmade controls in the basin; and 3) the degree of physical and climatological variety in the basin.

The first of these characteristics is important for the simple reason that in basins where channel flow is the dominant hydrologic process, it may be very difficult to detect the effect of changes in precipitation on the hydrologic system, except in the driest and wettest years. Under these conditions, it might be very difficult to use either empirical models or watershed models (which are intended for use in small watersheds) to study the impacts of climate change on the hydrologic system. Consequently, the mainstem portions of major rivers, such as the Mississippi, the Missouri, or the Colorado, have been ruled out as candidates for site selection. The placement of controls is important for similar reasons. In some basins, controls are so extensive that, in all but the most extreme years, the operation of the system by man can muffle the effects of nature. If such a basin were selected for study, it would be extremely difficult to use empirical methods to assess the effect of historical climate variability on the hydrologic system. The importance of the last of these three characteristics has already been discussed. By selecting a basin with a substantial degree of physical and climatological variability, it

will be possible to examine the effects of climate change on the hydrologic system under a much wider variety of conditions. In that case, one may be able to transfer the results obtained in a single basin to a larger number of areas.

Selection of National Scope

In the first phase of the site selection processes, the scope of potential sites was limited to the continental United States. The reasons for this are as follows:

- The U.S. has a wide variety of climate types and contains large areas that are subject to a great deal of annual and seasonal climate variability;
- All of the individual, generic issues are present in the U.S.;
- The causes, effects and technological remedies associated with these issues are identical worldwide, only the institutional and cultural frameworks within which they can be managed differ from country to country;
- The availability and quality of U.S. data are, on average, higher than for the rest of the world, with the exception of Eastern European countries;
- The costs of conducting research in the U.S. is considerably lower than would be the case for non-U.S. sites.

Selection of Alternative Regions

In the second phase of the selection process, the regional scope of potential sites was reduced to the four U.S. Water Resource Council Planning regions (WRC 1978) shown in Figure 5.4. These regions include:

- The Missouri River region,
- The Arkansas--White--Red Rivers Region,
- The California Region, and
- The Lower Colorado River Region.

FIGURE 5.4. Location of Selected Water Resource Regions in the Western United States

Of the 18 water resource regions identified by the WRC, these four were selected primarily on the basis of climate and the scope and severity of the generic issues that are currently found in these regions or which may arise in connection with a CO₂-induced climate change.

Climate

While there are a number of different ways of classifying climate (Bailey 1964; Maunder 1962; Hare 1951), the one which is perhaps most relevant to water

resources is Thornthwaite's (1948) moisture index which compares the water need at a place with the moisture surplus and deficit. This index, which is very similar to Budyko's (1956) raditional index of dryness, is written as

$$I_m = 100 \left(\frac{\text{moisture surplus} - 0.6 \text{ moisture deficit}}{\text{moisture need}} \right)$$

where, averaged over the year, the moisture surplus is equal to runoff; the moisture deficit is equal to the difference between potential and actual evapotranspiration; and the moisture need is equal to potential evapotranspiration. Thus, in places where the precipitation is just adequate to supply all of the water needed for maximum evaporation and transpiration during the year, $I_m = 0$. The values of the Thornwaite moisture index for six climate types are shown below in Table 5.2.

The Thornthwaite moisture index is a useful tool for examining the effect of climate variability on the water balance in individual regions. Figure 5.5 illustrates the effect of climate variability on the distribution of climate types in the U.S. for the wet year, 1915, in the upper figure and for the drought year, 1934, in the lower figure. With the exception of the penetration of the moist subhumid climate into the corn belt in 1934, most of the important shifts reflected in the moisture index took place in the Great Plains and the Rocky Mountain Region. On the other hand, the balance between moisture supply and demand was not greatly affected in the eastern half of the U.S. or in the

TABLE 5.2. Selected Climate Types Based on the Thornthwaite Moisture Index (I_m)

<u>Climate Type</u>	<u>Moisture Index</u>
Superhumid	$I_m > 100$
Humid	$20 \leq I_m < 100$
Moist Subhumid	$0 < I_m < 20$
Dry Subhumid	$-20 < I_m < 0$
Semiarid	$-40 < I_m \leq -20$
Arid	$I_m \leq -40$

(a)

(b)

CLIMATIC TYPE

FIGURE 5.5. Distribution of Climate Types in the United States in (a) the Wet Year (1915) and (b) the Drought Year (1934)

Pacific Coast states. Not surprisingly, the variability in average annual rainfall tends to be highest in those regions which are subject to extreme fluctuations in the Thornthwaite index.

On the basis of these observations, the WRC regions which appeared to be most subject to climate variations included those in the Great Plains, principally the Missouri River Region and the Arkansas-White-Red Rivers Region and, in the west, the Lower Colorado River Region.

Number and Scope of Generic Issues

The Thornthwaite moisture index is also directly relevant to the regional screening process in that the values of the index, when converted into regional climate type, have either a direct or indirect bearing on the severity of those generic issues broadly related to the supply and demand for the freshwater resource. At least seven of the nine generic issues--drought, inadequate storage/supply, groundwater mining, conflicts in use, water losses from storage systems, and aquatic vegetation--fall into this category.

Table 5.3 illustrates this point by showing the distribution of the generic issues according to three broad climate types--humid (including humid and superhumid), transitional (including moist and dry subhumid) and dry climates (including semiarid and arid). While water supply-related problems in the humid, eastern U.S. (particularly in the urban areas of the Northeast) cannot be minimized, annual precipitation is generally sufficient to satisfy demand even during drought years, which are usually no more than a year in duration. The real question in the humid East is the location of existing potential supplies in the Appalachian Mountains and Great Lakes in relation to the location of demand.

In the transitional climates of the Great Plains, including both the Missouri River and Arkansas-White-Red Rivers regions, supply-related problems can be critical during drought years. At present, the most critical of these issues in the Great Plains is the mining of groundwater from the Ogallala Formation in parts of Nebraska, Colorado, Kansas, Oklahoma, New Mexico and Texas. However, a CO₂-induced climate change which significantly increases potential evapotranspiration through warmer temperatures and/or causes a reduction in Spring and Summer precipitation may lead to a substantial rise in irrigated

TABLE 5.3. Distribution of Generic Issues by Climate Type

Issue	Humid	Transitional (Moist-Dry Subhumid)	Dry
Flooding	Moderate to severe damages from all causes	Moderate to severe damages due to rapid snowmelt, persistent spring rain, and convectional storms	Localized, moderate damages due to rapid snowmelt and convectional storms
Drought	Short duration, moderate impacts	Short and long duration, moderate to severe impacts	Long duration, severe impacts
Inadequate Storage/Supply	Moderate to severe problems in urban areas during dry years; major problem is not supply, but location of supply in relation to demand	Moderate problems in dry years; long-term problems may arise with increased irrigation in dryland farming areas	Moderate to severe problems; long-term supply sources are almost fully utilized
Groundwater Mining	Isolated impacts due to adequate recharge of most aquifers	Moderate to severe impacts, usually depending on amount of irrigation	Severe impacts due to limited recharge of most aquifers
River Sedimentation	Can be severe depending on soils and agricultural practices; climate is not usually a factor	Can be severe depending on soils and agricultural practices; climate is a factor in drought years	Severe impacts where precipitation averages 10-12 in/yr., below which sediment loads decrease as runoff declines
Conflicts in Use	Limited conflicts in years of average precipitation; moderate conflicts in dry years	Moderate conflicts in average years; may become severe in dry years	Moderate to severe conflicts in a average years, increasing to severe in dry years
Salinity Problems	Limited problem since dissolved solids are transported longer distances and are more limited	Moderate, usually localized impacts, sometimes severe in rivers that carry dissolved solids from dry to transitional areas	Moderate to severe impacts, due to low runoff and effect of extensive irrigation practices on return flows

TABLE 5.3. (Contd)

Issue	Humid	Transitional (Moist-Dry Subhumid)	Dry
Water Losses from Storage Systems	Not a significant problem	Currently not a significant problem, but could become so with increased temperatures	Large losses due to evaporation; increases in temperature may create severe problems because supply sources are almost fully utilized
Aquatic Vegetation	Extensive vegetation, impacts are usually low due to adequate supplies of water	Moderate to severe impacts in subhumid areas where supplies are less plentiful	Moderate to severe impacts due to phreatophytes along irrigation canals and reservoirs

acreage in the eastern portions of the Great Plains and the western part of the corn belt. This, in turn, could exert substantial pressure both in groundwater and surface water supplies which are currently considered adequate.

In dry regions, particularly the lower Colorado River Region, supply-related problems are potentially more severe than in the Great Plains. According to the U.S. WRC (1978), existing surface water uses of 4.6 billion gallons per day exceed the available supply of surface water by about 2.4 billion gallons per day, the difference being made up by groundwater pumping. As a result of this, groundwater levels are declining at an average of from 8 to 10 ft/yr. The completion of the Central Arizona Project in the mid-1980s will alleviate these problems in some sub-basins of the Lower Colorado. However, looking beyond this, major alternative sources of surface water do not exist in the region and additional supplies will have to come from as far away as Canada and the Pacific Northwest. Thus, a warmer, dryer climate would likely produce more problems in this region than in any other region of the U.S.

Finally, in terms of the information contained in Table 5.3, California is an anomaly. While only a small portion of the climate of this region can be classified as dry, when droughts do occur, they tend to directly affect the mountainous part of this region which represents the major source of supply for agriculture in the central part of the region and for the large urban areas concentrated along the Pacific Coast. Moreover, because of the tremendous

pressure which agricultural and urban development have placed on the freshwater resource in that region, California experiences all of the water resource problems associated with humid and dry climates. For these reasons, the California region was included in the list of four candidate areas for further assessment.

Selection of Target Region

The major criterion used to narrow down the number of candidate regions into a single one was the number and scope of generic issues in each region, although several of the criteria including the importance of snowmelt and the effect of manmade controls on runoff were also considered.

Number and Scope of Generic Issues

Table 5.4 shows the distribution of generic issues in the candidate water resource regions, along with an indication of the severity and pervasiveness of the issue within each region. As one can readily see, these issues are fairly widely distributed in terms of their severity in specific regions. Flooding appears to be most severe in the California region, based on the magnitude of average annual damages. Salinity problems are particularly severe in the Colorado, Salt and Gila River basins in the lower Colorado and in the Arkansas and Red River basins, although soil salinity in conjunction with waterlogging is a serious problem in the San Joaquin Valley of California. Sedimentation appears to be most severe in the Arkansas-White-Red River region, largely due to high sediment loads carried from the semiarid western portions of this region. Groundwater mining is more widely distributed than the ratios in Table 5.4 suggest and is a serious problem in all of the regions with the possible exception of California where the problem is more localized.

Of the remaining generic issues, which are directly or indirectly related to surface water supplies, all of them (with the possible exception of conflicts in use) can probably be considered to be most severe in the Lower Colorado River region. The importance of supply problems in that region are magnified both by rapid urban development, a strong comparative advantage nationally in irrigated cotton and, as mentioned earlier, the fact that, once the Central Arizona Project is completed, virtually all of the available storage in the region as well as all of the opportunities for interbasin transfers of water from the Upper Colorado and adjacent regions will have been exhausted.

TABLE 5.4. Distribution of Generic CO₂-Water Resource Issues in Selected Water Resource Regions

Issue	Water Resource Region			
	California	Lower Colorado	Arkansas-White-Red	Missouri
Flooding ^(a)	Average annual damages (AAD) = \$417 million (1975 \$)	AAD = \$122 million	AAD = \$224 million	AAD = \$350 million
Inadequate Supply/Storage ^(a)	Ratio of total use to total assessed streamflow, 1975, U/SF = 82%	U/SF = 225%	U/SF = 83%	U/SF = 87%
Groundwater Mining ^(a)	Ratio of groundwater overdraft to total assessed streamflow, 1975, GWM/SF = 3.1%	GWM/SF = 39.1%	GWM/SF = 8.4%	GWM/SF = 4.5%
River Sedimentation ^(c)	Sediment concentrations in excess of 1,900 ppm limited to southeastern region	Concentrations in excess of 1,900 ppm over entire region	Concentrations in excess of 1,900 ppm on the Arkansas and Red Rivers	Concentrations in excess of 1,900 ppm in northwestern portion and Kansas
Conflicts in Use ^(a)	Severe conflicts limited to Sacramento and San Joaquin Valleys	Severe conflicts between agricultural, urban, residential uses, thermal power generation and recreation	Principal conflicts are between agricultural and urban uses on the Arkansas River in Colorado	Current conflicts are between agriculture and urban uses in the east; potential conflicts are between energy development and all other uses, with regionwide effects
Salinity Problems ^{(a)(c)}	Salinity concentrations in excess of 1,000 mg/l are isolated	Concentrations in excess of 1,000 mg/l are present on the Colorado, Salt and Gila Rivers	Concentration in excess of 2,000 mg/l reported on Arkansas and Red Rivers	Not identified as a problem

TABLE 5.4. (Contd)

Issue	Water Resource Region			
	California	Lower Colorado	Arkansas-White-Red	Missouri
Water Losses from ^(c) Storage Systems	Evaporation from reservoirs ranges about 40 to 65 in./ yr in areas of principal storage	60 to 85 in./yr	45 to 65 in./yr	30 to 55 in./yr
Aquatic vegetation ^{(b)(a)}	Severe phreatophyte problems reported in southeastern California	Severe phreatophyte problems in the eastern, and the southern half of the region	Not identified as a problem	Not identified as a problem

Sources: (a) WRC, 1978 Vol. 2, Parts 2-4 (b) Timmons, 1960 (c) Geraghty et al., 1973

Other Criteria

The Lower Colorado River Region has at least two other, general features which make it the most attractive region for further investigation. The first of these is the importance of snowmelt in determining streamflow. While the total volume of runoff in the region is dominated by inflows from the Upper Colorado River region (which is fed largely by snowmelt), a significant portion of the runoff that flows into the Salt and Gila Rivers, the two second largest sources of freshwater in the region, comes from snowmelt in the northern and eastern portions of Arizona. Snowmelt is also an important source of runoff for the California region. However, the source of this runoff, the Sierra Mountains, is hundreds of miles in most cases from those locations in which surface water supply problems are experienced with any substantial degree of severity.

This raises the question of the effect which the placement and operation of manmade controls in the four regions have on the ability to detect the effect of changes in runoff in small watersheds on the severity of individual, generic issues. In the case of California, as suggested earlier, the effects of climate variability in the Sierra Mountains is usually muffled by the operation of the water supply and delivery system in that state in all but the driest and wettest years. This is also true, although to a lesser extent, of the operation of storage facilities on the Missouri River mainstem, portions of the North Platte River in Nebraska and the Red River mainstem along the border of Oklahoma and Texas, and east to its confluence with the Mississippi.

Flows in the major sub-basins of the Lower Colorado Region are also subject to extensive control by man. However, in the case of the Salt and Gila Rivers, all of these controls are located downstream of their respective drainage areas which is not the case, by and large, of the Arkansas-White-Red or Missouri River Regions. While some of the major river basins in California share this feature with the Salt and Gila Rivers, the nature of the delivery systems between the two regions is vastly different. In California, water is transported west from the mountains via an extensive system of viaducts and large canals, whereas in the Gila River much of the water that is released from upstream storage is conveyed in the main channel of the river. In the Salt River, on the other hand, very little water is released from storage directly

into the main channel, most of it being used in the area around Phoenix for urban, residential and agricultural purposes. In both of these basins, then, the impact of climate changes on runoff from their respective drainage areas should be easier to detect, as should the effects of climate-induced fluctuations in storage on individual, generic issues. At least that is a hypothesis that is advanced for further study. Thus, it would appear that the use of both empirical models and watershed models to characterize the effects of climate change on the hydrologic system is more easily accomplished in the Lower Colorado River Region (or portions of it) than in the others.

Since this can be done without sacrificing the importance of the number and scope of generic issues located in this region, the Lower Colorado River Region was singled out for further study.

River Basin Selection

Within the Lower Colorado River Region, four sub-basins were analyzed using the criteria identified earlier in this section of the report. These sub-basins included:

- The Lower Colorado River mainstem;
- The Little Colorado River;
- The Gila River, and;
- The Salt River.

Lower Colorado River Mainstream

The mainstem of the Lower Colorado River was rejected because, even though the area along the river experiences a number of severe problems common to the region as a whole, the hydrologic system is dominated by channel flow, and extensive manmade controls located all along the river would make it extremely difficult to determine the effect of climate change on either the river flow or the generic issues in the region. Added to this problem is the fact that the principal source of runoff for the Lower Colorado mainstem is located many hundreds of miles to the north in the central and southern Rocky Mountains.

Little Colorado River

Areas in the Little Colorado Basin experience a number of the generic issues. The most severe of these include inadequate water supplies and storage

facilities, groundwater mining, saline ground and surface water, and river sedimentation. Conflicts between urban and agricultural water uses have become particularly severe in recent years due to the rapid growth of Flagstaff. The relatively limited scope of storage facilities in the region would be beneficial to the analysis of this region using both the empirical and the systems-based approach.

Gila River

The Gila River shares all of the same problems that exist in the Little Colorado River, but with somewhat greater severity. In addition, this region experiences severe phreatophyte problems; flooding is a serious problem in upland areas of the basin due to lack of flow regulation and, downstream of Phoenix, due to spillage from reservoirs located on both the Gila and Salt Rivers. Because of its length and east-to-west orientation, the Gila experiences extensive climate variation over space, with precipitation ranging from more than 20 in. in the headwaters drainage areas to less than 6 in. at Yuma, Arizona where it flows into the Lower Colorado mainstem. While the Gila is somewhat more highly regulated than the Little Colorado, the placement of these controls (principally, the San Carlos Reservoir) are situated downstream from the principal sources of runoff, and it does not appear that their presence would represent a substantial hindrance to the methodologies proposed for characterizing the effects of climate change on the hydrologic system.

Salt River

The Salt River is located in central Arizona, flowing roughly from east to west. Along with the Verde River, which flows from north to south, this system contributes the major source of supply for the rapidly growing Phoenix area. The Salt River system, including the Verde, experiences most if not all of the generic issues that are present on the Gila. While surface water salinity and sedimentation are less of a problem on the Salt, groundwater salinity problems are just as severe, as is the case with groundwater mining and flooding in the Phoenix area. In addition, conflicts in use between irrigated agricultural use and urban and residential uses of water are more severe than on the Gila River, due to the rapid growth of Phoenix and the fact that nearly, if not all, of the available storage capacity in the region (which is substantial) is fully

developed. The Salt River basin shares the same degree of physical and climatological variety that is present in the Gila River Basin. Average annual precipitation ranges from as high as 26 in. in the alpine climates in the headwaters regions of the Salt to around 7 in. in the arid, desert climate around Phoenix. On an average, dry years exceed wet years by a ratio of 4 to 1.

The Salt River is highly controlled. Storage facilities on the Salt itself include Saguaro Lake (69,765 af), Canyon Lake (57,852 af), Apache Lake (245,238 af) and Roosevelt Lake (1,281,580 af). Storage facilities on the Verde River include Bartlett Lake (178,185 af) and Horseshoe Lake (139,238 af). Total storage capacity exceeds average annual runoff by a ratio of about 4 to 1. However, from 1941 to 1965, the region experienced a long period of drought during which all of the runoff had to be fully utilized for water supply and hydroelectric generation purposes. In 1965, the population of the area served by these reservoirs was approximately 650,000, and the water delivered was about one million acre feet (Smith 1972). In the period between 1970 and 1980, when runoff was above average, the population of the service area had increased to nearly one million and water deliveries averaged 1.2 million acre feet (SRP 1982). In view of the fact that the useable capacity of all of the reservoirs is less than total capacity (due to dam safety problems), officials are seriously worried about the implications of another period of long drought.^(a)

The placement of reservoirs on the Salt and Verde Rivers does not provide a problem in terms of characterizing the effect of climate change on flows from these facilities for the simple reason that very little water is purposely allowed to flow through these structures. With the exception of the spillage of water during the spring, which frequently produces flooding in Phoenix, and water used to generate power at the upstream dams, most of the remaining water is retained as storage. Since most of the generic issues in the Salt River Basin are associated with the storage, conveyance and use of water, the location of these storage facilities well below the principal drainage areas is ideal for the use of both the empirical and systems-based approaches.

(a) Personal communication with Mr. James C. Brown, Manager, Information Division, Salt River Project.

The final advantages of the Salt River as a site are the management expertise concentrated in the institution of the Salt River Project and the long period of historical records maintained by this organization. Originally formed in 1903 as the Salt River Valley Water Users Association (Smith 1972) to take advantage of the opportunities afforded by the Reclamation Act of 1902, the Salt River Project has a long history of water management in the region which is probably not duplicated anywhere else in the west, except California. Given, first, the rapid growth of population in the Salt River Project service area and, second, the high degree of climate variability in the region to which the system must adjust on a year-to-year basis, this institution represents an important information resource that can be utilized in connection with the case study.

For all of the above reasons, the Salt River was ultimately selected as the best available site for conducting an exhaustive case study of the potential impacts of a CO₂-induced climate change on the supply and allocation of freshwater resources. While the generalizations that can be drawn from such a study will necessarily be limited by demographic, institutional and hydrologic factors unique to the basin, the study will be certainly useful in terms of its ability to show whether or not one can tell if the supply and allocation of the freshwater resource in this area will be affected by a CO₂-induced climate change and, if so, the range of alternatives open for coping with such problems in arid regions.

TRANSFERABILITY OF CASE STUDY FINDINGS

Generalizing the results of hydrologic case studies to a larger number of river basins is complicated by the extreme variety and variability across space that characterize the interaction between climate and the hydrologic systems of individual river basins. Because the physical characteristics and the magnitude of the impacts associated with a water resource issue are to some extent conditioned by the interaction between climate and the component processes of the hydrologic system, selecting a single or even a group of sites which will be representative of a given issue is an extremely difficult undertaking. Increasing the number of issues to be analyzed within the framework of a case

study further complicates the problem of selecting a representative location to adequately characterize the variety and variability that may be associated with all of the issues selected.

With this problem in mind, the remainder of this section examines the extent to which it will be possible to transfer the results obtained for each generic issue from the Salt River case studies to other basins in the U.S. and the rest of the world.

Flooding

Flooding in and around Phoenix occurs when water in excess of the carrying capacity of the Salt River channel is released from the storage reservoirs on the Salt and Verde Rivers. Since the storage capacity of these reservoirs is approximately two times greater than average annual runoff, a series of wet years is normally required before it becomes necessary to spill large volumes of water into the Salt River channel. Flooding along the Salt River could be controlled in all but a few extreme cases by releasing more water from project reservoirs in winter months (thereby reducing the need to spill water during the runoff season). However, the benefits derived from doing so must be weighed against the risks of not having enough water stored behind project reservoirs to meet the demands for water in subsequent months. Because of the extreme variability that characterizes annual runoff in the Salt and Verde river drainages these risks are substantial.

A CO₂-induced climate change which alters the parameters of the distribution of annual runoff has the potential to change the nature of the risks which currently dictate the operating policy of project reservoirs. Thus, while flooding on the Salt River is somewhat atypical of conventional patterns of flooding that come readily to mind, the problems which climatic change may pose from a management perspective are certainly not unique. Balancing the objectives of flood control with water supply is a fairly common problem, particularly in arid regions, and it occurs likely that the results of the Salt River case studies will shed some light on this problem that will be applicable to other regions.

Drought

The return period of extended low flow conditions (e.g., drought) on the Salt and Verde Rivers is approximately 22 years (Smith and Stockton 1981). This finding is consistent with the results obtained by Mitchell et al. (1979) who found a 22 year periodicity in drought occurrence in the western United States. While the frequency of droughts in the Salt River basin is typical of this phenomenon in arid regions throughout the world, the severity of drought impacts in recent history have been mitigated by the large storage capacity available to the residents of the Salt River valley. On the other hand, flow records which have been reconstructed back to the year 1580 (Smith 1981) reveal that there have been several periods of sustained low flows far more severe than any that have occurred since the settlement of the region. The recurrence of any one of these periods of drought would strain the ability of the Salt River project to meet existing demands. Given some potential for a CO₂-induced climate change to increase the frequency of extended low periods, the results of the Salt River case studies regarding drought may be transferrable to many other arid river basins.

Inadequate Storage/Supply

The Salt River is somewhat atypical of developed arid regions with respect to the availability of surface water. Despite the large storage capacity of the Salt River project reservoirs, existing supplies of surface water are usually not adequate to meet the demand for water and must be augmented by groundwater pumping. In addition, there is recent evidence (Smith 1981) to support earlier findings (Anderson 1956) that the productivity of the watersheds in the Salt and Verde basins has been declining since the second decade of the twentieth century. These two factors, coupled with projected growth in the demand for water, suggest that the Salt River basin is characteristic of many basins throughout the world in which future water supply problems are projected to occur around the same time that the concentration of CO₂ reaches 630 ppmv.

Groundwater Mining

The primary source of groundwater in the Salt River valley is an alluvial aquifer which consists mainly of unconsolidated and weakly consolidated clay, silt, sand and gravel. Since 1923, approximately 80 million acre feet of water

have been withdrawn from this formation (USGS 1983). Recharge to the formation depends heavily upon streamflow which, in turn, depends upon the amount of water released from upstream reservoirs. From 1942 to 1964, all of the runoff from the Salt and Verde River drainages was held in storage; no water was released into the main channel of the Salt River. The resulting impact of this policy, coupled with extensive pumping of groundwater to augment surface water supplies, produced a general decline in groundwater levels ranging from 50 to 400 feet (USGS 1978a, 1978b). This trend was reversed briefly during the extremely wet period from February 1978 to May 1980, but in more recent years water levels have once again begun to decline.

From a physical standpoint, the Salt River valley alluvium is by no means unique. Such groundwater formations are fairly common throughout arid portions of the world. Intensive pumping from these formations, as well as the conjunctive supply aspects of the Salt River ground and surface water systems are also not unique. As a result, some of the findings from the Salt River case studies should be transferable to other basins, with similar groundwater formations, in which reservoir management directly affects groundwater recharge.

Sedimentation of Rivers

River sedimentation is not a serious problem on the Salt or Verde rivers, from a practical standpoint, since all of the sediment carried from the drainages of these two rivers is deposited in the Salt River project reservoirs. The impact of erosion and sedimentation in the upstream watersheds of the two rivers is minimal because these areas are largely undeveloped. To the extent that a CO₂-induced climate change may affect either vegetative cover or runoff in these watersheds there is some potential for a change in the amount of sediment transported into project reservoirs. A CO₂-induced climate change could also change erosion rates in upstream watersheds as a result of management practices which might be adopted in the future in order to increase water yields (Rich and Gottfried 1976). However, because of the complex and highly variable nature of the relationship which governs erosion and sedimentation from watershed to watershed, this issue will probably not receive extensive treatment in the Salt River case studies.

Conflicts in Use

Conflicts in use that may be affected by a CO₂-induced climate change involve: 1) the conflict between the objectives of water supply and flood control in the operation of the Salt River project reservoirs; 2) competition between agricultural and non-agricultural uses of water; and 3) competition between non-agricultural uses of water. The first of these conflicts, as pointed out earlier, has somewhat unique overtones. However, the second is fairly commonplace throughout arid regions of the world which are currently undergoing, or are expected to undergo, rapid urban economic growth. The last type of conflict, which is just now emerging in the arid American southwest, involves the competition between rural and urban values in the use of water (Smith 1962). Upward pressure on land values created by rapid growth in the Phoenix area can reasonably be expected to resolve the competition for water between agricultural and non-agricultural uses. However, the desire to preserve rural elements in an otherwise urban lifestyle through ownership of small hobby farms and the maintenance of grass lawns may be less amenable to change through market processes.

Salinity Problems

Surface water salinity is not a serious problem in the Salt River basin. While the concentration of dissolved solids on some of the tributaries of the Salt River is in excess of 2000 mg/l (milligrams per litre) for short periods during the summer (Sommerfeld et al. 1974), this water becomes highly diluted in the Salt River project reservoirs. The dissolved solids concentrations in groundwater in the Salt River valley range from 500 to more than 3,000 mg/l, although most groundwater that contains more than 1,000 mg/l of dissolved solids lies well to the southwest of Phoenix (Kister 1974). Saline water that is pumped from the Salt River valley alluvium may contain dissolved solids in excess of 500 mg/l, but adverse impacts from the use of this water are lessened through mixing with surface water and by its application to relatively salt-tolerant crops such as cotton. At the current time, it seems unlikely that a CO₂-induced climate change would have a major impact on either surface or groundwater salinity.

Water Losses From Storage Systems

Annual average water losses from the Salt River project reservoir and conveyance system due to all causes is around 275 thousand acre feet. Approximately two-thirds of this amount, enough to irrigate approximately 33 thousand acres of cropland per year, is due to surface water evaporation from project reservoirs. Extremely high rates of surface water evaporation, in excess of 70 inches annually, are common throughout the arid American Southwest and other arid regions of the world. As such, the impacts of a CO₂-induced climate change on evaporation from Salt River project reservoirs should be transferable in a general sense to many other arid regions of the world.

Aquatic Vegetation

Water losses due to aquatic vegetation in and along canals and to phreatophytes in the Salt and Verde river watersheds are assumed to be substantial, although the exact amount of these losses is not documented. Losses from canals and laterals are expected to decrease in the future as a result of an ambitious program of canal lining that is now under way. A substantially larger volume of runoff is lost each year due to noxious vegetation, chaparral, pinyon-juniper and stream channel phreatophytes (Barr 1956). Because annual average evapotranspiration is 90 percent or more of average annual precipitation in many of the watersheds, large increases in runoff can be generated by various forms of watershed treatment (Rich and Gottfried 1976). Similar losses and potential gains are common in arid regions throughout the world which again suggests that the findings obtained from the Salt River case studies may be transferable to similar regions.

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APPENDIX A

"SPECIFIC" WORLD WATER SUPPLY/ALLOCATION IMPACT MATRIX

SUPPLY ISSUES					
Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				I_p^+ or I_t^+ = increased magnitude	
				I_p^- or I_t^- = decreased magnitude	
				I_p^0 or I_t^0 = no effect	
<u>Surface Water</u>					
1. Flooding					
a. Upper Mississippi Region, USA	Region is subject to frequent and severe floods. Average annual damages of \$235 million (1975). Projected damages in 2000 are \$380 million/yr.	No change in flood event; Increase in damages.	Flood plain regulation and structural measures could limit increased damages to \$302 million by 2000.	I_p^+ ; increased precipitation increases runoff and flood flows. I_t^+ ; warmer than average winters reduce flooding; rapid spring warming increases flooding.	Soil Conservation Service; Army Corps of Engineers
b. Uttar Pradesh, India	1980 floods claimed 1200 lives; \$325 million in damages; 29,000 km ² of crops suffered.	No change.	Changing settlement patterns affect range and extent of impacts; financing and erecting control structures would mitigate impacts.	I_p^+ ; increases runoff and flood flows. I_t^0 : relatively minor effects in region.	Central Flood Control Board
c. Japan	Average annual property losses from floods (often resulting from monsoons and tropical storms), amount to \$600 million.	Believed to be increasing.	Increased development and occupancy of flood-prone areas increases damage potential.	I_p^+ ; increased precipitation may increase flooding. I_t^+ ; temperature changes may alter timing and magnitude of seasonal storms.	Meteorological Agency River Bureau Ministry of Agriculture and Forestry
d. Pakistan	August, 1973 flood event cost 1500 lives and over \$400 million in damage.	Unknown.	Flood warning and evacuation measures are becoming more effective, but population is increasingly inhabiting flood-prone areas.	I_p^+ ; increases runoff and flood flows. I_t^0 ; relatively minor effect in region.	Water and Power Development Authority
2. Drought					
a. Tanzania	Drought occurs in some regions 2 out of 3 years; one year in five it affects more than half the population; one year in ten it causes major famine. Cost per year of \$19 million (1964-65), or 1.84% GNP.	No change in event; Decrease in impact.	Problem and impacts can be mitigated by development and adoption of drought-resistant crops and by increased climatological sensitivity in development planning.	I_p^+ ; I_t^+ ; extremely sensitive to changes in precipitation and temperature.	Ministry of Water Development and Power

SUPPLY ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)		Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect		
Surface Water (contd)						
b. Australia	Drought affects a substantial part of the continent one year in three. Costs of damage and adjustment are about \$43 million/yr. Most impacts are in agricultural sector.	No change in event; Decrease in impact.	"Drought Watch" information service, drought bonds as insurance for pastoralists, and improved farm management have reduced impacts of drought.	$I_p \uparrow$; effect is important only in transitional climates, $I_t \uparrow$; effect is strongest in transitional climates.		Australian Consultative Committee on Drought
c. Metropolitan New York and sub-areas supplying regional water needs	1960's drought had significant economic impact on the region; the future occurrence of a drought of similar magnitude could cause losses on the order of \$1 billion/yr if the problem remains unsolved.	Increasing impacts	Long-range planning of supplies and regional coordination can help prepare for and mitigate drought effects. However, there is no substantial progress in these areas.	$I_p \uparrow$; strong effect because droughts are short-lived. $I_t \uparrow$; seasonal effects most important in summer.		Currently there is no regional institution with responsibility for future supply problems.
d. Sahelian Region, Africa (Chad, Mali, Mauritania, Niger, Senegal, Upper Volta)	Estimated 100,000 deaths due to drought in 1973 alone. Approx. 2 million people affected by famine, malnutrition, and other drought-related impacts.	Decreasing impacts, but vulnerability to future droughts remains high.	Population distribution, drought planning and emergency preparedness will determine range of impacts of future droughts.	$I_p \uparrow$; increases water supply. $I_t \uparrow$; increased temperature aggravates drought conditions.		Numerous national, local, and international planning and disaster prevention/relief agencies.
3. Sedimentation of Reservoirs						
a. Sanmenxia Reservoir Yellow River, China	Sediment outflow/inflow ratio = 80% in 1974 resulting in more rapid sedimentation than expected; reduces effective life of project.	Decreasing.	Soil conservation and sediment control practices are improving, reducing erosion and sedimentation.	$I_p \uparrow$; $I_t 0$; extreme rain and flood events increase runoff, erosion, and sedimentation.		Yellow River Planning Commission
b. India	On many reservoirs, sedimentation is occurring up to three times faster than expected.	Increasing.	Lack of improved soil conservation schemes results in continued erosion.	$I_p \uparrow$; depends upon annual average precipitation base in region. $I_t \uparrow$; + in dry climates ET increases, reducing runoff and sediment loads		Ministry of Agriculture and Irrigation

SUPPLY ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	
				$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect	
<u>Surface Water (contd)</u>					
c. Lower Colorado River Region, USA	107,000 acre-feet of sediment/yr accumulate in Colorado River and reservoirs; leads to increased salinity concentrations.	No change to moderate decrease.	Land/soil management programs have been designed and are being implemented. Their effectiveness will affect the rate of sedimentation.	$I_p \uparrow$; increases sediment loads $I_t \uparrow$; increases ET and reduces sediment loads	U.S. Bureau of Reclamation, Soil Conservation Service (U.S.D.A.), Local and State Agencies
4. Aquatic Vegetation					
a. West Bengal, India	Aquatic weeds prevent cultivation of 30,000 acres, due to increased ET from irrigation channels, and decreased flows. Agricultural losses in 1974 were \$5.5 million.	Slightly decreasing.	Improvements will result from adoption and use of herbicides, manual control methods, and structural changes in canals. Existing earth bottom canals promote aquatic weeds.	$I_p \uparrow$; precipitation increases water replenishment and supply. $I_t \uparrow$; increases ET and thus water loss.	Ministry of Agriculture and Engineering
b. Texas, USA	Estimated 2,175,000 acre-feet of annual water loss due to evapotranspiration of aquatic vegetation. Estimated value of water lost is \$83 million. Approx. 20% of surface water area is infested.	Increasing.	Level of funding for weed control is a major determinant. Transportation of new weed varieties (primarily by recreational users) affects spread of infestation.	$I_p \uparrow$; replenishes water supplies. $I_t \uparrow$; increases water losses, may promote spread.	Primarily State of Texas, with some Federal assistance.
c. Indonesia	Severe water losses and disruption of flow to agriculture. Agricultural losses due to closing canals for weed control; provides habitat for disease vectors.	Decreasing.	Oil revenues and development policies are resulting in improved weed control through structural, chemical, and manual methods.	$I_p \uparrow$; replenishes water supplies. $I_t \uparrow$; increases water losses	Ministry of Public Works and Electric Power

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				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect		
<u>Surface Water (contd)</u>						
5. Water Losses from Storage Systems						
a. Lake Nasser, Egypt	Evaporation losses are approx. 2500 mm/yr.	No change.	Slightly affected by operation of dam, which affects lake level and surface area available for evaporation.	$I_p \uparrow$; increased rainfall replenishes evaporation losses. $I_t \uparrow$; higher temperatures increase evaporation.		Ministry of Irrigation
b. Lake Mead, Nevada USA	700,000 acre-feet/yr are lost to evaporation; 2-3% of capacity lost leads to increased salinity concentrations.	No change.	Slightly affected by operation of dam, which affects lake level and surface area available for evaporation.	See above.		Bureau of Reclamation
c. Sudan	Daily evaporative losses reach 7.5 mm/yr, causing increased salinity concentrations.	No change.	Slightly affected by dam operation which controls surface area available for evaporation. Use of molecular film to prevent evaporation loss is uneconomical.	See above.		Unknown.
6. Eutrophication						
a. New England, USA	Average of 15% of significant lakes in the region are showing signs of eutrophication at rapid rates that are largely attributed to anthropogenic inputs.	Increasing.	Rate of eutrophication is affected by the nutrient content of point and non-point discharges. Although regulated, the sources and quantities are increasing.	$I_p \uparrow$; precipitation may increase dilution and improve water quality, but may also accelerate some eutrophic processes. $I_t \uparrow$; if water temperatures are increased, biological activity may also increase.		State Water Pollution Control Agencies
b. Lago di Lugano, Italy	Shows serious signs of rapid eutrophication, with 3.5 mg/liter of O_2 at depth of 50 m.	Increasing.	The inflow of nitrates through sewage is a principal cause of increases in eutrophic processes.	$I_p \uparrow$; may reduce nitrate concentration. $I_t 0$.		Ministry of Public Works

SUPPLY ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)		Institutional Responsibility
				I_p^+ or I_t^+ = increased magnitude	I_p^+ or I_t^+ = decreased magnitude	
				I_p^+ or I_t^+ = increased magnitude	I_p^+ or I_t^+ = decreased magnitude	
				I_p^0 or I_t^0 = no effect	I_p^0 or I_t^0 = no effect	
<u>Surface Water (contd)</u>						
c. Lake Constance, (Germany, Austria, Switzerland)	The lake is characterized as rapidly changing from oligotrophic to eutrophic state. Oxygen deficit of up to 50% in some areas; phosphate has increased since 1936 from undetectable levels to 20 micrograms/litre; primary production of organic substances has increased 20-fold in the past 40 years.	Decreasing.	Control of municipal and industrial discharges and construction of treatment facilities have been implemented and should result in improved conditions.	I_p^+ ; may reduce effluent concentrations. I_p^0 .		International Water Water Protection Commission for Lake Constance
7. Effects of Land Use Changes on Basin Hydrology						
a. Upper Amazon River Basin, Peru and Ecuador	Moderate problem of increased runoff and increasing flood crest due to large scale foresting.	Increasing.	Deforestation, which changes the soil regime and thus the runoff, is increasing. Few controls on foresting practices exist at present.	I_p^+ ; increased precipitation increases runoff. I_t^+ ; increased temperature may affect re-vegetation and transpiration.		SENAMHI (Service Nacional de Meteorologia e Hidrologia de Peru)
b. Puerto Rico and Virgin Islands	Urban expansion reduces natural aquifer recharge area; reduces aquifer recharge; moderate problem in island area with limited fresh water supplies.	Increasing.	As urban expansion and development increases, the recharge area will decrease further.	I_p^+ ; increased precipitation increases recharge in those areas not deteriorated. I_t^0 .		Puerto Rico Department of Natural Resources
c. Upper Mississippi Region (Minnesota, Iowa, N. Dakota), USA	Widespread draining of wetlands for agriculture has changed drainage characteristics of basin. Exacerbates flooding; reduces groundwater recharge.	Increasing.	Expanding agriculture requires greater acreage, thereby increasing the use of poorly drained soils.	I_p^+ ; increased precipitation increases flooding. I_t ; effect unknown. (See 1.a. for effect of flooding.)		Soil Conservation Service; State Drainage Districts and Water Resources Agencies

SUPPLY ISSUES

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				$I_p 0$ or $I_t 0$ = no effect		
<u>Surface Water (contd)</u>						
8. Inadequate Storage/Supply						
a. Boston, Massachusetts, USA	The metropolitan area has "critical water supply problems." The dependable supply is 300 mgd, whereas average daily use in 1976 was 317 mgd, and is projected to be 441 mgd by 1990.	Increasing.	Demand is rapidly increasing, but no plans have been approved for augmenting supplies. Will probably require a mass transfer from Connecticut River.	$I_p \uparrow$; increased precipitation would help alleviate supply problem. $I_t \uparrow$; increased temperature aggravates problem by increasing evaporative losses and consumption.		Metropolitan District Commission
b. Hong Kong	Water demand for 1984 is projected to be 138% of annual dependable water supply given current level of water development.	Increasing.	Ability to increase storage capacity for seasonal precipitation and increases in imported water from China and in desalination will determine the severity of the supply problem in the next decade.	See above.		H. K. Public Works Department
c. India	Given current trends, the demand for water will exceed the total dependable supply by around 1990. In some areas (notably Tamil Nadu and Uttar Pradesh states), demand already exceeds dependable supplies or will do so by 1985.	Increasing.	Rapid growth in irrigated agriculture, and to a lesser extent in industry, is causing equally rapid growth in demand for water. More efficient irrigation practices and increased storage capacity for monsoon rains will help reduce the disparity between demand and dependable supplies.	See above.		Ministry of Agriculture; Irrigation Commission

SUPPLY ISSUES

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				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect	$I_p 0$ or $I_t 0$ = no effect	
<u>Groundwater</u>						
1. Groundwater Mining						
a. San Joaquin Valley, California, USA	Aquifer mining supports 600,000 acres of crops, production value \$613 million in 1975. Overdraft = 1.5 million acre feet/yr. Land subsidence up to 8.5 m.	Increasing.	Increasing irrigation and municipal demands for water, and the declining quality of surface water aggravate the problem.	$I_p \uparrow$; precipitation augments available supplies and may increase rate of aquifer recharge. $I_t \uparrow$; temperature increase aggravates problem by increasing evaporation and consumption		California Department of Water Resources
b. Tokyo, Japan	Groundwater overdraft has resulted in land-subsidence of 3-4 meters, causing damage to buildings and infrastructure.	Decreasing.	Improvement of surface water supplies by damming streams has reduced reliance on groundwater.	See above.		Tokyo Metropolitan Government
c. Mexico City	Aquifer being drained twice as fast as recharge at 50 m ³ /s; serious problem. Land subsidence up to 8 m in some areas over past 100 years.	Increasing 5-10 years, decreasing after that.	Rapid increase in demand aggravates problem (population increase ~600 k/yr); mass transfer schemes from 3 river basins are in the planning stages.	See above.		Commision de Aguas del Valle de Mexico
d. Texas (Ogallala Aquifer), USA	Groundwater supplies are declining beneath 6.4 million acres (82% of the irrigated land). Annual decline averages 2 feet. At current rates, irrigated acres will decline by 50% by the year 2020.	Increasing.	Trend will be affected by changes in technology, agricultural practices, mass water transfers, relocation of certain water intensive crops, and energy prices.	$I_p 0$; large increases required to reverse drawn-down $I_t \uparrow$; increases ET.		Texas Department of Water Resources

DISTRIBUTION ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
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<u>Quantity</u>					
1. River Sedimentation					
a. Mississippi River River Basin, USA	Average sediment load at St. Louis is 500,000 tons/day; at mouth 825,000 tons/day. Maintenance dredging at ports of New Orleans, Baton Rouge and elsewhere is required to maintain navigability.	No change due to channel control.	Highly erosive character of area soils, poor soil conservation practices of farmers, increased flooding, and changing shoreline all affect erosion and sedimentation.	$I_p \uparrow$; increased precipitation affects runoff and erosion. $I_t 0$; effects of temperatures on flooding are indirect.	Corps of Engineers; USDA; State Water Resources Agencies
b. Bangladesh	Most major rivers are badly silted up, aggravating monsoon flooding problem.	Increasing.	Sediment control and channelization are needed, but not yet planned.	$I_p \uparrow$; through flooding. $I_t 0$; effects on flooding are indirect.	National Economic Council; Bangladesh Water Development Board
c. Rio Grande Region, USA	45,000 acre-feet/year of sediment load; results in siltation of canals, aggraded stream channels, and rising water table which enhance phreatophyte growth, thus increasing ET losses.	Increasing.	Control requires improved soil management and designation of sediment storage reservoirs.	$I_p \uparrow$; increases runoff and sediment load. $I_t \uparrow$; increases ET and reduces runoff carrying sediment loads.	USDA; Bureau of Reclamation
2. Conveyance Losses					
a. Western USA	Up to 21.7% water loss rate from conveyance systems, of which 23% was attributed to seepage and 14% to operational waste.	Slightly decreasing.	Canal lining and improvement projects will continue to reduce seepage, but not necessarily reduce operational waste.	$I_p \uparrow$; precipitation reduces impact of losses. $I_t \uparrow$; increased temperature indirectly impacts seepage through increased transpiration of plants using fugitive water.	USDA; Bureau of Reclamation
b. Australia	41.4% of inflow to canal systems is lost due to seepage and operational waste.	Increasing.	As more pressure is placed on agricultural production by local population and export demand growth, structural measures may have to be implemented to cut the losses.	See above.	Australian Department of Natural Resources

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DISTRIBUTION ISSUES

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				$I_p 0$ or $I_t 0$ = no effect	
<u>Quantity (contd)</u>					
c. France	Serious losses from systems due to leaks, seepage, evaporation; impacts are amplified in times of drought.	Decreasing.	Improvement programs underway to correct structural flaws and to line canals.	See above.	Service de l'Hydraulique
d. Uttar Pradesh and Punjab, India	Seepage losses up to 36% of flow are reported, having severe impact on efficiency and availability of irrigation water.	Decreasing.	Development and adoption of seepage controls such as canal lining, closed conveyance systems, and surface film are underway. If successful, these programs will improve efficiency.	See above.	Ministry of Agriculture and Irrigation
3. Availability of Potable Water					
a. Nigeria	77% of population is without access to safe, modern water supplies.	Decreasing.	Primary determinants are the availability of technical, financial and human resources for improving distribution planning and construction.	$I_p \uparrow$; problem is mainly infrastructure/institutional, but increased precipitation would help alleviate some regional stresses on supply. $I_t \uparrow$; increased consumption would strain existing distribution systems.	Federal Ministry of Water Resources; Western Nigeria Water Corporation; River Basin Development Authorities
b. Latin America	94 million rural people are without "reasonable access to minimum quantities of drinking water essential to health." This is 28% of the region's population.	Decreasing.	Plans are being developed and implemented to improve access by 1990.	See above.	At Regional Level, Economic Commission for Latin America
c. Thailand	Only 20-25% of rural population have access to safe water.	Decreasing.	Aggressive program plans to provide safe water to 100% of population by the year 1991.	$I_p \uparrow$; increased flooding may lead to more severe public health and conditions. $I_t \uparrow$; increases ET and consumptive demands for water.	Rural Water Supply Agency

DISTRIBUTION ISSUES

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<u>Quality</u>					
1. Channel Erosion/ Channel Scour					
a. San Joaquin-Sacramento Valley, USA	Bank erosion is destroying fertile farm land and causing navigation problems damaging habitat; requires maintenance dredging.	Increasing.	Land use practices are primary factor in erosion problem.	$I_p \uparrow$; increased precipitation increases runoff and erosion. $I_t \uparrow$; increased temperature may increase ET, leaving less water for runoff and erosion.	Corps of Engineers; State Land and Water Resource Agencies
b. Irtys River, USSR	76.3% of total length (4248 km) is subject to serious bank erosion or channel scour.	Unknown.	Construction of hydro-electric series on the river affects bank erosion and channel scour, but direction and magnitude of the effect will vary depending on location, dam operation, etc.	See above.	Ministry of Land Reclamation and Water Management
c. Lower Mississippi, New Orleans and Baton Rouge Area, USA	Flood control measures prevent silt deposition from annual floods, and delta area is rapidly eroding. Net land loss throughout area is 16.5 square miles.	Increasing.	Methods needed to effectively control stream bank erosion.	$I_p \uparrow$; precipitation and increased streamflow might increase erosion. $I_t 0$; effects of temperature on flooding are indirect.	Corps of Engineers

USE AND REUSE ISSUES

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Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	Institutional Responsibility
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$I_p 0$ or $I_t 0$ = no effect					
<u>Quantity</u>					
1. Inefficient Irrigation Practice/Management					
a. Minidoka Irrigation District, Idaho, USA	Crops receive 3-4 times the amount of water they actually require for optimum yield. Results in raised water table, increased salinity in root zone, and reduction in yield. Crop value reduced by 25% relative to those grown with more efficient irrigation practices.	No change.	The price structure of irrigation water is a prime cause of inefficiency. Farmers are assessed a one-time annual fee for water use, based on acreage farmed rather than quantity used.	$I_p \uparrow$; increased precipitation augments available supplies. $I_t \uparrow$; increases demand for water due to higher ET.	Minidoka Irrigation District
b. Pakistan	Efficiency of use of available irrigation water approx. 30-40%.	Moderate decrease.	Poor irrigation techniques and an inadequate distribution system are key determinants, and these are gradually changing.	See above.	Water and Power Development Authority
c. Bangladesh	Deep tubewells are designed to serve 33 hectares, but in practice only serve 22 ha. Shallow tubewells designed for 8 ha, but serve <3.5 ha. Total of 31,000 wells installed by 1981.	Decreasing.	Mainly due to inadequate distribution and waste caused by social elite controlling well output & distribution.	Primarily institutional problem, but: $I_p \uparrow$; increased supply would lessen impact on those not in control of wells. $I_t \uparrow$; increased consumption might aggravate problems particularly for those not in control of wells.	Bangladesh Agricultural Development Corp (BADC) Agency for Int'l Development

USE AND REUSE ISSUES

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<u>Quantity (contd)</u>					
2. Waterlogging (of soils)					
a. Pakistan	24% of irrigated area sampled (1978) had watertable depth 0-6 ft.	0-10 yrs increase; 10-20 yrs decrease.	Problem is a function of poor drainage, structural faults in irrigation systems, poor design and imple- mentation of remedial programs, lack of financing. These fac- tors are beginning to improve.	$I_p \uparrow$; increased precipitation could aggravate problem by raising the water table. $I_t \uparrow$; increased temperatures increase evapotranspiration and thus reduce water-logging.	Water and Power Development Authority.
b. Egypt	Poor drainage in irrigated lands reduces yields up to 30%.	Increasing.	New year-round abun- dance of water in some areas results in excessive use; lack of price on water and outdated practices are two causes.	$I_p \uparrow$; aggravates drainage problems. $I_t 0$	Ministry of Irrigation
c. Western U.S.A (17 Western States)	About 42% of the presently irrigated land is "drain- age deficient," and suffering varying degrees of waterlog- ging. Average cost/ hectare of installing drainage would be \$1150-\$1870.	Increasing	Construction of drainage systems will improve con- ditions, but this is a long-term and expensive task for the 9.2 million hectares requiring drainage.	$I_p \uparrow$; may cause rise in saline water table. $I_t \uparrow$; increases in ET may stabilize rise in water table, but could also increase irrigation leaching practices, causing water table to rise into the root zone.	Bureau of Reclamation

USE AND REUSE ISSUES

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				$I_p 0$ or $I_t 0$ = no effect		
<u>Quantity (contd)</u>						
3. Groundwater Infiltration into Municipal Sewer System						
a. 65 U.S. Cities	Groundwater infiltration & inflow ranges from 89-166 gal/person/day compared to sewage input of 70 gal/person/day. Increases costs and reduces effectiveness of sewage treatment systems and programs.	Increasing.	The condition of the structural system and the ability for state, Federal and local gov't to coordinate improvements will affect the extent of the problem.	$I_p \uparrow; I_t 0$; average infiltration rates increase by 37% at times of high groundwater.		State and local gov't responsibility with Federal financial assistance
b. Quebec City, Canada	80% of the flow in the sewer system consists of freshwater infiltration and inflow. Increases costs of conveyance and treatment.	Increasing.	The condition of the system deteriorates with age, and at present little is being done to rehabilitate it.	See above.		City and Provincial Responsibility
4. Effect of Changing Water Levels on Aquatic Ecosystems						
a. Sahelian Zone, West Africa (Lake Chad; Senegal & Niger Rivers)	Reduction in fish catch attributed to changing water levels, 1969-1973: Niger River - 38% reduction, Senegal River - 57% reduction. Lake Chad: the bulk of the migratory species have disappeared.	Dependent on climate variations.	Primarily a function of changing precip. & flood patterns, 1962-1974. Aggravated by other stresses on the fishery, such as overfishing.	$I_p \uparrow; I_t \uparrow$; Highly sensitive to medium- and long-term climate variability. Changes in precipitation and temperatures cause significant water level fluctuations, which affect spawning habitat.		Chad: Bureau de L'Eau. Senegal: Service Hydrologique. Nigeria: Federal Department of Agriculture.
b. Lake Chilwa, Malawi	Fish harvest at high water (1965) = 10,000 tons. Fish harvest at low water (1968) = 100 tons. Extreme catch variation with changing lake levels.	Depends on climate variability.	Recovery can be accelerated by restocking, but this is costly.	See above.		Water Resources Division, Ministry of Agriculture and Natural Resources

USE AND REUSE ISSUES

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				$I_p 0$ or $I_t 0$ = no effect		
<u>Quantity (contd)</u>						
c. Caspian Sea, USSR	Lake Surface area declined 10% since 1929; fish catches declined more than 50%.	Increasing to 1983-85, then decreasing.	Consumptive uses of streams feeding the Caspian increase water deficit. There are plans to divert flow of other rivers into Caspian to increase fresh-water input.	$I_p \uparrow$; increased precipitation may help alleviate the stresses of consumptive uses on the lake water budget. $I_t \uparrow$; increased temperature will increase consumption and evaporation.		Caspian Sea Committee, USSR Ministry of Water Resources
5. Navigation Problems						
a. Niger River & Benue River, West Africa	Of available navigation time, 15% lost to un-navigable river due to seasonal conditions; 5-7.5% lost to groundings or waiting due to river conditions.	Decreasing.	The rate of economic development and the demand for river transportation affect the magnitude of the problem. A multi-objective river management plan (including improved navigation) is being implemented.	$I_p \uparrow$; increased precipitation may increase flows. $I_t \uparrow$; increased temperature may increase evaporation and consumption of water by competing uses.		Unknown
b. York River, Chesapeake Bay, USA	Lack of sufficient channel depth for large petroleum tankers; and lightering results in increased costs and increased spills.	Increasing.	Increasing petroleum movements (100% increase by 2000) and lightering operations will increase spill probability. Channel deepening would permit larger vessels, reduce spill probability.	$I_p 0$; because of floodplain topology increased precipitation will not enhance navigability. However, a decrease in precipitation will reduce flows needed to maintain channel depth.		Corps of Engineers

USE AND REUSE ISSUES

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				I_p0 or I_t0 = no effect	
<u>Quantity (contd)</u>					
c. Missouri River System, USA	During droughts, because of upstream depletions, there is not enough water for full 8-month navigation season. Reduces tonnage shipped, negative effect on shippers' desire to use waterway, and consequent effect on economic development.	Increasing slightly.	Upstream depletion for irrigation, municipal and industrial uses contributes to reduced flows, but primarily a function of climatic variability.	$I_p\uparrow$; increased precipitation may increase flows. $I_t\uparrow$; increased temperature may cause evaporation losses and increased consumption of water by competing uses.	Missouri River Basin Commission; Gov'ts of affected states; Corps of Engineers
d. White Nile River, Southern Sudan	Currently navigability is impeded by intermittent swamps.	Decreasing.	Jonglei Canal Project which will be completed in early 1980s, will provide a more direct and navigable route.	$I_p\uparrow$; increased precipitation might improve flow and navigability. $I_t\uparrow$; increased temperatures might reduce flow.	Unknown
6. Conflicts in Use					
a. Between Instream Uses					
1. Ohio River near Cincinnati, USA	The construction of Markland Dam, primarily for purposes of improving navigability, has resulted in decreased dissolved O_2 levels in river. This has reduced the waste assimilative capacity of the river in the Cincinnati reach by about 30%. Thus, it is a conflict between navigation and the use of the river as a waste water receiving body.	No change.	The need for improved flow regulation for shipping resulted in the construction of the dam. Increase in wastewater discharges from the city could further aggravate the problem, although improved water treatment is likely to be implemented in the near future.	$I_p\uparrow$; increased precipitation flow could help improve water quality through dilution. $I_t\uparrow$; increased temperature may increase consumption and thus waste water. If warmer atmosphere acts to raise water temperature, then the problem will be aggravated further since warm water holds less O_2 in solution.	Corps of Engineers; City of Cincinnati

USE AND REUSE ISSUES

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				$I_{p\downarrow}$ or $I_{t\downarrow}$ = decreased magnitude	
				I_{p0} or I_{t0} = no effect	
<u>Quantity (contd)</u>					
2. Indus River, Pakistan	Although fish ladders have been constructed on all dams and diversion weirs, their design has not functioned properly, and consequently fish migrations and populations have been reduced. This will become of growing concern with expected increased reliance on fish as a food source, and with further construction of structures on the river.	Increasing.	Primarily a function of poor design of fish ladders to permit fish migrations.	I_{p0} ; I_{t0} ; Entirely a structural problem.	WADPA (Water and Power Development Administration)
3. Columbia River Basin, Washington, USA	Conflict between hydroelectric power generation and instream flow protection for salmon has produced 60% decline in fish runs since mid-1950's.	No change to slight decrease.	Hatchery programs and fish "ladders" have helped enhance fish stocks, but increased electricity demand might affect magnitude of issue.	$I_{p\uparrow}$; increased precipitation will permit greater instream flows. $I_{t\uparrow}$; increased temperature causes greater evaporation losses and increases electricity demand in summer.	Bonneville Power Administration, Local Utilities, Washington State Departments of Ecology and Fisheries, Northwest Power Council
b. Between Offstream Uses					
1. Four Corners Region, USA (Utah, Colorado, New Mexico, Arizona)	Rapid energy development in the region--in which existing surface water supplies are fully allocated--may require by 1985-2000 up to 30% of the quantity of water currently allocated to agriculture. Associated regional income and job losses would be approximately \$8.5 million and 416 respectively. A \$5 million reduction in farm income is projected.	Increasing.	Increasing demand for energy is the primary determinant. Changes in energy demand and/or development of new water supplies through mass transfers could help mitigate impacts. More efficient Irrigation could have similar effect.	$I_{p\uparrow}$; increased precipitation increased available supply, reduced irrigation requirements. $I_{t\uparrow}$; increased temperature increases demand for water for agriculture, human consumption and electricity generation.	U.S. Department of Interior; State Water Resource Agencies

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	
				$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect	
<u>Quantity (contd)</u>					
2. Punjab, India	Up to 15-20% of irrigation water delivered to canals is being pumped as fugitive groundwater outside the project. This results from seepage from canals and the conjunctive nature of surface and groundwater supplies in the area.	No change to increasing.	Primarily caused by seepage from canals to aquifer. Increased demand for food has led to increased pumping of fugitive irrigation water. Lining of canals would help reduce seepage losses.	$I_p \uparrow$; increased precipitation increases supply to mitigate conflict. $I_t \uparrow$; increased temperatures increase transpiration, thus magnifying competition for irrigation water inside and outside the project area.	Ministry of Agriculture and Irrigation
3. Maipo Basin, Chile (includes Santiago)	Conflict between agriculture and drinking water demands will result in 32% reduction in irrigated agriculture by 2000 if no new supplies become available. Population will double by then, increasing demand.	Increasing.	Mass water transfers, improved efficiency, rate of population growth, and ability to change to non-irrigated agriculture will affect magnitude of conflict.	$I_p \uparrow$; precipitation augments supply. $I_t \uparrow$; increased temperature increases consumption.	Direcion General de Aguas Canal Users Association Private, Municipal and State Water Companies
c. Between Instream and Offstream Uses					
1. Danube River (Austria, Czech., Hungary, Yugoslavia, Bulgaria, Romania, USSR, FGR)	Rapid growth in irrigated agriculture will increase withdrawals from 1300 m ³ /s in next 20 years. In fall months of low flow, this is expected to conflict with instream flow requirements for navigation, which accounts for over 73 million tons of cargo transportation.	Increasing.	The concurrent growth in irrigated acreage and shipping intensify the conflict between instream flow needs to maintain navigability, and water requirements for agriculture.	$I_p \uparrow$; increased precipitation increases available supply to reduce competition among users. $I_t \uparrow$; increased temperatures increase agricultural consumption, thus intensifying conflict.	Danube Commission

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)		Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
<u>Quantity</u> (contd)				$I_p 0$ or $I_t 0$ = no effect		
2. Snake River, Idaho, USA	Conflict between water demands for hydro-electric power and irrigation. Tradeoff ranges from 51 to 1821 kWh of electricity foregone per acre-foot of irrigation water diverted.	Increasing.	There is currently a moratorium on electricity hook-ups for irrigation water pumping. Increased population in the region intensifies competition through greater demands for electricity and agricultural commodities.	$I_p \uparrow$; increase in summer rainfall would have greatest impact. $I_t \uparrow$; increase in summer temperatures would have the greatest impact.		Bonneville Power Administration Local Utilities Local Irrigation Districts Northwest Power Council
3. Sinaloa and Sonora, N.W. Mexico	Freshwater is diverted to upstream agricultural users, causing reduced flows to coastal lagoons which are spawning grounds for valuable blue shrimp; production has decreased markedly since initiation of rapid irrigation development.	Increasing.	Mexico is pursuing a policy of agricultural development in this area, which will require increased diversions for irrigations.	$I_p \uparrow$; increased precipitation would help alleviate problem. $I_t \uparrow$; increased temperatures would increase irrigation diversions.		Secretaria de Recursos

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	
				$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect	
<u>Quality</u>					
1. Saline Intrusion of Aquifers					
a. Long Island, New York, USA	Pumping has lowered water table to as much as 35 feet below sea level. Serous saline intrusion problems resulted in abandoning of ground-water and turning to imported water supply.	No change to slight decrease.	Efforts to salvage storm runoff and waste water for aquifer recharge may reduce saline intrusion.	$I_p \uparrow$; increased precipitation increases freshwater recharge. $I_t \uparrow$; increased temperature increases consumption and thus aquifer depletion and intrusion.	U.S. Geological Survey; Local Water
b. Brighton, England	Winter chloride levels of pumped groundwater were 30 mg/l. Summer value after winters of low rainfall were 300+mg/l. Pumping has been discontinued at times due to high chloride levels.	Decreasing.	Since chloride levels are associated with tidal cycles, pumping is being programmed to coincide with low tide period to avoid high salinity.	See above. Although salinity problem is primarily a function of tidal infiltration through fracture zones, changes in temperature and precipitation can affect magnitude of problem.	Brighton Water Department
c. Puerto Rico and Virgin Islands	Currently not serious, since growth in population, development, and ground-water use are in early stages.	Increasing.	The rate of ground-water depletion (which is a function of population growth and development) lowers water table and increases salt-water intrusion; urban expansion reduces aquifer recharge.	$I_p \uparrow$; increased precipitation increases freshwater recharge $I_t \uparrow$; increased temperature increases demand for consumptive uses of water.	Corps of Engineers; Department of Natural Resources; Virgin Islands Department of Conservation and Cultural Affairs
d. Lebanon	At Khalie, total dissolved solids = 1000 ppm at a depth of 50 m. This prevents large groundwater pumping since seawater intrusion would increase. Problem occurs in many Lebanese coastal areas.	Increasing.	Increased economic and agricultural development may require greater reliance on ground-water, thus increasing potential for saltwater intrusion.	See above.	Unknown

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)		Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude		
				$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude		
				$I_p 0$ or $I_t 0$ = no effect		
<u>Quality (contd)</u>						
2. Salinity Problems						
a. Surface Water Salinity						
1. The Gambia: "maritime sector" of Gambia R. Basin	At the height of the dry season, coastal saline waters intrude 290 km inland	Increasing..	Due to: a) Quantity of fresh-water discharge b) Level of prevailing spring and leap tides; c) Small gradient of river bed.	$I_p \uparrow$, increased freshwater flow reduces intrusion. $I_t 0$; coastal problem.	Unknown.	
2. Murray River, Australia	In the downstream reaches, salinity may rise as high as 1200 mg/l under conditions of low flow. Under normal flow conditions, the salt load is increased by 350,000 tons contained in surface drainage, and a further 50,000 tons contained in groundwater inflow. Affects productivity of some crops and the water supply for the city of Adelaide.	No change to slight decrease.	Efforts are under way to improve conditions by increasing dilution flows from storages and reducing saline return flows from irrigation.	$I_p \uparrow$; increased precipitation improves dilution, but may also increase leaching of soil salts. $I_t \uparrow$; increased temperature aggravates problem by increasing evaporation and concentration of dissolved solids.	River Murray Commission	
3. Lower Colorado River Basin, USA	Dissolved solids usually range 500-900 mg/l, with increases to 1150 mg/l at Imperial Dam. Total dissolved solids transport is about 8 million tons/yr. Projected increase of 35-50% by 2000, with projected damages of \$165 million/yr. Each 1 ppm increase in salt results in \$230,000 in damages.	Increasing.	Primarily a result of agricultural return flows and natural salt sources, which account for 37% and 47% respectively of river salinity. Improved irrigation management could reduce salinity. Desalinization plants also might improve conditions.	$I_p \uparrow$; increase in flash floods in lower basin could transport additional salts to soil. $I_t \uparrow$; increases ET which may lead to more extensive leaching of salts into soil and increase saline return flows.	Bureau of Reclamation	

USE AND REUSE ISSUES					
Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	
				$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect	
<u>Quality</u> (contd)					
b. Soil Salinity					
1. Pakistan	30% of 21 million irrigated acres surveyed in 1978 were slightly too strongly saline; 12% saline, 8% moderately saline; 10% strongly saline.	Decreasing slightly to 2000.	A poor and antiquated irrigation system contributes to problem. If successful, the current aggressive tubewell drilling program will help reduce salinity through leaching.	$I_p \uparrow$; precipitation promotes leaching of salts out of soil. $I_t \uparrow$; evaporation increases salinity concentrations.	Salinity Control-Reclamation Program
2. San Joaquin Valley, California USA	In 1975, 600,000 acres suffered productivity loss or required shift to more salt-tolerant crop, due to high salinity and waterlogging problems. By 2000, the total is expected to increase to 1 million acres. Estimated economic losses are \$37 million.	Increasing.	Continued use of saline irrigation waters, and poor drainage systems, will increase problem, but improved salinity management and drainage systems are gradually being installed in some areas.	$I_p \uparrow$; increased precipitation improved leaching, but also may aggravate waterlogging. $I_t \uparrow$; increased temperatures may increase salinity concentration through evaporation.	Bureau of Reclamation; Soil Conservation Service
3. Egypt	Salinization affects 33% of cultivated land in Nile; 25% of cultivated land in Upper Egypt; 54% of cultivated land in N.W. Nile Delta; Total of 4 million acres affected; agricultural losses of \$600 million/yr.	Increasing in most areas.	Poor agricultural practices, the land tenure system and the increased water salinity due to Aswan Dam all contribute to the problem.	$I_p \uparrow$; precipitation decreases the salinity of irrigation water and improves leaching. $I_t \uparrow$; increased evaporation raises salinity concentration.	National Water Authority, Ministry of Irrigation

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				$I_p^{\uparrow}$ or $I_t^{\uparrow}$ = increased magnitude $I_p^{\downarrow}$ or $I_t^{\downarrow}$ = decreased magnitude I_p^0 or I_t^0 = no effect	
Quality (contd)					
3. Waterborne Disease					
a. Nile Valley, Egypt	Schistosomiasis: population infection rates up to 100% in some areas. Associated losses in economic productivity were \$100-200 million in 1977, excluding medical costs.	Increasing.	Poor sanitation and waste disposal provide favorable habitat for disease vectors, as does the change from sporadic to perennial irrigation.	Unknown, although temperature may be a limiting factor in disease propagation and distribution.	Ministry of Health
b. Philippines	Schistosomiasis: economic losses (1963) >\$6.5 million/yr.	Unknown.	Poor sanitation and waste disposal provide habitat for disease vectors.	See above	National Irrigation Administration; Bureau of Public Works
c. Red and White Volta Rivers, Ghana	Onchocerciasis has caused the area to become virtually depopulated, going from 120 people/mi ² to less than 20 people/mi ² in this fertile river valley.	No Change.	Effective disease control programs and safe drinking water facilities might eventually allay local fears and result in resettlement.	See above.	World Health Organization World Bank Government of Ghana
5. Groundwater Contamination					
a. San Gabriel Valley, California USA	In 1980, 39 public wells supplying water to 400,000 people were closed due to TCE contamination up to 600 ppb.	Increasing. (regionally)	Availability and adoption of control, monitoring and waste recycling processes is necessary to prevent further contamination.	I_p^0 ; increased precipitation dilutes waste, but raises water table. I_t^0 .	EPA, State Water Pollution Control Board
b. Poland	Of 90,600 wells only 5% have clean water, and in almost 70% of the wells the water was not fit for drinking. In 1974, only 44% of the wells were found to be unfit for drinking.	Increasing.	It is believed that the discharge of untreated sewage is a primary cause of both surface and groundwater contamination.	Unknown	Ministry of Administration; Regional Economy, and Environmental Protection

A 43

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)	Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude $I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude $I_p 0$ or $I_t 0$ = no effect	
Quality (contd)					
c. Love Canal, New York, USA	Poorly disposed toxic chemicals have contaminated the soil and groundwater. More than 80 chemicals have been identified, of which at least 7 are known carcinogens. Resulted in total evacuation of surrounding community, increased miscarriage and birth defects.	Unknown	Uncontrolled and unmonitored toxic waste disposal, and subsequent uncontrolled settlement were primary causes.	$I_p \uparrow$; toxicities of PCB's are too high to be diluted, but increased precipitation might affect percolation and/or raise water table. $I_t 0$.	U.S. EPA
d. Rhine Aquifer, Eastern France	Rainwater has percolated through potash mine waste dumps, resulting in severe groundwater pollution by sodium chloride. This has had adverse effect on the drinking water quality of the city of Colmar.	Increasing.	Although industrial discharges have been controlled, the contamination is spreading. This may be because of the disappearance of industrial wells which once acted to collect a major part of the effluent.	$I_p \uparrow$; increased precipitation could increase the rate of recharge with fresh water, but might also aggravate the deep percolation of contaminants from mine sites. $I_t 0$.	City of Colmar
6. Surface Water Contamination					
a. Laguna de Bay Basin, Philippines	Lake is severely degraded by feedlot runoff, human waste, and ag. runoff. In dry season, lake level drops and high tide pushes highly polluted water from Pasig River into the lake.	Decreasing.	There is a lack of industrial and domestic wastewater treatment, but 2 such plants are being planned. The rate of industrial & population growth will affect the issue magnitude.	$I_p \uparrow$; enhances dilution of wastes; but problem may be aggravated by flooding of waste sites. $I_t \uparrow$; increased temperatures increase consumption and concentration of contaminants by evaporation.	Laguna Bay Development Authority.

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)		Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude		
				$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude		
				$I_p 0$ or $I_t 0$ = no effect		
<u>Quality (contd)</u>						
b. Mexico (particularly the Rio Lerma and Pamuco Basins)	95,000 dischargers of pollutants. 11 river basins of "extreme urgency". 45 river basins of "priority attention". Large amounts of untreated effluents discharged.	Very slow decrease.	The effectiveness of new laws against industrial and municipal waste dumping and cooperation between Federal & State agencies will determine the rate of improvement.	$I_p \downarrow$; reduces concentration of effluents in surface water. $I_t \uparrow$; increases ET and concentration of effluents.	Direcion General de Protecion y Ordenacion Ecologa.	
c. Hudson River, New York, USA	An estimated 500,000 pounds of polychlorinated biphenyls is lodged in the river bed, the result of decades of unregulated discharges. PCB levels in fish average above 5 ppm which is the recommended limit for human consumption.	Discharges are decreasing, but the problem persists due to the nature of PCB's in the environment.	Dredging the entire contaminated section of the river is being considered (it would cost \$204 million), but it could cause more harm than good.	$I_p \downarrow$; toxicities of PCB's are too high to be diluted effectively, but flooding may increase contamination in soils. $I_t 0$.	N.Y. Department Environmental Conservation; U.S. EPA	
d. Ria River, Spain	Mercury levels in the river's fish range from 1-24 ppm, while acceptable level for human consumption is 10 ppm. Also, Biological Oxygen Demand level is around 10 ppm.	Unknown.	Industrial discharges are responsible for high mercury levels. Discharge controls would help alleviate problem.	$I_p 0$; $I_t 0$; although precipitation might increase dilution, generally mercury contamination is not climate sensitive.	Ponteverde Health Department	
7. Acidification of Lakes						
a. Sweden	10,000 lakes have been "killed" or badly disturbed by increased acidity. pH <5.5, which is critical point for survival of many species.	Increasing.	May be caused by acid deposition due to burning of fossil fuels and/or by natural acidification in soils.	$I_p \uparrow$; increased runoff may increase deposition in lakes and streams. I_t ; unknown.	Because of international nature of problem, responsibility is unclear.	

USE AND REUSE ISSUES

Issue/Location	Current Magnitude of Issue	Issue Trend	Non-Climatic Determinants	Sensitivity of Issue to Increases in Precipitation (I_p) or Temperature (I_t)		Institutional Responsibility
				$I_p \uparrow$ or $I_t \uparrow$ = increased magnitude	$I_p \downarrow$ or $I_t \downarrow$ = decreased magnitude	
				$I_p 0$ or $I_t 0$ = no effect		
<u>Quality (contd)</u>						
b. Canada	Estimated 60,000 lakes are degraded or endangered. Nine important rivers have lost their ability to support Atlantic Salmon primarily due to changes in acidity from acid rain.	Increasing.	See above.	See above		Canadian Center for Inland Waters; Joint U.S.-Canada Commission
c. New England/ New York Region, Northeast	Losses to recreational fisheries estimated at \$20-50 million/yr. In Adirondacks, 10% of all lakes are presumed "dead," though the causal relationship is not certain.	Increasing.	See above.	See above.		State and Local Water Quality Agencies
8. Inadequate Water Treatment Facilities						
a. Bolivia	3% of total population and 6% of rural population have sanitation facilities; Less than 2% of total population has access to clean water.	Decreasing slowly.	The availability of technology and financing determine ability for remedial action.	$I_p 0$; primarily an infrastructure problem $I_t \uparrow$; temperature increases result in greater food consumption and volumes of waste.		Unknown
b. Burma	Inadequate excreta disposal for 95% rural and 42% urban population.		See above.	$I_p \uparrow$; increased runoff reduces concentration of contaminants, but flooding increases contamination of water supplies $I_t \uparrow$; increases in human intake of water increase waste loads.		Ministry of Agriculture and Lands
c. Ethiopia	2% of population (rural) have excreta disposal facilities; 4% have safe water.		See above.	$I_p 0$. $I_t \uparrow$; increases in human intake of water increase waste loads.		Ethiopian Water Resources Authority

APPENDIX B

DEFINITIONS OF WATER RESOURCE ISSUES GENERATED IN TASK 1

APPENDIX B

DEFINITIONS OF WATER RESOURCE ISSUES GENERATED IN TASK 1

This section provides brief definitions of the specific water resource issues which were generated in Task 1, and which appear in the "Specific" World Water Supply/Allocation Impact Matrix. While the complexion of the issues may vary widely depending on the specific location, these general definitions are appropriate across locations. A list of reference sources used to construct many of the definitions listed below is contained at the end of this appendix.

SUPPLY

Surface Water

- Floods. A flood is any relatively high flow that overtops the natural or artificial banks in a stream. The flood event may be measured by frequency and duration of stage, area inundated, peak discharge, and volume of flow. The impact of floods on man is usually measured in terms of property damage and loss of life.
- Drought. A drought is a lack of precipitation for a period long enough to injure the plant and animal life of an area and to seriously deplete water supplies for human uses. Droughts may be measured by the frequency and duration of minimum flows, and their impacts in terms of loss of life and economic losses.
- Sedimentation of Reservoirs. The creation of a reservoir by damming a natural watercourse traps sediment that normally would be carried downstream and deposited on floodplains or in oceans. Sediment accumulation can affect both the operation, storage capacity, and effective lifespan of a reservoir.
- Aquatic Vegetation. The presence of aquatic vegetation (water weeds, phreatophytes, etc.) in or around waterways and reservoirs increases water losses through transpiration, reduces flow rates and clogs conveyance systems.

- Water Losses from Storage Systems. Water losses from storage systems can occur through evaporation and seepage. While most storage systems are designed to accommodate a certain amount of water loss, the losses may exceed design standards and result in reduction in available water supply and in increased salinity concentrations.
- Eutrophication. Eutrophication is the process by which a freshwater body, rich in nutrients, hosts a bloom of algal production, often resulting in anaerobic conditions and ultimately a transformation of the aquatic ecosystem. This process may be accelerated by the introduction of nutrients from anthropogenic sources (e.g., phosphates), and reduces both the quality and available supply of water.
- Effect of Land-Use Changes on Basin Hydrology. Land-use changes such as urbanization, deforestation, and cultivation can drastically alter the hydrological characteristics of a drainage basin. The impacts of such changes include increased runoff, reduction in the natural aquifer recharge area, increased sedimentation, and changes in streamflow characteristics. Generally these changes affect the quantity, timing, and distribution of water supplies.

Groundwater

- Groundwater Mining. Groundwater mining is the extraction over time of groundwater at a rate greater than the natural recharge rate of the aquifer. This causes long-term depletion, and potential problems include land subsidence, coastal saltwater intrusion, and increased pumping costs.

DISTRIBUTION

Quantity

- River Sedimentation. Due to runoff and streambed/channel erosion, sediment is deposited in the streambed, altering channel characteristics and flow capacity. This in turn may affect flood patterns, navigation, and water treatment requirements.

- Conveyance Losses. Faulty or mismanaged conveyance systems lose significant amounts of water through evaporation, seepage, operational overflows, and poor monitoring. Conveyance via surface aqueducts is subject to evaporative losses as well.
- Availability of Potable Water. Due to faulty or inadequate water delivery systems, potable water is inaccessible in some areas. The U.N. has set standards for "reasonable access to minimum quantities of drinking water essential to human health," (U.N. 1980) and many areas--particularly in developing nations--lack the infrastructure to provide quantities of water to meet these standards.

Quality

- Channel Scour/Channel Erosion. The wearing away of soil from stream channels is a natural process, but may be accelerated by some human activities. This problem may affect the quality of both the channel for carrying water and of the water itself by increasing turbidity. It may also affect riparian users, flood patterns, and navigation.

USE AND REUSE

Quantity

- Inefficient Irrigation Practices/Management. Inefficient irrigation usually consists of the application of water to crops in excess of that needed for optimal yield. This may be the result of a lack of information on crop water requirements, a lack of adjustment to newly introduced irrigation systems, inefficient pricing of irrigation water, or poor management of irrigation supply systems. Some consequences include waterlogging, salinization, reduced crop yields, and water shortages for some irrigators.
- Groundwater Infiltration of Municipal Sewer Systems. In many cities with older sewer systems, water seeps into the system through cracks and faults in the piping. Very often, the volume of this infiltration of water exceeds the volume of sewage the system was designed to

carry. This additional flow results in greater treatment costs and can require the construction of additional treatment capacity. It may also cause the breakdown of the biological processes used to treat municipal sewage.

- Effect of Changing Water Level on Aquatic Ecosystems. Changes in the water level in rivers and lakes, due to fluctuations in precipitation, dams, or water consumption, affect turbidity, water flow, temperature, salinity concentrations, and the availability of spawning areas. All of these changes affect the ability of the ecosystem to support some forms of aquatic life, and may have adverse effects on inland fisheries.
- Navigation Problems. The feasibility and efficiency of inland navigation are affected by water levels and flow rates, channel depth and sedimentation, seasonal variations such as flooding and ice flows, and the presence of obstructions such as plant growth and debris.
- Conflicts in Use. Conflicts may result from competing users' water quantity or quality needs, and from the timing of those needs. Conflicts may be resolved legally, technologically, through market mechanisms, or not at all. Conflicts may be between two (or more) instream uses, such as navigation and power generation; between two offstream uses, such as irrigation and municipal users; or between instream and offstream uses, as in the case of conjunctive ground and surface water use conflicts.

Quality

- Saline Intrusion of Aquifers. Saltwater intrusion most often occurs in island or coastal areas, where groundwater pumping may result in saltwater migration into what were previously freshwater zones of the aquifer. Increased salinity of groundwater may prohibit domestic consumption, increase treatment costs, cause corrosion in industrial use, and reduce crop yields in agriculture.

- Salinity Problems. The diversion or consumption of freshwater upstream may reduce flows to coastal areas and result in seawater intrusion further upstream. Surface waters may also become saline from irrigation return flows or from natural sources. Highly saline surface waters can result in increased treatment costs, corrosion in municipal systems and industrial use, reduced crop yields, reduced fish harvest, and may even be unfit for consumption.
- Waterborne Disease. Some major waterborne diseases are schistosomiasis, onchocerciasis, malaria, and cholera. Structural water systems such as dams and irrigation canals provide the slow-moving water habitat for disease vectors, and human use and contact with these waters contributes to the spreading of disease. Infection rates in some areas are as high as 100% of the exposed population.
- Waterlogging. When excess water reaches the groundwater through the soil moisture zone (usually a product of poor drainage or over-watering in irrigation), the water table rises toward, and may saturate the root zone of plants causing decreased crop yields, and in some cases requiring changes in crop mix toward more salt-tolerant crops.
- Groundwater Contamination. Important sources of groundwater contamination include: leachates from waste disposal sites, agricultural fertilizers and pesticides, industrial waste water, mining residues, and seepage from sewage systems. The impact on water quality affects most users.
- Surface Water Contamination. Surface water contamination results from point and nonpoint sources of agricultural, domestic and industrial waste, as well as from thermal pollution from power generation. The effect on water quality, and concentration of contaminants in the food chain, may result in restricted or prohibited use.
- Acidification of Lakes. The atmospheric transport of sulfur and nitrogen oxides may result in the deposit of strong mineral acids in

precipitation. This acid precipitation may, depending on the buffering capabilities of the minerals in the region, lead to an increase in the acidity of freshwater, potentially creating an environment uninhabitable by many aquatic species. Acidification of lakes may also be due to natural causes related to changes in the buffering capacity of the atmosphere and oxidization of sulfur from shallow water bodies and swamps.

- Inadequate Water Treatment Facilities. The lack of adequate sewage and wastewater disposal and treatment facilities in many nations results in severely degraded water quality. Primarily a problem of inadequate financing and infrastructure, this problem has a significant impact on human health.

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APPENDIX C

SPECIFIC ISSUE PROFILE FORM

Literature Source:

Place/Location:

Water Resource

Issue Description:

Current Magnitude:

(quantitative or qualitative)

Projected Trend:

(better/worse: qualitative/quantitative)

Time Frame if:

(No CO₂ Change)

Institutional Responsibility/Response:

Climate Sensitive?:
(yes/no; degree; why?)

Effect of Δ Temperature:
($\uparrow T$; $\downarrow T$)

Effect of Δ Precipitation:
($\uparrow P$; $\downarrow P$)

Comments/Notes:

APPENDIX D

SPECIFIC ISSUE SUMMARIES

APPENDIX D

SPECIFIC ISSUE SUMMARIES

The purpose of this section is to provide a brief summary statement for each of the specific water resource issues. Each of these summary statements contains a brief description of the issue. This is followed by a short discussion of the magnitude of the issue around the world and several examples to illustrate the magnitude of the physical or economic impacts associated with the issue. The next piece of information covers the persistence of the issue and identifies the general factors which may account for future changes in the magnitude of the impacts created by the issue. Finally, each of the summaries contains a brief discussion of the climate sensitivity of the issue being highlighted. Materials cited in these summaries are presented at the end of each summary statement.

SUPPLY ISSUES--SURFACE WATER

Flooding

A flood is any high flow that overtops the natural or artificial banks of a stream and encroaches upon the adjacent lands. Flood events may be measured by their frequency (or recurrence intervals) by the duration of the flood stage at a particular location, by the associated peak discharge and by the area inundated. The causes of flooding include:

- rapid and/or early snow melt;
- persistent spring rain;
- convective type storms producing torrential rain;
- cyclonic storms;
- ice jams; and
- rain - induced mudflows.

Flooding can also be caused by torrential rains which produce impervious area runoff in excess of the capacity of urban storm sewers.

The impacts of individual flood events are usually measured in terms of the value of the property damage and crop losses caused by a flood and the attendant loss of human life. The potential damage from flooding in any given year is measured in terms of average annual damages. This latter measure bears no direct relationship to the value of the damages that actually occur in a specific year, but represents a weighted average of the damages caused by floods with different recurrence intervals.

Magnitude

In general, the greatest property damage caused by flooding occurs in developed nations, primarily in urban areas, whereas substantial losses of life are most often associated with flooding in the developing nations, particularly in Asia and the Pacific. For example, the average loss of life in many Asian countries has been put at about 300 persons/year by the U.N. (1976) as compared to about 50-60/yr in the U.S.A (OTA 1980). However, single flood catastrophes in recent times have claimed over 2500 lives. Between 1947 and 1970, over 173,000 deaths were attributed directly to flooding, worldwide, or about 7500 deaths/year (U.N. 1976).

Global estimates of average annual damages caused by flooding are extremely crude. However, one estimate that has received some attention places this figure at about \$16 billion/year (U.N. 1976). Average annual damages, by country, vary widely. For Japan this figure has been estimated to be about \$600 million/year, while in India, a substantially larger nation, average annual damages are around \$200 million/year (U.N. 1976). By comparison, estimates of average annual flooding damages in the U.S. range from \$1.8-3.8 billion (Burton et al. 1978; OTA 1980; WRC 1978).

Persistence

There is no evidence of any general change in the occurrence of large (i.e., low frequency) floods on the great rivers of the world (UNEP 1982). However, the volume of discharge from high and medium frequency floods has been increasing in watersheds due to urbanization upstream, and in rural watersheds subject to widespread removal of trees and vegetation. There is also general agreement that flood hazards and flood losses are growing in many nations of the world, although at varying rates, due to the encroachment of human settlement and economic activity on flood plains (UNEP 1982). Thus, the magnitude of flooding impacts are increasing, even though climate is essentially stable.

Climate Sensitivity

Floods are extremely sensitive to changes in both precipitation and temperature. However, it is the timing, the duration and the correlation between these changes which is sometime more important than their magnitudes in determining the magnitude and duration of individual flood events. For example, an increase in average annual temperature due to a CO₂-induced climate change could alleviate flooding problems if it contributed to more gradual snow melt during winter months, or it could aggravate flooding if this increase was concentrated in the early spring. Hence, very detailed data about the timing, duration, direction and magnitude of expected changes in temperature and precipitation will be required, in some cases on a daily basis, before it is possible to make reasonably accurate projections about the impact of climate change on flooding problems.

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Drought

Conflicting definitions of drought advanced by a variety of academic disciplines have contributed to the problem of identifying and characterizing drought events and their impacts. Meteorologists are concerned with drought as a period of below normal precipitation; agronomists view drought in the context of insufficient soil moisture to support crops; hydrologists tend to view droughts as periods of below normal streamflow and depleted reservoir storage; and economists generally are concerned with drought as it affects societies' productive and consumptive activities (Dracup et al. 1980). Furthermore, different regions and cultures define drought in different ways. In Bali, six or more days without rain is considered a drought, while in Libya, droughts are recognized only after two years without rain (Hudson and Hazen 1964). As a guideline, the U.S. Weather Bureau has defined drought as a lack of rainfall for a period long enough to injure plant and animal life of an area, and to seriously deplete water supplies for domestic purposes and the generation of power (Havens 1954).

Drought impacts usually are measured in terms of economic losses (most often to agriculture), social disruption, and human health and loss of life (usually a result of crop failures, malnutrition, and the ensuing low resistance to disease).

Magnitude

The difficulty in defining--and consequently identifying--drought makes it hard to assess the magnitude of drought impacts on society. No reliable global estimates are available, but drought often is classified as one of the world's three most serious natural hazards (Burton et al. 1978). Several individual drought examples help give an indication of the potential magnitude of the impacts. The 1972-1973 Afro-Asian drought coincided with a 4% drop in world grain production and is identified as the principal cause of this reduction (Burton et al. 1978). During the 6-year drought in the Sahel region of Africa in the early 1970's it is estimated that 100,000 lives were lost due to the resulting malnutrition and disease (Loftin 1978), and large areas of land were lost due to desertification, a process in which drought is a major catalyst. Finally, in the California drought of 1976-77, an estimated \$2.4 billion was lost in gross income to the state's farm production and agriculture related industries (GAO 1977). These examples illustrate the potential magnitude of drought impacts, which may affect dryland and irrigated farming, livestock rearing, hydroelectricity generation, fisheries, industrial and municipal water users, etc.

According to Kovda (1980), 50-60% of the continental surfaces of the earth have a drought frequency of 10-15%; i.e., drought is experienced in 10 to 15 years out of every century. Drought is experienced with greater or lesser frequency in all areas which ordinarily have adequate water supplies. However, as Hazen first demonstrated (1916), areas which are most subject to recurrent droughts are those in which the variations in annual rainfall are highest, in relative terms. These areas include the far western and southwestern portions of the U.S., the west coast and eastern tip of South America, all of northern Africa above about 15° N. Lat., a large portion of central Asia (in what used to be Mongolia) and large portions of western and

central Australia. The total affected area, excluding drought-prone areas above the Arctic Circle, amounts to about one-fifth of the earth's surface (Petterssen 1958). In addition, as with floods, the economic damages from drought tend to be greater in developed nations, while the human health impacts are generally larger in developing countries (Burton et al. 1978).

Persistence

Despite some evidence for the cyclical nature of droughts, there does not appear to be any long-term trend in drought frequency as a climatic phenomenon (Landsberg 1975). However, the magnitude of drought impacts appear to be increasing, although time-series data to support such a conclusion are not available (CEQ 1981). If this is indeed the case, then any such increase must be due to expansion of human population and settlement in drought-prone regions.

Climate Sensitivity

Drought is highly climate sensitive, but the nature of the relationship between decreased precipitation, on the one hand, and the severity, frequency and duration of droughts, on the other, is difficult to determine given current levels of knowledge. For example, a small increase in average annual precipitation in a region may have little or no effect on the frequency and severity of droughts if there is no change in the relative variability of annual average precipitation. By the same token, an increase in the year-to-year variation in average annual precipitation could increase the frequency of droughts, even in the presence of a moderate increase in average yearly precipitation.

The impact of changes in temperature on the frequency and severity of droughts is also hard to determine. However, a major consideration in this regard involves the relationships between precipitation, evapotranspiration (ET) and runoff (R). Holding precipitation constant, an increase in temperature will generally cause an increase in ET, and some decline in R. In dry regions, ET is particularly sensitive to changes in temperature. Thus, a small increase in temperature has the potential to offset the impact of

increased additional precipitation on drought conditions, thereby increasing the severity of specific droughts that may occur in the future.

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Reservoir Sedimentation

Reservoir sedimentation is an inevitable by-product of dam construction. The rate at which the capacity of a reservoir is reduced depends upon the quantity of sediment inflow (due to watershed characteristics), the percentage of this inflow trapped in the reservoir (which depends on the rate of flow through the reservoir and the size and location of the reservoir outlet), and the density of the deposited sediment. Excessive sediment

accumulation affects the storage capacity of a reservoir and its operation, at any given point in time, and reduces the effective life-span of a reservoir project. In almost all cases, the effect of sediment deposition on the useful life of a reservoir project is carefully considered prior to constructing a dam. However, there are notable cases where such calculations have been in error and reservoirs are becoming filled with sediment at a much faster rate than expected.

Magnitude

A survey of U.S. reservoirs conducted by Dendy (1968), revealed that, while the average observed sedimentation rate of .2% of total storage capacity per year is well within the design specification of most reservoirs, average sedimentation rates for small upland reservoirs (with a capacity of less than 100 acre-feet) are much higher. These reservoirs experienced depleted storage due to sedimentation at a rate of about 3% of total capacity per year. Although such reservoirs account for a small portion of the total U.S. storage capacity, they constitute 40% of the total number of reservoirs.

Although aggregate data on the sedimentation of reservoirs in the U.S. is sparse, it has been estimated that up to one million acre-feet of surface water storage capacity may be lost each year in the U.S. due to this problem. Based on the capital cost of constructing storage facilities in the eastern U.S., it could cost up to \$100 million per year (1975 dollars) to replace this lost capacity (J. AWWA 1975).

Reservoir sedimentation in excess of design standards is probably an isolated problem. However, where the problem exists it can result in substantial losses of storage capacity (ESCAP 1981). It has been estimated that in India, for example, many large reservoirs are experiencing sedimentation at rates of up to three times above those initially calculated (Water Power and Dam Construction 1981). Perhaps the most noteworthy example of this problem is Lake Nasser in Egypt where some experts predict that the useful life of the Aswan High Dam may be cut by more than one-half (Wisely 1972).

Persistence

As noted earlier, sedimentation is an inevitable consequence of dam construction. The construction of new dams will, therefore, cause an increase in the volume of sediment deposits. With the exception of poorly planned reservoirs, the only other possible source of increase lies in the volume of sediment loads transported into reservoirs. Here we can expect, that as erosion of soils continues to increase on a worldwide basis, existing and future reservoirs will experience a rise in sediment loads.

Climate Sensitivity

Sedimentation rates in reservoirs are a function of sediment yields, which is a function of climate. Langbein and Schumm (1958) have shown that sediment yields are highest where annual precipitation averages about 10 to 14 inches per year. Sediment yield then decreases sharply about this maximum, with less precipitation producing sharp decreases in the amount of runoff that carries sediment into streams. Under conditions of higher precipitation, they hypothesize that the observed reduction in sediment loads is due to the increased density of vegetation commonly associated with higher precipitation. Thus, it would appear that the effect of an increase in precipitation on the sedimentation of reservoirs will depend upon the amount of precipitation that currently falls within a given watershed and the magnitude of the increase. Changes in the type and intensity of precipitation may also affect reservoir sedimentation insofar as very intense rainfall events might increase soil erosion.

Changes in temperature will probably offset reservoir sedimentation through changes in evapotranspiration and runoff. Since runoff is often extremely sensitive to changes in evapotranspiration, a CO₂-induced temperature increase could substantially reduce the runoff that carries sediment into streams and rivers.

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Aquatic Vegetation

The presence of aquatic weeds, such as water hyacinth and hydrilla and phreatophytes in and around waterways, reservoirs and irrigation ditches can dramatically increase water losses through transpiration, reduce flow rates in channels, clog conveyance systems and water intake pipes, as well as render water bodies initially unfit for recreational uses. Moreover, in many areas infestation by aquatic vegetation provides a suitable environment for waterborne disease vectors, increasing the incidence of such diseases as schistosomiasis, malaria and onchocerciasis.

Magnitude

It has been estimated that the global costs of water weeds is on the order of one billion dollars per year, including control costs, agricultural losses due to the closing of irrigation canals, and water lost through transpiration (Pirie 1980). In Texas alone, the annual average water loss due to aquatic weeds represents about 19.5% of total water yield (Benton 1976). The corresponding value of these losses has been estimated at \$83 million/year (1976 dollars)(Benton 1978). Although the problem exists worldwide, it often is most severe in warmer climates and in areas with perennial irrigated agriculture where canals are not drained and cleared annually.

Persistence

Although more effective mechanical, chemical and biological control technologies are being developed and implemented, in general the problem of aquatic vegetation is becoming more severe. Species are spreading to new areas, irrigated agriculture is becoming more widespread, and eutrophication, which enhances the environment for water weeds, is also on the increase.

Climate Sensitivity

The rate of aquatic plant growth, reproduction, and transpiration tends to be extremely sensitive to changes in temperature, with this sensitivity varying from species to species. Moreover, since the ability of aquatic weeds to spread, and the viability of some biological controls, may be limited by seasonal temperature and frost conditions, their general spatial distribution is also highly climate sensitive. In general, however, an increase in precipitation should help to relieve the problem of water losses caused by aquatic weeds, while a rise in temperature will probably increase transpiration, causing additional water losses from reservoirs and irrigation canals.

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Water Losses from Storage Systems

The primary cause of water losses from natural and manmade storage systems is through evaporation. Additional losses may be due to seepage through permeable soils or reservoir banks or through excess leakage through the face of a dam due to faulty construction practices. In virtually all cases, the design of manmade storage systems takes into account evaporation and seepage losses, so that neither poses a serious problem to the computed reliability of most storage systems, under the existing climatic regime for

which those calculations were made. In a small number of isolated cases, however, actual losses exceed design losses and this can result in increased salinity concentrations in the system, a rise in the water table due to seepage (which may be beneficial or detrimental to adjacent land uses depending on the depth of the water table), property damage due to reservoir leakage, and water supply shortages.

Magnitude

Water losses in manmade storage systems can be substantial. For example, at Lake Meade in Nevada, evaporation averaged about 70 inches/year for the period 1936 and 1949, which translates into an average annual water loss of about 700,000 acre-feet/year (Slayter and Mabbutt 1964). By comparison, annual average losses due to evaporation at Lake Nasser in Egypt are in excess of 2 million acre-feet/year (FAO 1973). While critics of large water supply systems in the U.S. note that the combined evaporative losses of the largest storage projects constructed in this country would be sufficient to supply the minimal water needs of all major U.S. cities (Boyle et al. 1971), they fail to recognize that such losses are balanced off by the ability of these systems to provide water when it is not available in dry seasons.

Still, methods for reducing evaporation from storage systems are being developed. These include the use of floating covers (Cooley 1970) floating granular materials (Myers and Frasier 1970) and monomolecular films (Mansfield 1955). However, none of these methods have proved cost-effective enough to use on large lakes or reservoirs.

Persistence

As a physical process, evaporation of water from reservoirs is an extremely persistent phenomenon for which there is currently no economically feasible method of control.

Climate Sensitivity

As pointed out earlier, evaporation losses are not generally viewed as a serious problem by water resources experts, as long as actual evaporation is close to the design figure for a reservoir. Thus, as long as climate does not

close to the design figure for a reservoir. Thus, as long as climate does not change, no predictable problem will arise. However, evaporation of water from lakes and reservoirs can be highly sensitive to climate change, primarily through changes in temperature, wind speed and barometric pressure. While evaporation from surface water bodies tends to be highest in hot, dry climates, the relationship between evaporation and temperature is not direct. This is due to the fact that evaporation is a function of the difference between the temperature of the air and the temperature of the water and ceases when air and water temperature are equalized (Veihmeyer 1964). Thus, an increase in the seasonal variability of temperature could also lead to higher evaporative losses because of the greater lags this might induce between changes in air and water temperatures. It should be noted, however, that evaporation losses could be offset to some degree if warmer temperatures are accompanied by increased rainfall and runoff, thereby replenishing supplies that would otherwise be lost.

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Eutrophication

Excessive supply of nitrogen and phosphorous compounds in waterways has been identified as a primary cause of eutrophication--a term which refers to the over-fertilization of a water body. Extreme or hypereutrophic conditions eventually may result in the water body being unavailable for most uses. Less severe eutrophic conditions lead to water quality deterioration, oxygen depletion, decline of fisheries, clogging of waterways, and in some areas, excessive water loss through evapotranspiration.

Magnitude

Controversy over definitions of eutrophication, and a lack of consistency in its measurement (where it is measured at all), make it infeasible to assess the extent of the problem on a global scale. According to Vollenweider (1981), 75% of 800 lakes surveyed in the U.S. were classified as eutrophic or hypereutrophic, and only 5% were oligotrophic. In Canada, however, only 25% of 120 lakes surveyed were eutrophic or mesotrophic. There is some debate that the criteria used in these surveys may account for the large discrepancy.

A sampling of some of the most serious cases of accelerated eutrophication illustrates that the problem occurs to some degree in most regions of the world. Accelerated eutrophication generally is associated with 1) rapid population increases, urbanization, and increases in urban waste; 2) industrialization and increased industrial wastes; and 3) intensification of and changes in agricultural production methods (Vollenweider 1981).

In the U.S., lake restoration costs may average as much as \$1.1 million/lake, although these expenditures tend to include the provision of non-eutrophication related benefits such as control of floods, resource recovery, fish and wildlife, etc. (EPA 1980). Actual costs depend on the technique utilized and extent of project benefits sought. The U.S. Environmental Protection Agency (EPA) (1980) has estimated that the ratio of all benefits to costs resulting from such lake restoration projects is about

4.15:1, indicating that controlling the extent of eutrophication (primarily through reductions in the phosphate content of lakes) is economically feasible.

Persistence

Since eutrophication tends to accompany increasing population, urbanization, industrialization, and agricultural development, the problem will probably continue to grow in the future. Control and rehabilitation technologies have been successful in restoring the quality of some water bodies, but generally these methods are very costly and implemented retroactively, if at all. In many developing nations, preventive measures tend to be of a low priority relative to other needs.

Climate Sensitivity

Theoretically, changes in temperature and precipitation could affect the rate of eutrophication, but there is no evidence regarding the degree of climatic change necessary to effect specific changes in eutrophication rates. If warmer temperatures act to significantly increase the thermal stratification of a lake, dissolved material (O_2 and nutrients) would be transported less easily between layers and eutrophication might be slightly retarded (Crossland and McCaul 1972). Conversely, increased temperatures might increase biological activity and enhance eutrophic processes. Finally, if warmer temperatures increase evaporation, nutrients will become more concentrated, further enhancing eutrophication. Not enough is known about these effects to reach definitive conclusions. Changes in precipitation might slightly alter the rate of dilution of nutrients and the O_2 level of surface wastes, but the effect of this on eutrophic processes likely would be negligible. Also, if additional precipitation increases runoff, more nutrients might be supplied to enhance eutrophication.

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Effects of Land-Use Changes on Basin Hydrology

Land-use changes such as urbanization, drainage of wetlands, deforestation, overgrazing and cultivation can drastically alter the hydrologic characteristics of a drainage basin. The impacts of such changes include increased runoff and sedimentation, decreased aquifer recharge, changes in the timing, frequency and duration of floods, and reduced water quality (Moore and Morgan 1969).

Magnitude

Very rough estimates reviewed by Sagan et al. (1979) suggest that 5% of the earth's surface (17% of the continental surface), has been anthropogenically altered, and that an additional 200,000 km²/year undergoes significant change of land use (there has been no verification of these estimates, which are accurate to no better than a factor of 2).

Urbanization produces a sediment load in streams that is 2-5 times greater than under natural conditions, and may increase runoff by 200-400% (UNESCO 1974). Conversion of 20% of a catchment to urban use can result in a doubling of the peak runoff rate (UNESCO 1974). In the U.S. it is estimated that 170,000-400,000 hectares/year of agricultural land is lost to urban and industrial uses, and a similarly rapid rate is occurring globally (Rusk and Christopher 1980; UNESCO 1974). Since 60% of stream and river flood damage in the U.S. is in urban areas, which often occupy flood plains, some portion of the \$3.8 billion annual flood damage can be attributed to urbanization effects on hydrology (OTA 1980). Generally, basin lag time is reduced and stormflow is concentrated in sharper, shorter, higher peaks than under natural runoff conditions. For example, in one Boston watershed the estimated 100-year flood became a 20-year flood in the course of 15 years of rapid urbanization (OTA

1980). Increased flood damage, erosion and sedimentation, and reduced aquifer recharge appear to be the most serious impacts of urbanization. Similar changes in hydrology occur with deforestation and other land-use changes which remove vegetative cover. These changes also are occurring worldwide, but may be more extensive in developing nations where land use regulation is not as widely practiced.

It has also been speculated that land-use changes--and particularly urbanization--alter the micro climate of a basin further influencing the hydrologic cycle in affected regions (Sagan et al. 1979).

Persistence

The expansion of urban areas throughout the world, the increased exploitation of the world's tropical forests, and the pressures to grow more food to feed a growing population all suggest that the rate of land use change and the occurrence of associated impacts will remain constant or increase in the foreseeable future. It should also be noted that altering the surface terrain may at times be beneficial, such as in cases where catchments are created to harvest precipitation either for surface or groundwater storage, which otherwise would be lost for human use.

Climate Sensitivity

The rate of land-use change is largely independent of climate. However changes in precipitation and temperature have the potential to either dampen or magnify the impacts of land-use changes on a watershed. In that regard, the effects of increased precipitation would probably be detrimental insofar as runoff changes could be magnified, causing increased flooding and higher sediment loads. Increases in temperature may have some offsetting effect, through increased evapotranspiration which, other things being equal, could be expected to reduce runoff. However, this would depend on the extent of pre-existing land-use changes on vegetative covering. Thus, in urban areas, where extensive development has removed a large portion of the vegetative covering, increases in temperature may not substantially reduce runoff. Thus, while land-use changes are not climate sensitive, the effects of land-use changes on the hydrologic balance within a watershed may be extremely climate

sensitive. However, without detailed knowledge of watershed characteristics, the impacts of climate change are difficult to predict.

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Inadequate Storage/Supply Facilities

In many areas of the world there is currently or anticipated the problem of inadequate water supply to meet expected demand under normal conditions. This may be due to seasonal or year-to-year variations in streamflow, population shifts to areas not well endowed with natural water supplies, or to increasing demand primarily in agriculture, energy, and municipal consumption. Generally, the storage of a portion of seasonal or annual surplus water, or the water from adjacent basins, has been relied upon to ensure dependable supplies to meet existing and projected demands for water. Problems arise in areas where current or projected water demand exceeds existing dependable supplies.

Magnitude

The primary impact of inadequate storage is water shortage, particularly during years of low precipitation. Shortages may affect all water users, and may increase conflicts among them. The specific impacts of water shortages, when they occur, depends largely on the legal and institutional policies adopted historically, or on an emergency basis, to deal with the problem. In the western U.S., for example, where water use is governed by the prior appropriations doctrine, shortages in rural areas are "managed" according to the historical priority of individual use rights. However, this rule does not generally apply in urban areas where, by constitutional provisions or statutory law, consumptive uses for human health and welfare are granted an over-riding priority over all other uses.

Although the problem of inadequate water supply is evident in most regions of the world due to the uneven distribution of water over time and space, it is most prevalent in arid and semi-arid areas and areas with rapid population growth. Thus, while in the U.S. the risk of water shortages exists nationwide, the West and Southwest, and many urban areas in the East exhibit the most serious problems. In many western states and eastern cities, existing dependable supplies would not provide for projected demand in the year 2000 (GAO 1982). The estimated price tag of augmenting supplies for southern California alone is over \$5.1-23 billion (Pfatz 1982), and in the High Plains the cost of supplementing the rapidly diminishing Ogallala Aquifer is estimated at \$13.4-40 billion.^(a) In urban areas, many of which now have or are expected to have problems in meeting the demand for water, the cost of providing adequate supply and storage ranges from \$11.5 million for Atlanta to \$3.7 billion for New York City. EPA has projected that given current trends, 200 New England cities and towns would suffer severe shortages by 2000 (GAO 1979). Similar problems exist in Europe, where demand already exceeds dependable supply in Bulgaria, Poland, East and West Germany, and Rumania, and

(a) Stokes, B. 1982. Bread and Water: Growing Tomorrow's Food.
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on a more local scale in many other nations (UNWC 1978). In other regions, notably western Asia, extreme seasonal variability in streamflow necessitates adequate storage facilities both for flood control and dry season supply. However, many developing countries in the region lack such structures due to inadequate resources.

Persistence

According to UNEP (1982), most countries will experience a greater percentage increase in water use between 1981-2000 than they did between 1970-1980. Increased demand further will strain many existing storage systems and require the development of new, generally more costly, supplies. Although groundwater sources increasingly are being utilized, surface supply/storage systems will continue to provide the majority of the world's water supply.

Climate Sensitivity

Surface water supply and water demand are extremely climate sensitive, and so are the problems associated with storage systems. Where storage/supply facilities do not provide dependable supply for current demand, increased temperature may aggravate the problem by increasing water losses through evaporation and by increasing consumption. Increased precipitation, depending on the timing, may help reduce supply problems by increasing surface water availability. Of equal concern is the effect of climate on those systems which are adequate for current and projected demand. Increased temperature may create supply problems in areas where water resources planning previously had accommodated long-range demand requirements. Increases in temperature also have the potential to cause snow lines to move to higher elevations, to increase the evaporation of water from snowpack and thus reduce runoff and storage, and to increase system losses through evaporation of water from lakes and reservoirs. Warmer temperatures, depending upon how they are distributed seasonally, would reduce or increase the demand for water to satisfy a wide variety of needs. If demands are increased, then this would place additional pressure on existing and projected supplies.

The impact of climatic changes which take the form of increased frequency in the occurrence of extreme events (i.e., droughts and abnormally high

amounts of precipitation) may have an effect on the reliability built into future storage systems. Increasing frequency of droughts poses a particularly serious problem in existing arid and semi-arid regions, where the high reliability levels (e.g., a low probability that future demands will exceed current supply) currently used in constructing water storage systems may have to be relaxed, thus increasing the probability of shortages, even with additional water supplies. This suggests that, even though the rate of anticipated climatic change may well be slow enough to permit adjustments in water supply, water users may have to live with systems which will be less reliable than those which currently exist.

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SUPPLY ISSUES--GROUNDWATER

Groundwater Mining

Groundwater represents the largest source of fresh water available on the planet, accounting for about 4 million cubic kilometers of water less than one-half mile from the earth's surface (U.N. 1975). Groundwater mining of this

resource occurs when the water withdrawn exceeds the rate at which an aquifer can be recharged by natural processes. This practice may have a number of consequences, including:

- eventual loss of the source of supply;
- reduced baseflow in streams and rivers;
- saltwater intrusion in coastal aquifers; and
- land subsidence.

Magnitude

In the U.S., groundwater levels are declining beneath 29 million of the 32 million acres of land that is currently irrigated by groundwater (Slogett 1981). The areas most severely affected include the area above the Ogallala formation in the High Plains of parts of Nebraska, Colorado, Kansas, Oklahoma, New Mexico and Texas, the Gila River Basin in Arizona and New Mexico, the San Joaquin Valley of California, the upper Susquehanna River Basin in Pennsylvania, parts of southeastern Georgia, the Houston-Galveston area in Texas and the island of Oahu in Hawaii (WRC 1978). According to Slogett, the rates of decline in these and other problem areas range from one-half to six feet per year. On 15 million of these acres, the decline in groundwater has been labeled as chronic (GAO 1977).

Perhaps the most easily measured impact of groundwater mining is land subsidence. In Houston, Texas, land subsidence attributed to groundwater mining causes about \$32 million worth of property damages each year (Jones and Warren 1976). In the Santa Clara Valley of California, the direct costs attributed to land subsidence from groundwater mining are estimated to be in excess of \$130 million annually (Fowler 1981). In Tokyo, Japan, millions of dollars worth of damages have resulted from damaged structures and from increased urban flooding due to land subsidence of up to 4 meters in certain areas of the city (Tokyo 1969).

Other impacts of groundwater mining are less easily measured in economic terms. However, saltwater intrusion has necessitated the construction of desalination plants in the Middle East, on the Mediterranean coast of Northern Africa, the U.S. and many other island nations. Elsewhere in the world, salt-

water intrusion has reduced the productivity of agricultural land in Mexico and many other coastal areas of Latin America (Crosson et al. 1978), India and Africa (U.N. 1975).

Persistence

The incidence of groundwater mining is increasing globally, and probably will continue to do so as: 1) existing surface water supplies become more fully utilized and 2) more effective and less costly techniques are developed for locating groundwater and pumping it to the surface (U.N. 1979). This trend may be counteracted to some degree by rising energy prices which increase pumping costs and make it economically infeasible for pumping to continue below certain depths (Sloggett 1981).

Climate Sensitivity

The effect of a possible CO₂-induced climate change on groundwater mining will depend, regionally, upon the sensitivity of recharge rates in affected aquifers to changes in precipitation. Increased precipitation will, by no means, alleviate this problem in cases involving deep aquifers with extremely low (or zero) rates of natural recharge. Moreover, the amount of additional precipitation that reaches an aquifer will depend upon the type, the intensity, the timing and duration of precipitation events. For example, an increase in rainfall of a given magnitude will produce a larger volume of surface runoff, making less water available for groundwater recharge, if it is concentrated in short duration, high intensity events than would be true if this precipitation was distributed more evenly over a longer period of time. Aquifer recharge rates will also depend upon any changes in temperature which will affect evaporation and transpiration. Increases in temperature which lead to a rise in either of these two phenomena may have the effect of reducing the proportion of additional precipitation that infiltrates the soil and percolates into a groundwater system. In both of these cases, groundwater mining may become a more, rather than less serious problem, even though an increase in precipitation takes place.

Finally, changes in temperature and precipitation could have an indirect effect on groundwater mining due to the impact of these changes on irrigation

water demands. Depending on the availability of storage and the timing of additional precipitation, increased rainfall/snowfall could ease the pressure being placed on groundwater supplies. Conversely, an increase in temperature which lengthens the growing season and/or raises average temperatures during this period could have the opposite effect, due to increases in evapotranspiration.

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DISTRIBUTION ISSUES--WATER QUANTITY

River Sedimentation

Soil is constantly being eroded from the land surfaces of the earth by the action of wind and water and is then transported downstream in rivers until it is eventually deposited in lakes, estuaries and oceans.

Sedimentation of rivers creates a number of problems for users, including changes in channel depths and locations, alteration of flow regimes, increased turbidity and degradation of the aesthetic value of water for recreational uses. All but the last of these problems are created when the sediment load of a river or stream exceeds its carrying capacity. When this occurs, material is deposited in the channel. Under natural conditions, most rivers achieve a state of equilibrium such that the channel neither aggrades or degrades. Conditions which can alter this equilibrium include changes in land use, the construction of reservoirs and channel improvements, and climatic change--all of which have the ability to alter sediment supplies or change the distribution of supplies along a river (Morisawa 1968).

Sedimentation is closely associated with erosion, since this is a primary source of the sediment load of a stream. Inasmuch as erosion often accelerates as human activities disturb the natural characteristics of a drainage basin, sedimentation of rivers is sensitive to many land-use changes--particularly agriculture and urbanization (Water Resources Council 1978).

Magnitude

The Water Resources Council of the U.S. (1978) has identified sedimentation and erosion as among the most widespread water related problems in the U.S., affecting virtually every area of the country. Sedimentation can have beneficial effects, such as fertilization of downstream reaches of a stream, but generally excessive sedimentation is viewed as a problem. Although no reliable estimates concerning the magnitude of the impacts of sedimentation are available, Brown, in 1948, estimated annual sedimentation damages in the U.S. at \$150 million (Blench 1966), and characterized these costs as rising as the number of land development and water resources projects increased. Approximately \$260 million/year is spent by the Corps of Engineers

for dredging either to control sedimentation problems or to deepen existing channels for navigation.^(a) Presumably, the economic benefits from dredging exceed this cost. Sedimentation also may damage fish and wildlife habitats, may increase water treatment costs, and may clog irrigation canals. Problems of sedimentation occur on many of the world's rivers (Water Quality Bulletin 1979), particularly where human activities result in increased sediment load. For example, on the Mississippi River, maintenance dredging is required to control sedimentation caused by changing shoreland uses which contribute to soil loss in excess of 20 tons/acre (WRC 1978). Since protective vegetative cover is often lacking in semi-arid and arid areas, these areas tend to have significant sedimentation problems due to erosion (Langbein and Schumm 1958).

Persistence

Although sedimentation problems vary in severity over time and space, general increases in erosion rates will continue to exacerbate sedimentation (WRC 1978). Although techniques are available to control some sedimentation, in the U.S. at least, costs are high and incentives weak for the implementation of these control methods (WRC 1978). Therefore, given current trends, sedimentation problems will continue on most rivers, and will be dealt with retroactively through dredging.

Climate Sensitivity

Sedimentation of rivers is sensitive to changes in temperature and precipitation through the effect of these parameters on stream energy, runoff, and vegetative cover as it affects erosion (Langbein and Schumm 1958). Increased temperature will increase evapotranspiration demands upon soil moisture, leaving less moisture for runoff and erosion. Thus, more precipitation is required to produce a given amount of runoff and erosion in a warm climate than in a cool one (Langbein and Schumm 1958). Sedimentation also is affected by the annual amount of precipitation, which influences the

(a) Personal communication with Mr. Jon Mickel, Chief, Operations Branch, U.S. Army Corps of Engineers, Washington, D.C.

amount of vegetation cover available to control erosion. Langebein and Schumm found that within zones of 0-12 inches of precipitation, an increase in annual precipitation would be accompanied by an increase in erosion and probably sedimentation. In zones of 12-45 inches of rainfall, erosion generally will decrease with increased precipitation. Whereas in regions where annual precipitation is 45 inches or greater, erosion generally will not change with increased precipitation. The complex relationship between precipitation, erosion, and sediment yield and channel aggradation is not fully understood, but it appears that the resulting change in sedimentation depends on the amount of rainfall before the change in precipitation, and on the relative magnitude of the separate effects on runoff and vegetative cover (Mackin 1948; Langbein and Schumm 1958).

Erosion, and thus sedimentation, also may be affected by changes in the frequency, duration, and intensity of precipitation events, even though annual precipitation does not change (Leopold 1951).

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Conveyance Losses

Losses from irrigation conveyance systems occur primarily through seepage, evaporation, and operational overflows, and may result in water shortages to some irrigators. If seepage and overflows are severe, waterlogging problems may be aggravated or may appear where they previously did not exist.

Magnitude

Since accurate data on conveyance losses are scarce, there is some controversy regarding both the total volume of water lost and the portion of this loss attributed to seepage, evaporation, overflows, and poor management. Many estimates place seepage losses from unlined canals at 25-60% and evaporative losses at 5-25% (Christopher 1981; Luthra 1980; GAO 1977). In the U.S. a number of estimates exist, ranging from an average seepage loss of 20% to 59%, depending on the project considered and the agency reporting (GAO 1977). However, at least one expert has questioned these seepage estimates. On the basis of extensive field observations one expert^(a) estimates that, in general, canal losses are less than 35%. In the most severe cases, seepage is about 5-10%, and evaporation is under 5%, with most of the "lost" water accounted for by operational waste (20-25%) due to poor system operation, and over-delivery which goes unrecorded (25%). If these estimates are correct, then the cost of lining canals to reduce seepage (about \$940 per acre in U.S.)

(a) Personal communication with Mr. Jack Christopher, U.S. Bureau of Reclamation, Denver, Colorado, September, 1982.

would not be justified solely on the basis of water saved (Rusk and Christopher 1980). It might be justified, though, as a means for controlling waterlogging and salinity.

Although the value of the water lost in conveyance is difficult to estimate, many of the regions with large conveyance losses are affected by annual or seasonal water shortages. In some cases expensive diversion projects are being considered or planned to compensate for these shortages which may partly be due to conveyance losses (Howe and Easter 1971).

The magnitude of seepage losses is fairly consistent from one region to the next. The extent of the losses largely depends on canal size and soil characteristics. Although evaporative losses from conveyance systems vary with climate, they are in most cases considered negligible. Losses attributed to mismanagement of delivery systems occur to some extent in virtually all regions with irrigation, but appear to be more extreme in S.E. Asia and the Indian sub-continent.^(a)

Persistence

Problems of conveyance losses will continue to plague irrigation systems in the future, and as irrigated agriculture expands and water consumption increases, the impacts of these losses will be amplified. While some improvements are being implemented in conveyance structures and in system management, prohibitive costs and expanding irrigation probably will leave many areas without such improvements.

Climate Sensitivity

The only direct impact of climate change on conveyance losses would be on evaporation, and given the relatively small portion of the loss attributed to evaporation, this impact would be negligible. Several indirect effects of climate change in conveyance losses are possible: 1) increased precipitation

(a) Christopher, J. N. 1981. Comments on Canal Seepage Measuring and Estimating Procedures. Paper delivered as a World Bank Seminar, 1981. (Mimeo)

might reduce the impact of losses in areas of water shortage, 2) increased temperature could aggravate seepage losses by increasing transpiration of plants using fugitive waters, 3) increased temperature could create or aggravate a shortage situation by increasing crop water consumption and 4) increased temperature could stimulate more efficient operation of delivery systems, thus reducing operational losses.

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Availability of Potable Water

The lack of access to potable water has severe impacts on human health and welfare. Waterborne disease and water-washed disease (disease due to a lack of water for personal hygiene) account for millions of deaths and even more chronic illness, and frequently are traced to inadequate supply of potable water (Intermediate Technology Development Group 1977). In addition, long trips to fetch water consume a great deal of time (up to 6 hours/day) and energy in developing nations which otherwise could be used in more productive ways (U.N. 1980). The provision of access to potable water primarily is a problem of ensuring adequate structures for water distribution, and is closely linked to proper sanitation to maintain potable supplies.

Magnitude

According to the U.N. (1980) roughly 60% of the population of developing countries is without access to safe drinking water. There is about a 29% and 75% coverage rate for urban and rural populations, respectively.

Inadequate access to potable water is almost entirely a problem of the developing countries, with a very small percentage of the industrialized world without such access. Southeast Asia, sub-Saharan Africa, and West Asia exhibit the lowest coverage rates. It was estimated in 1977 that at least \$132 billion, and possibly as much as \$600 billion in water supply and sanitation construction would be required to provide adequate water supply and sanitation for the world's population (U.N. 1980). It is difficult to isolate the portion of this cost attributable to water supply, since potable supply and sanitation are closely linked. Achieving this level of investment by 1990 (a goal set by the U.N. Drinking Water Supply and Sanitation Decade, but now recognized as unrealistic) would require an annual rate of investment 5-10 times greater than 1979 levels.

Persistence

Despite ambitious goals set by the U.N. to significantly improve access to drinking water by 1990, it appears that population growth and a lack of the necessary financing are resulting in progress much below expectations. Some areas--notably Latin America--are showing considerable improvements, and in general coverage is increasing, but not at rates rapid enough to alleviate the problem by the end of the century (U.N. 1980).

Climate Sensitivity

The problem of access to potable water is viewed primarily as an infrastructure problem. Nevertheless the problem is moderately climate sensitive. Increases in temperature may have the effect of increasing the demand for water for agriculture and human consumption. If so, this would place some additional strain on available water supplies. Increased precipitation could have an offsetting effect by making more water available for all uses. However, if climate change is manifested in the form of

increased flooding, then potable water supplies may become contaminated more frequently (see Inadequate Water Treatment Facilities).

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DISTRIBUTION ISSUES--WATER QUALITY

Channel Scour/Channel Erosion

The wearing away of soil from stream channels and stream banks is a natural process, but may be affected by some human activities, particularly by flow regulation, wave action from river traffic, and certain land uses which encroach upon stream and river banks. This problem may affect the quality of both the channel for carrying water and sustaining instream uses, and the water quality itself through changes in turbidity.

Magnitude

Except in the most extreme cases where streambed changes drastically alter flood patterns for an entire region, or remove large areas of productive land, the effects of these changes tend to be local and of relatively low magnitude. Moreover, according to Shirokov (1979), where changes in sediment transport are the result of flow regulation, the sediment transport equilibrium may eventually be restored.

Where land losses do occur, they can be relatively serious: for example in the New Orleans and Baton Rouge areas of Louisiana where the estimated land loss is 16.5 square miles (U.S. WRC 1978). However, most land losses are confined to stream bank losses in small urban watersheds, due to over-development. The extent of these losses has not been estimated.

For the U.S., significant channel erosion and scour problems are most prevalent in the upper and lower Colorado and upper and lower Mississippi (WRC 1978). A lack of adequate information on scour/erosion problems overseas--primarily the result of a low-level of monitoring--prevents an accurate assessment of the situation. However, it is likely that channel scour/erosion problems appear to some extent on most major rivers, particularly those with large flow regulation works.

Persistence

Although channel scour and erosion occur naturally, the problems are accelerated by watershed changes (Moore & Morgan 1969). Since anthropogenic watershed changes are continuing and in many areas increasing, it is likely that these problems also will persist and in some areas intensify. However, if the findings of Shirokov (1979) can be generalized, then where channel alteration is the result of flow regulation projects, equilibrium may be restored, potentially mitigating damages.

Climate Sensitivity

Increased precipitation may affect erosion through increased runoff and streamflow. However, this effect depends on the nature of the change in the frequency, duration, and intensity of precipitation events. Increased temperature may increase evapotranspiration, thereby reducing runoff and erosion, and may increase vegetation cover, which also would reduce erosion. Generally, though, the sensitivity of this issue to climate change would likely be relatively low.

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USE AND REUSE ISSUES--WATER QUANTITY

Inefficient Irrigation Practices/Management

Inefficient irrigation practices refer to the application of significantly more water to crops than is consistent with the objectives being pursued by the farmer. While not all of the water that is wasted by over-irrigation is lost (i.e., some of it is returned to the stream and some of it is pumped from groundwater), inefficient irrigation practices tend to widen the gap between the temporal and spatial distributions of water supply and demand.

As seen above, inefficient irrigation practices depend very much on the objectives being pursued by a farmer. Thus, given two identical farming operations subject to the same environmental conditions, a farmer who maximizes his total profit will, in general, use a different amount of water than a farmer who faithfully pursues the objectives of maximizing the physical yield of his crops. Thus one farmer's waste may be another's profit--a factor that is usually downplayed in most discussions of inefficient irrigation practices. Taking note of the fact that farmers who irrigate attempt to pursue a broad range of sometimes contradictory objectives (Maas and Anderson, 1978), it is still possible to identify a number of common causes for inefficient irrigation practices that are independent of the objectives being pursued by farmers (White 1977). These include:

- inadequate information about the response of different crops (particularly newer varieties) to water;
- inadequate training in the operation and maintenance of on-farm irrigation systems;
- lack of access to credit and infrastructure required to adopt more cost-effective methods of irrigation; and
- water prices that do not fully reflect the foregone value of the resources used to supply water.

Magnitude

There are no reliable estimates for the amount of water now lost annually due to the causes attributed above, although many water resources experts believe these losses are substantial.^(a) Most of the evidence that is found to support the existence of inefficient irrigation practices points to the disparity between the technical efficiency of water use that is found throughout most of the world today in contrast to the technical efficiency that can be achieved by newer methods of irrigation (Stokes 1982; White 1977). (Technical efficiency refers here to the ratio of water used consumptively by crops to the amount of water applied to crops.) For example, traditional methods of flood irrigation are only about 50% efficient whereas the efficiency of low pressure drip irrigation (which is widely practiced in Israel) can be as high as 95%.^(b)

There are at least three problems with these calculations. First, actual field efficiencies are generally lower than the efficiencies which are reported from controlled experiments, under optimal conditions. Second, national and global efficiency estimates generally include conveyance losses, the actual extent of which are subject to some controversy (see Conveyance Losses). Finally, and perhaps most importantly, these calculations fail to take into account the fact that the substantially higher irrigation efficiencies associated with newer forms of irrigation technology can only be achieved at substantially higher costs, which may not be economically justifiable in many regions of the world, due to the low cash value of the crops being irrigated.

However, it is still true that irrigation efficiencies on the order of 20% and 30%, which are commonplace in Asia and the Pacific (Coward 1980), can

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- (a) Personal communications with Professor K. William Easter, Department of Agricultural Economics, University of Minnesota, St. Paul, Minnesota; Professor Robert A. Young, Department of Agricultural Economics, Colorado State University, Ft. Collins, Colorado; and Professor Charles Howe, Department of Economics, University of Colorado, Boulder, Colorado.
- (b) B. Stokes. 1982. Bread and Water: Growing Tomorrow's Food. Unpublished manuscript. World Watch Institution, Washington, D.C.

be substantially improved by better management (Coward 1980; White 1977). According to Abel (1977), remarkable progress has been made in this regard over the last twenty or so years in Taiwan. For the state of Colorado, in the U.S., Whittlesey (1977) has estimated that, holding demand conditions constant, a 16% annual water saving could be achieved there through improved management practices (4%), by lining canals (1%), and by introducing new, and cost-effective irrigation technology (11%).

Persistence

It is likely that the overall efficiency of irrigation will improve with time in most parts of the world, primarily for economic reasons. Increasing population growth in the world will probably place additional strain on the demand for food, increasing the value of the crops that are irrigated and making it economically feasible to adopt these systems where they are environmentally compatible. Moreover, as agricultural information, training, and expertise become more widely disseminated through existing and planned programs of technology transfer, the expectation is that the efficiency of water use will improve (White 1977).

However, there is one source of inefficiency which is likely to remain, namely: the artificially low pricing of water provided to farmers from public water supply projects. This is a serious problem in the U.S. and throughout the world (Kelso et al. 1973; Seagraves 1980) which does not appear to be changing with time, and which will, for the foreseeable future, result in the inefficient use of water.

Climate Sensitivity

Inefficient irrigation practices are sensitive to climatic change to the extent that changes in temperature and precipitation affect crop irrigation requirements or a farmer's perceptions of those requirements. Increased precipitation might lead to a reduction in irrigation water use if this increase coincides, in time, with the growing season. However, where farmers perceive that "more water is better," and do not curtail irrigation, increased precipitation may aggravate waterlogging and salinity problems, and contribute to reduced crop yields. Similarly, increased temperature may result in a

more-than-proportional increase in irrigation, and may also amplify the water supply problems associated with inefficient irrigation practices.

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Waterlogging (of Soils)

Waterlogging of soils occurs when the root zones of plants become saturated by groundwater or by excessive soil moisture. This phenomenon is

usually associated with flat topography, coarse permeable soils and the presence of an impervious strata of material located close to the soil surface, resulting in a high water table. Although waterlogging may occur naturally in regions of abundant rainfall, it is usually associated with intensive irrigation practices, inadequate drainage facilities, seepage from irrigation canals and laterals, and/or the intrusion of manmade structures beneath the soil surface which cuts off the lateral flow of groundwater (Rusk and Christopher 1980). When these factors lead to waterlogging, excess water in the root zone results in reduced crop yields. This condition is exacerbated greatly when the water used to irrigate crops is highly saline. In these situations, the practice of leaching salts from the root zone through additional applications of irrigation water contributes to the rise of the water table, and crop losses are magnified by high salinity concentrations that are present. Remedial measures that can be used to reduce this problem include the construction of drainage works, modification of irrigation practices, and where saline water is an associated problem switching to more salt-tolerant plants.

Magnitude and Distribution

Waterlogging to some degree affects virtually all regions of the world where irrigated agriculture is practiced (Worthington 1977). It is estimated that 10% of all irrigated land suffers some reduced yields from waterlogging^(a). In the U.S., it is estimated that 44% (5.2 million hectares) of the irrigated land is drainage deficient, and in Pakistan about 67% is affected.^(a)

The magnitude of decreased crop yields due to waterlogging cannot be quantified without specific knowledge of the area and crops, but generally speaking, crop yields decline more rapidly as the proportion of the root zone saturated by water increases. However, the magnitude of this response varies widely among crops. For example, a crop that is sensitive to waterlogging may experience only 30% of normal yield when 50% of the root zone is saturated by

(a) Stokes B. 1982. Bread and Water: Growing Tomorrow's Food. Unpublished Manuscript. World Watch Institution, Washington, D.C.

water, whereas the yield of a crop that is insensitive to water-logging may experience 80% of its normal yield under the same conditions. In Egypt, it is estimated that waterlogging reduces productivity by at least 30%, and that a \$500 million investment in improved drainage will result in more than a \$1 billion increase in productivity (Stokes). In the U.S., the total cost of improving drainage and reducing waterlogging is estimated at \$6.3 billion (Rusk and Christopher). Although the benefits derived from improved soil conditions have not been calculated, many observers believe they would greatly exceed the costs of drainage (Maierhofer 1967).

Persistence

Although many projects are underway throughout the world to reduce waterlogging it is estimated that an additional one-half million hectares of irrigated land become waterlogged each year (Stokes). At the same time that drainage projects are improving soil condition in many areas, the amount of irrigated acreage is increasing on a world-wide basis. Since much of this land in the developing nations is poorly drained, the problem of waterlogging continues to increase slowly. The problem is further aggravated by the large capital investment--anywhere from \$250/ha to \$2300/ha (Rusk and Christopher 1980)--required to install necessary remedial structures to improve soil moisture conditions.

Climate Sensitivity

It is likely that waterlogging is extremely climate sensitive, although the relationships involved in making this determination are not simple. Precipitation increases are likely to aggravate the problem by increasing soil moisture and raising the water table closer to the root zone. While an increase in temperature would presumably have the effect of increasing evapotranspiration and thus reducing the problem somewhat, any rise in evapotranspiration would also lead to some offsetting increase in the irrigation water requirements of commercial crops, including water used for leaching salts from the root zone.

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Groundwater Infiltration of Municipal Sewer Systems

Groundwater infiltration of municipal sewage conveyance systems, which consists of water entering pipes through cracks and joints, affects a majority of sewer systems in the U.S. and presents a serious problem in relation to the operation of sewage treatment facilities. One survey of over 65 sewer systems in the U.S. found that, at times of low groundwater, 56% of all flow at the treatment plant is the result of groundwater infiltration; under high groundwater conditions, this infiltration jumps to 89% of the total flow (ADS 1981). Thus, more than half the flow to an average wastewater treatment plant consists of clean water which has entered the system through infiltration.

Magnitude

Several, fairly costly consequences of infiltration are observed as a result of this problem. Operation and maintenance costs of treatment facilities are proportionally higher (56-89%) as a result of having to treat flows in excess of the design capacity (ADS 1981). Treatment plants often are overloaded, resulting in violations of discharge standards under the Clean Water Act. Of 585 treatment plant failures studied by EPA, 297 were identified as directly related to infiltration, and in 120 cases it was considered as a contributing factor (ADS 1981). In treatment plants which utilize biological processes to treat wastewater, the efficiency of the treatment is reduced because microorganisms do not have enough nutrients to work properly, due to the dilution effect of the clean infiltration water. And finally, overbuilding of treatment capacity to accommodate the increased

flows from infiltration is occurring nationwide in the U.S. The total cost of the treatment plant building program between 1980 and 2000 is estimated at over \$28 billion, which may be as much as double that necessary to provide treatment just for actual sewage (Cullen 1981).

EPA estimates that the national costs of correcting the infiltration and associated inflow problem to ensure compliance with the Clean Water Act is about \$2.5 billion, just a fraction of the treatment plant construction program (Cullen 1981). This estimate takes into account the contribution of new plant construction, advanced treatment processes and other programs to the reduction of effluent, but nonetheless provides an indication of the relative magnitudes of the costs of treatment and the costs of reducing infiltration. One study, using a conservative 10-year design period, estimated that savings in waste treatment plant construction and operating costs would be 2.2-5.2 times greater than the costs of rehabilitating sewer systems to realize such savings, i.e., it would be 2.2-5.2 times more expensive to build and operate treatment plants to accommodate infiltration flows than it would be to correct the infiltration problem itself (Daugherty 1981).

There is some evidence that an infiltration problem exists in older cities and rural areas of Europe, but the problem is overshadowed by a more extensive state of disrepair of the sewer systems which require more general overhaul than just correcting infiltration (sewer collapses are a more immediate problem).^(a) Moreover, the somewhat less modern system of wastewater treatment used in many parts of Europe reduces the significance of large volumes of flow attributed to infiltration. Thus, it seems that the problem of infiltration is most serious in the U.S., although it does plague many other older cities in Canada and Europe.

Persistence

In view of the high costs of correcting this problem, it appears likely that the problem will persist until existing sewer systems are replaced over

(a) Personal correspondence with M. J. Green, Water Research Centre, Medmenham, Marlow, England, October 1982.

the next fifty to one hundred or more years. On the other hand, the magnitude of the problem appears to be remaining about constant.

Climate Sensitivity

As noted above, there is a difference of approximately 37% between infiltration under high, as opposed to low groundwater conditions. This suggests that increases in precipitation which raise groundwater levels will have an aggravating effect upon the operation of municipal sewage treatment plants. Otherwise, the problem of groundwater infiltration of municipal sewer systems is not particularly climate sensitive.

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Effect of Changing Water Levels on Aquatic Ecosystems

Fluctuations in the water level and surface area of rivers and lakes may be caused by climatic variations, flow regulation, and changes in the amount of water used to satisfy human and industry demands for that resource. Such fluctuations can change the productivity of water bodies in terms of fish catch, the structure and diversity of the aquatic ecosystem and property values (Welcomme 1979). Water quality effects such as changes in turbidity and salinity may also impact non-fisheries related uses such as municipal, industrial, and agricultural water supplies. Inasmuch as anthropogenic water level fluctuations are considered under the heading "Conflicts in Use," this section primarily is concerned with natural and climatically induced

fluctuations in water levels, although most of the characteristic effects are similar. Moreover, climate-induced fluctuations may be aggravated by human pressures on water supply.

Magnitude

A survey of the relevant literature reveals few locations where climate-induced water level fluctuations have a significant effect on aquatic ecosystems--particularly commercial and subsistence fisheries. Most notable of these are the Sahelian region, where a progressive decline in precipitation from 1962-73 lowered water levels in lakes and reduced floods, resulting in a significant decrease in fish catch; and in East Africa, where a rise in the level of Lake Victoria contributed to a quadrupling of fish catch (water level--and fish catch--fluctuations occur often in this region) (Welcomme 1979).

Whether such short- and medium-term fluctuations are limited to Africa and/or to areas with extreme climatic variation, or whether it is a more widespread phenomenon cannot be determined from the literature. It has been asserted, though, that approximately 30% of the average streamflow is required to maintain a "good" survival habitat for most aquatic life forms (Bayha 1976). It is also apparent that in many regions of the world such streamflow conditions are not always maintained, whether due to climatic or anthropogenic causes. The magnitude of the effects of water level changes on aquatic ecosystems, which are most significant in the fisheries sector, varies widely and is difficult to generalize.

Persistence

The effects of a given water level change on aquatic life generally range from several months to several years, and depend on the duration of the event causing the fluctuation and on the recovery time of the species involved. Some water bodies are subject to relatively frequent changes. For example, Lake Victoria experienced changes in 1895-96, 1918-19, 1931, 1949-50, 1959-60, and 1962-64 (Welcomme 1979). Thus, the phenomenon itself, may be extremely persistent even though individual events involving changes in water levels are only one or two years in duration and widely spaced over time.

Climate Sensitivity

Where the problem currently exists, water level changes are the product of extreme climatic variability. Thus, any climate change which increases the existing degree of climate variability will probably aggravate the current problem. Whether a CO₂-induced climate change will make this problem more widespread will depend upon the extent to which any such change is manifested in the form of increasing climate variability. If this does occur, an increase in the frequencies of extremely wet and extremely dry years might cause the problem to become more severe where it currently exists and perhaps more widespread, as well.

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Navigation Problems

The feasibility and efficiency of inland navigation are affected by water levels and flow rates, sedimentation and meandering of channels, extreme climatic events such as flooding and unusually cold winters, and by the presence of obstructions such as plant growth and debris. Navigation problems include channel aggradation/degradation, curtailment of navigation seasons due to climate variability, and problems created by the competition between navigation and other uses. Of these problems, the first two generally receive the most attention where they occur.

Channel improvements required to maintain navigation on portions of nearly all of the great rivers of the world include: dredging to remove sediment deposits, the construction of contraction works to encourage the formation of wider, deeper channels, bank stabilization to prevent the

meandering of channels, channel straightening and snag and ice removal. In lakes subject to ice formation, year-round navigability may require the use of ice breakers to clear channels, and bubbler systems to prevent ice formation around dock facilities.

Magnitude

Reliable estimates of the cost of all kinds of channel improvements required to improve navigation conditions are generally not available even on a country-by-country basis. However, in the U.S. more than \$525 million is spent annually on maintaining the navigability of existing waterways, and several hundred million more dollars are spent on new multi-purpose navigation, the total price for some of which can exceed a billion dollars.^(a)

The icing over of navigable lakes is a problem of some severity in affected nations. Perhaps the most noteworthy example of this occurs in the Great Lakes system of the U.S. where navigation is frequently closed for most traffic after January 8 due to lake and harbor ice conditions (COE 1979). The estimated economic loss of this closure has been placed at around \$200-220 million per year (about 40% of the total annual cost of dredging operations in all of the U.S.), while the cost of extending the season has been placed at about \$50-55 million per year (COE). Hence, substantial benefits in excess of costs appear to be attainable if the current season is extended on a year-round basis.

Persistence

Given a stable climate, the primary causes of navigation problems should not increase appreciably. Contributing factors that could aggravate navigation problems include the effects of increased traffic on bank erosion and the effect of land use changes, upstream, on erosion and sediment loads. At the same time, increased traffic coupled with population and economic growth could create additional conflicts between navigation, instream and off-stream users of water. However, since most water resources projects which

(a) Personal communication with Jon Mikel, Chief, Operations Branch, U.S. Army Corps of Engineers, Washington, D.C.

affect the navigability of rivers are multi-purpose projects, design standards are usually such that these conflicts arise only at very low rates of discharge (which occur infrequently in time).

Climate Sensitivity

The technical and economic feasibility of navigation projects and channel improvements are very sensitive to climate, as are ice conditions in northern lakes. Changes in precipitation and temperature (through the effect on vegetation cover) have been shown to be closely correlated with changes in sediment loads (Langbein and Schumm 1958). Increased precipitation may also increase channel depths on currently non-navigable and navigable streams. However, depending on the type, timing, duration and intensity of precipitation events, increased precipitation could aggravate navigation problems through flooding and increases in peak discharges which could make navigation more difficult and cause increased meandering of channels.

The effect of temperature changes on navigation will also depend on the timing and duration of these changes. Thus, warmer temperatures might reduce ice flows which affect navigation in winter months on rivers like the Mississippi and the Ohio, but warmer temperatures could also alter the time distribution of snow melt such that summer flows would be less than required to maintain navigation.

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Conflicts in Use

Conflicts between different types of water uses (as opposed to conflicts between individual water users) can be broken down into three categories:

1) conflicts between instream uses, such as hydroelectric power generation and maintenance of instream flows for fish runs, recreation and preservation of water quality; 2) conflicts between offstream uses, such as irrigation and synthetic fuels production; and 3) conflicts between instream and offstream uses such as irrigation and hydroelectric power generation, or between irrigation from surface water and irrigation from a conjunctive groundwater source.

Conflicts in use arise for two reasons. First, because surface and most groundwater flows through space, the action of a single user can affect the actions of other users, through both beneficial and detrimental changes in water quantity and water quality. The second reason for conflicts in use is largely institutional in the sense that existing legal mechanisms for defining access to, and the ownership of, freshwater by and large do not provide the correct incentives for reducing the problems created by mutually interfering use, and in some cases exacerbate these problems (Ditwiler 1975). Thus, resolution of the institutional aspects of this problem would not eliminate competition between users; however, it would provide a basis for eliminating conflicts that occur because of the problem of mutually interfering use.

Magnitude

Conflicts in use exist in every nation of the world, in regions where freshwater is scarce. The impacts of these conflicts can be measured by the distributive tradeoffs that are fostered by a conflict in economic and/or physical terms. These tradeoffs can be further assessed to determine whether the economic losses experienced by those who are adversely affected by the conflict are greater than the benefits to users who are positively affected by the conflict.

Among the most commonly cited examples of conflicts between instream uses are those which occur between recreational users of water and the use of water to assimilate waste. In the U.S., estimates of the foregone value of water to all recreational users due to lack of pollution control has been estimated to lie between \$6 and \$17 billion per year (1978 dollars) (Heintz et al. 1976; Mills and Feenberg 1979; Freeman 1979). However, more recent research on

recreational fishing benefits suggests that these estimates may be as much as an order of magnitude too high (Russell and Vaughn 1982).

Perhaps the most widely publicized conflict in use to be addressed in recent years involving competition between offstream uses is in the American West, where traditional agricultural uses of water are currently being threatened by large-scale energy development projects. In one study, Whittlesey (1979) noted that, while there appear to be ample supplies of water to meet projected agricultural and shale oil demands for water in Wyoming and Utah, as much as 20% of the land now being irrigated in Colorado could be lost due to shale oil development. In another study, focusing on the development of steam electric generating plants in the Four Corners area in the southwestern U.S., Gisser et al. (1979) showed that a 30% reduction in agricultural water use would generate a total regional income loss of about \$8.5 million per year. However, given the far greater value of water in alternative energy uses, it appears likely that compensation for the water rights that are transferred from agricultural uses to energy-related uses will exceed these losses, substantially.

Conflicts between offstream and instream uses are also numerous. For example, in the U.S.S.R., regulation of the Volga River has substantially altered the volume and time distribution of its flows that are discharged into the Caspian Sea. This has helped to increase salinity problems in that body of water; it threatens the freshwater ecosystem of that body of water; and commercial fisheries catches have fallen off by about 60% in the last thirty years, disrupting the structure of the regional fishing economy in the process (Voropaev and Kosarev 1982).

Persistence

Competition between alternative uses of water is likely to intensify, as regional population and economic growth place greater demands on existing supplies of freshwater. Improved water management practices may alleviate some of these conflicts; however, substantial revision of water law throughout the world may be required if the impacts of these conflicts are to be reduced significantly.

Climate Sensitivity

Conflicts in use are sensitive to climate change through the effects which changes in precipitation and temperature will have upon water supply and water demand. In general, an increase in average annual precipitation will reduce competition for freshwater resources by increasing supply and reducing the demand for water for irrigation, household and commercial use. An increase in average annual temperature will likely have the opposite effect. It must be understood, however, that many conflicts in use are more directly related to the timing of water supply relative to demand than they are to the average availability of water. Thus, an increase in temperature that coincided with peak demands for hydroelectric power and irrigation water in summer months would have a much greater impact on the conflict between those uses than an increase in temperature that was concentrated in off-peak periods.

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USE AND REUSE ISSUES--WATER QUALITY

Saline Intrusion of Aquifers

Saltwater intrusion is the movement of saline water into the freshwater zone of an aquifer. In coastal areas, salt water enters an aquifer when the natural balance between water discharged from the aquifer to the sea and saltwater pressing in from the sea is disturbed. Conditions which may be conducive to saltwater intrusion include regulated streamflows and sea-level canals, both of which permit sea water to advance inland. This usually is due to groundwater mining, reduction of the natural recharge area, or extreme tidal variations. Saltwater intrusion of inland aquifers occurs when saline water, which in the U.S. underlies about two thirds of the continent (GAO 1980), migrates vertically or horizontally into freshwater aquifers. This usually is due to anthropogenic changes in hydraulic pressure in the aquifer. Inland aquifers also may become saline by deep percolation of saline irrigation water. In general, as little as 2% sea water in an aquifer can render it unpotable (GAO 1980). Given the relatively slow movement of most groundwater, saline contamination can persist from a minimum of several years to several decades or longer (GAO 1980).

Once the problem of intrusion has developed in a coastal aquifer, it is not easy to control. The most obvious method for alleviating the problem is to reduce pumping and restore the natural interface between fresh and saline water in the aquifer. However this approach is usually infeasible for 1) legal-institutional reasons and 2) the high cost of supplemental water. Other methods which have been tested include artificial recharging of the aquifer, pumping of saltwater through coastal wells and the construction of impermeable barriers to prevent sea water inflow (Todd 1964). All but the last method have been implemented in various cases, but the very high costs of these options makes them economically feasible only for protecting municipal

water supplies. None of them correct the source of the problem, overpumping, which is responsible for saltwater intrusion.

Magnitude

Damages resulting from saline groundwater include reduced crop yield when groundwater is used for irrigation (El-Ashry 1980); corrosion damage to plumbing, household appliances, and industrial machinery; increased water treatment costs for municipal and industrial users; and the abandoning of wells previously used for drinking water. The extent of these damages is highly dependent upon salinity concentrations, location, and degree of reliance on groundwater for water supply.

While it is difficult to generalize the costs associated with these damages, one study (Andersen 1978) found that an increase in salinity from 200 mg/l to 700 mg/l in the Los Angeles municipal water supply would result in economic losses of \$620-\$1010 per household over the typical 60 year economic lifetime of a housing unit. This translates into aggregate damages of \$880 million-\$1.44 billion for the area served by the municipal water supply system.

Saline intrusion occurs in or threatens most coastal aquifers, particularly where there is urban or industrial development which utilizes groundwater supplies. Since the U.S. has one of the most comprehensive groundwater surveying and monitoring capabilities, this is where the most information is available. In 1973, it was reported that 42 of 50 states had serious saltwater intrusion problems (GAO 1980). Florida, California, Texas and New York (in that order) are generally considered to be the most severe of these cases in the United States (Todd 1960).

Persistence

Since urban and industrial development are increasing in coastal regions, problems of saline intrusion of coastal aquifers also are increasing. Moreover, improved methods of locating and exploiting new aquifers--both coastal and inland--will further increase intrusion problems. Improvements in artificial aquifer recharge techniques likely will help mitigate this problem,

but the relatively long residence time of most groundwater indicates that existing and future intrusion problems will persist for many years.

Climate Sensitivity

Saltwater intrusion is climate sensitive in at least two different ways. First of all, changes in temperature and precipitation which affect the demand for water are likely to affect pumping rates, as well. In that regard, increases in temperature may increase the demand for water to supply households and agriculture, thereby placing additional pressure on available groundwater supplies, whereas increased precipitation could lead to a decline in pumping rates, primarily through reduced agricultural demands and possible augmentation of surface water supplies.

The problem of saltwater intrusion may also be affected by climatic changes which directly augment groundwater supplies. Depending on the characteristics of the affected aquifer, increased precipitation may also increase the supply of groundwater through the infiltration of this precipitation into the soil and subsequent percolation into the groundwater system. Assuming that the rate of withdrawal remained constant, then this would have the effect of at least partially restoring the natural interface between freshwater and saltwater in the aquifer.

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Salinity Problems

The principal sources of sodium and chloride in surface water include many sedimentary rocks, particularly the evaporates, salt "seeps," oilfield drainage, and domestic and industrial contamination. In humid climates, heavy rains usually leach these contaminants into the groundwater, from which they are transported to streams and oceans in relatively low concentrations. However, in dry climates, where leaching is localized due to less rainfall, soluble salts and chloride may not be transported far and surface water salinity generally becomes a more severe problem (Slatyer and Mabbutt 1964). Surface water may also become highly saline in the upper portions of estuaries when the natural saltwater-freshwater interface is altered by droughts or abnormally high tides. The impacts of surface water salinity include increased corrosion of water pipes, higher water treatment costs, reduced fish harvests and reduced crop yields. In some cases, salinity and chloride concentrations may make surface water unfit for human consumption.

In dry regions, highly saline surface water is frequently associated with saline and alkali soil problems. Highly saline and alkali soils can be traced to natural and anthropogenic sources. In arid regions, surface drainage channels are often poorly developed with no outlet to permanent streams (i.e., continuous flows, year-round). Under these conditions, salt-bearing waters may temporarily flood the soil surface and, because evaporates are high, salts become heavily concentrated in soils and dry lakes (Slatyer and Mabbutt 1964). Anthropogenic causes of saline and alkali soils can usually be traced to one of two sources: 1) the use of saline irrigation water which, through evaporation, leaves behind salts in the soil and 2) extensive leaching of salts by irrigators which increases the salinity concentrations present in return flows, and/or causes a rise in the contiguous groundwater system leading to the saturation of the root zone with saline water (see Waterlogging)(Kovda 1977). Regardless of the cause, soil salinity can have a serious effect on agricultural productivity. Historically, many civilizations

with well-developed irrigated agriculture have "collapsed" because of the inability to recognize and solve soil salinity problems (FAO 1973).

Magnitude

The magnitude of the impacts associated with surface water and soil salinity problems depends on the concentration of salts present and the number and types of water users, but generally speaking, the impacts are greatest in the agricultural sector. According to Yaron (1981), about one-third of all irrigated land in the world is affected by salinity problems, but in some areas in Israel, India, Northern Africa, and the southwestern U.S. , 50 to 75% of the land may be affected. Salinity problems in the Lower Colorado River Basin and the Red River Basin of the U.S. have been studied extensively. According to El-Ashry (1980), salinity damages to Colorado River water users is about \$53 million/yr, with an estimated additional \$230 thousand/yr in damages for each one ppm increase in salinity (Evans 1975). In the Red River (Texas and Oklahoma), salinity and chloride control measures would increase the value of regional agricultural production by an estimated \$66 to 117 million/yr (Laughlin and Lacewell 1981). For the U.S. as a whole, Kovda (1980) has estimated that, during the 1960s, about \$350 million/yr in agricultural production was lost because of salinity problems.

Persistence

According to Yaron (1981), about 100,000 acres of agricultural land are taken out of production annually because of salinity problems, and these problems appear to becoming worse if current trends continue (El-Ashry 1980). The expansion of irrigated agriculture in dry climates is likely to increase the salt concentrations of streams, rivers, and adjacent soils. Large drainage projects and other structural means for reducing salinity problems faced by irrigated agriculture have been proposed in a number of countries. Benefits substantially greater than control costs have been demonstrated for a number of projects including those on the Red River (Laughlin and Lacewell 1981), Northwestern Mexico (McFarland 1978) and the San Joaquin Valley of California where some 400,000 acres of cropland is exposed

to high salinity concentrations (Sudman 1982). However, water policy politics (particularly in the U.S.) and the lack of access to credit markets (a common problem in developing nations) may slow the implementation of these and similar projects throughout the world.

In many parts of the world, where salinity problems are not yet severe, the leaching of salts into the water table can forestall these problems in the short-run. In the long-run, however, this practice may give rise to serious waterlogging problems.

Climate Sensitivity

Surface water and soil salinity problems are highly climate sensitive, and as shown earlier are most severe in dry climates. Increases in annual average precipitation, if substantial enough, can be expected to reduce salinity problems through additional leaching and runoff and increased streamflow. Increases in average annual temperature will have the opposite effect due to higher evaporation, which will increase not only the concentration of salts in the soil, but also irrigation water demands. Thus, additional pressure would be placed on existing (and already contaminated) supplies and increases in the salinity of irrigation return flows would likely cause the concentration of salts in streams, rivers, and adjacent soils to rise as well.

In humid regions, on the other hand, it is unlikely that small changes in precipitation or temperature will have any major impact on the low level of salinity problems usually associated with these climates.

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Waterborne Disease

Numerous varieties of waterborne disease exist, with health effects ranging from temporary gastrointestinal discomfort to death. Typhoid, cholera, filariasis, and trachoma thrive in waters subject to fecal contamination, most often in areas lacking sanitary facilities. Malaria carrying insects breed in tropical waters and swampland. Onchocerciasis (river blindness), is transmitted by insects which thrive in fast flowing waters such as dam spillways. Schistosomiasis, perhaps the most widespread and studied waterborne disease, which alone affects over 250 million people depends on an aquatic snail host that flourishes in slow moving waters

characteristic of many water/irrigation development projects. Structural water systems such as dams, irrigation canals, and irrigated fields with poor drainage, can provide a suitable habitat for one or more of these disease vectors.

Magnitude

Globally, there are 250 million new cases of waterborne disease each year, and approximately 25,000 deaths/day are attributed to this cause (Stein 1977). Waterborne diseases are most widespread in developing countries, where unsanitary water supplies, lack of water treatment, expanding irrigation, and poor sanitary habits contribute to their spread and frustrate control efforts. Although nearly 10 million deaths each year are attributed to some form of waterborne disease, most individuals affected do not die. Rather, they suffer short and long term debilitating effects which, among other things, can significantly reduce productivity. In Africa (excluding Egypt), it was estimated that productivity losses from schistosomiasis in 1968 amounted to \$212 million, not including medical treatment and public health program costs, and in the Philippines, the estimated economic losses in 1963 were roughly \$6.5 million (Obeng 1978). And in Egypt, perhaps the most studied site, this figure was \$100-200 million in 1977 (Stein 1977).

Although waterborne disease is less persistent or widespread in developed countries, between 1971 and 1978 the U.S. recorded 224 outbreaks, affecting 48,193 people, including two deaths. The number of outbreaks appears to be on the rise. (It is estimated that the number of unrecorded outbreaks may be equally as large.) The main causes of these outbreaks are cross connection, backsiphoning, and treatment deficiencies in water supply systems (Graun 1981).

Persistence

Although biological, mechanical, and medical controls have shown limited success, the anticipated rapid expansion of irrigation and water delivery systems suggests that problems of waterborne disease will not be eradicated in the near future. Moreover, the damming of major rivers in connection with

large, multi-purpose water resource projects such as the Aswan High Dam in Egypt, may expand the natural habitats of many waterborne disease hosts.

Climate Sensitivity

Malaria, schistosomiasis and onchocerciasis, which are widely viewed as the three most serious waterborne disease, are all communicated to human populations by intermediate hosts. While the spatial distribution of each of these hosts is climate sensitive, small changes in temperature and precipitation will probably not affect the severity or the distribution of waterborne diseases in the world. In general, the problem tends to be a latent (i.e., unintended) consequence related more closely to the design of water supply systems and the behavior of those who use these systems.

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Groundwater Contamination

Important sources of groundwater contamination include: leachates from waste disposal sites, agricultural fertilizers and pesticides, industrial wastes, mining residue, seepage from sewage systems, and accidental spills of hazardous substances. The severity and extent of groundwater contamination in a given location is determined by the hydrological setting and the nature of the contaminant (Lindorff 1979).

Magnitude

Groundwater contamination usually occurs in a confined area, but the effects can be serious for the population that depends on the aquifer (Pettyjohn 1979). These effects range from increased water treatment requirements and cost to the closing down of wells. Due to less-than-

comprehensive monitoring of groundwater, difficulties in detection, and insufficient knowledge of the health effects of some contaminants, the extent of exposure and health impacts is unknown in many cases where groundwater is contaminated. Because many contaminated aquifers tend to be large in size and have slow turnover times, groundwater contamination is generally more critical than that of surface water (Barabas 1980).

All regions of the U.S. have been found to have significant groundwater contamination problems, although these are believed to be most critical in the Eastern states (Burmaster 1981). The problem also is prevalent in Europe, and probably exists undetected in many other regions of the world, particularly where industrial activity is great (Fried 1976). In the U.S., it is estimated that there are more than 1000 sites similar to Love Canal, New York, where uncontrolled dumping of toxic chemicals rendered wellwater unpotable and posed health hazards for the local population (Pettyjohn 1979). The estimated restoration costs for an average contaminated aquifer and adjacent soils are \$5-10 million, where it is feasible at all (Miller 1979).

Persistence

Groundwater contamination is an extremely persistent problem in light of the slow movement of most groundwater formations. Most problems persist for decades or centuries (Lindorff 1979). Moreover, since the number of undetected contaminated aquifers is believed to be large, and since the volume of waste and the potential for groundwater pollution are increasing, it is likely that problems of groundwater contamination will continue to increase.

Climate Sensitivity

Groundwater contamination is not very climate sensitive when the rate of aquifer recharge is slow (the average residence time of aquifers is more than 100 years). On the other hand, contaminated aquifers with a short residence time will be more sensitive to changes in precipitation. However, even in these cases, the impact of increased precipitation is difficult to evaluate, since the effect of an increase in the volume of contaminated water reaching these aquifers at any given point in time may be offset by a reduction in the concentration of contaminants in the water that percolates through the soil.

An increase in the frequency and intensity of individual precipitation events also has the potential to magnify the problem of groundwater contamination. In this instance, torrential rains could cause contaminated groundwater to percolate back to the surface in poorly drained soils or swamps which underlie many landfills used for dumping of toxic and hazardous wastes before stricter regulations were imposed on such practices.

The effect of increased temperatures on groundwater contamination appears to be somewhat more straightforward. To the extent that warmer temperatures increase evapotranspiration, less water will be available for groundwater recharge. Hence, an increase in temperatures may partially offset the impacts of increased precipitation on groundwater contamination.

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Surface Water Contamination

Surface water contamination results from point and non-point sources of industrial, agricultural and domestic water from accidental spills, and from thermal pollution from power generation. Depending on the quantities, concentrations, and toxicities of the contaminants involved, the deteriorated

water quality may affect fish and wildlife, treatment costs, potability, and may have significant impacts on human health.

Magnitude

The magnitude of the impacts of surface water contamination has in many instances, been quite large. On the Hudson River, where well over 500,000 pounds of PCB's are concentrated in the riverbed and backwaters, it would cost an estimated \$204 million to clean up that persistent carcinogen (Boyle and Highland 1979). In Poland, water from the Vistula and Oder rivers is totally undrinkable, primarily due to the discharge of sewage (Environment 1980). And in Spain's Ria River, fish are inedible and human health is threatened due to high mercury levels. In the U.S., where controlling water pollution and improving water quality has been emphasized for a decade, the Federal government has authorized about \$28 billion for wastewater treatment plants since 1972, and private industry has spent another \$12 billion in control technology. In 1978 alone, total expenditures for all wastewater functions was aproximatley \$22 billion (1980 dollars) (Cullen 1981).

Although there is debate over what constitutes "acceptable" water quality the level of expenditure and public concern illustrates the relative importance of this issue.

Surface water contamination is evident to some extent in most regions of the world, but the most critical problems appear in the vicinity of high population density and extensive industrial development (UNEP 1982). Thus, while pollution problems caused by domestic sewage may occur in any settled area without adequate treatment facilities, the more toxic and persistent contaminants tend to be associated with urban, industrial and (particularly in the case of pesticides) agricultural development.

Persistence

If current trends continue, surface water contamination generally will increase in the decades to come. Although some industrialized nations have controlled point-source discharges, many have not, and in general non-point pollution is increasing (UNEP 1982). In developing nations, both of these

sources continue to increase, and the regulation of toxic substances generally is not as comprehensive as in many of the industrial nations.

Climate Sensitivity

Theoretically most pollutants can be diluted to a relatively harmless state if enough water is available. Surface water contamination by non-toxic substances and naturally occurring pollutants is likely to be sensitive to increased runoff and streamflow which reduces their concentrations in rivers, lakes and streams. However, because the health impacts of low level exposure to many carcinogenic and mutagenic contaminants are not well defined, "safe" concentration levels that have been established in the U.S. and Europe tend to be extremely small and it is unlikely that increased runoff and streamflows due to climate change would greatly affect the cost or methods required to treat water contaminated by these sources.

A more serious aspect of climate sensitivity related to this issue concerns possible changes in the frequency and intensity of rainfall. If climate change increases the frequency of floods, then contamination of surface water from point sources may become a more serious problem, first by increasing the number of sources exposed to flood hazards, and secondly by increasing the area inundated by contaminated flood waters. In the case of non-point pollution, an increase in the frequency and intensity of rainfall would increase runoff from agricultural land. However, because the volume of runoff would be increased, it is not clear whether the concentration of pesticides, herbicides, etc. would also rise.

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Acidification of Lakes

The atmospheric transport of sulfur and nitrogen oxides from fossil fuel combustion may result in the deposition of strong mineral acids in precipitation which are deposited in a watershed. Other, natural causes/sources of acid deposition may include hydrogen sulfide which is evaporated from swamps and oxidized into sulphur oxides in the atmosphere, sulfate deposits from oceans and a climatically induced reduction in the buffering capacity of suspended particulates in the atmosphere. Runoff water from a drainage area becomes acidified when the amount of deposited acid is greater than the buffering capacity of the watershed.

Resultant increases in the acidity of freshwater bodies can create an environment which is potentially uninhabitable by many freshwater species. In addition to the ecological consequences of acid deposition in lakes, loss of commercial and sport fishing activities may be expected to have indirect impacts on other service industries within regions affected by this problem. Loss of jobs and income where this occurs is likely to be small, nationally, but such impacts can be extremely disruptive of local economies.

Magnitude

Currently, the best documented effects of acidification in aquatic ecosystems are in Sweden, Norway, Finland, Canada and the Northeastern U.S. A recent study by the Office of Technology Assessment (Environment 1982) reports that, within the 27-state region covered by the study, one of every six lakes and one in every five streams have been damaged by acid precipitation. In Sweden, it has been estimated that the lake area affected by acid precipitation is approximately 5,000 km². For Norway and Finland, the comparable estimates are 1,650 km² and 280 km² (OECD 1981).

Estimates of the economic losses caused by acid precipitation are extremely tentative. Losses to recreational fisheries in New England and New York have been placed at from \$20-50 million per year^(a) and the estimated total impact of acid rain on existing economic activities east of the Mississippi River is around \$250 million per year. In Sweden, the loss in productivity of fish-stocks due to acidification has been estimated to be about \$18 million per year. Comparable impacts in Norway and Finland have been placed at approximately \$10 million and \$1 million, per year, respectively (OECD 1981).

Persistence

Changes in the amount of acid deposition which can be related back to anthropogenic sources will depend upon the rate of fossil fuel use, worldwide, and the implementation of future control/mitigation strategies in the industrialized nations of the world where this is a problem (Likens et al. 1979).

Climate Sensitivity

Since no clearcut relationship has been identified yet between the quantity of SO_x and NO_x emissions and the extent of acidification, nor between the quantity of precipitation and the degree of acidification, it is difficult to make any conclusive statements about the sensitivity of the acid rain problem to climate change, and particularly to changes in precipitation. Moreover, the occurrence in some locations of acidification from natural sources further complicates any understanding of the climatic and non-climatic determinants of acidification of surface water, and of the relative contribution of anthropogenic sources to this phenomenon.

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Inadequate Water Treatment Facilities

A lack of adequate sanitation (primarily excreta disposal) coupled with little or no drinking water treatment, causes serious health problems in many nations. Drinking water sources may become contaminated due to poor sanitation facilities, and numerous water related diseases infect the population using these supplies. It generally is recognized that the provision of reasonable access to potable water must be accompanied by adequate sanitation if such water related health problems are to be ameliorated (Stein 1977).

Magnitude

It is estimated that only 23% of the world's population receive "adequate" sanitation services. There is roughly a 13% coverage in rural areas, and about 53% coverage in urban areas (these estimates exclude the People's Republic of China) (U.N. 1980). The extent of the impacts of waterborne disease--which usually is a result of poor sanitation--is severe, and is outlined under Waterborne Disease.

Problems of inadequate sanitation are much more prevalent in developing nations than industrial ones. Southeast Asia, sub-Saharan Africa, and West Asia are the areas where the problem is most severe. It has been estimated that the total costs of providing water supply and sanitation to the world's population would be roughly \$132-600 billion, but it is unclear what portion of this sum is for sanitation projects (U.N. 1980). This estimate is exclusive of operation and maintenance costs. Thus, although the provision of adequate sanitation services is not a serious problem in most industrial nations, it is a critical problem with severe impacts on human health for a large portion of the population in many developing nations.

Persistence

Some improvements are being made in terms of absolute numbers of individuals with adequate sanitation, but not in the percentage of the total population covered (U.N. 1980). Thus, while improvements are being made, given current levels of expenditures (\$6-7 billion/year) full, or even near-full, coverage appears to be at least 50 years away.

Climate Sensitivity

The provision of adequate water treatment facilities is viewed by the U.N. primarily as an infrastructure problem. However, increases in temperature will have the likely effect of increasing water intake by humans, resulting in higher waste loads that must be treated. The effect of changes in precipitation on the provision of adequate water treatment facilities would be indirect. Changes in precipitation which affect runoff and streamflow could affect the concentration of contaminants in existing and future sources of water supply. This could influence the degree of treatment required and, subsequently, the cost of providing the necessary infrastructure. While increased runoff might reduce these costs (by lowering the concentration of contaminants), an increase in precipitation that raised the frequency of flooding would have an offsetting effect due to the sanitation and drinking water contamination problems traditionally caused by flooding.

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