Ecological Impacts of Water Use and Changes in Levels and Flows

A Literature Review

Prepared For:

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PREFACE

This literature review was prepared for the Great Lakes Commission as a component of an ongoing project, *Development of a Water Resources Decision Support System for the Great Lakes/St. Lawrence System*. The project is sponsored by the Great Lakes Protection Fund. Financial support was also provided by Environment Canada.

EXECUTIVE SUMMARY

The Great Lakes Commission is currently developing the framework for a decision support system that will provide the data, information and process required to ensure timely and well-informed public policy decisions concerning the use and management of ground and surface water in the Great Lakes Basin. The Great Lakes Protection Fund is supporting this effort, which is titled: *Development of a Water Resources Decision Support System for the Great Lakes/St. Lawrence System.* Project Element Four addresses the compilation of an inventory of information on ecological impacts of current and prospective water use. One Element Four task involves a literature review that may be used to contribute to a better understanding of ecological impacts (Great Lakes Commission, 2000).

The thrust of this literature review was to compile the body of research relevant to the identification and quantification of ecological impacts that might arise from water withdrawals/diversions in the Great Lakes Basin. Because this topic really encompasses the entire body of knowledge on the effect of physical, chemical, and biological conditions in a freshwater ecosystem on its structure and function, we had to be reasonably selective in the inclusion of literature in this document. Also, in an effort to organize the included literature in a logical and understandable way, we have grouped the literature in four broad categories: 1) effects on physical/chemical habitat; 2) effects on populations and/or communities; 3) ecosystem effects; and 4) synoptic modeling studies. There were also a number of large, focused studies that have or are making significant contributions to these four categories. We have dealt with each of these studies individually.

Both the published and the "gray literature" (*i.e.* the numerous provincial, state and federal, and private sector publications) were searched. More than 260 documents were reviewed and summarized. Our review indicates that while there have been a great many studies that are relevant to assessment of ecological impacts of water withdrawals/diversions, most of these studies have been site-specific and descriptive in nature. Often they test a hypothesis that there is or is not a significant response of the system, but do not collect sufficient information for <u>quantitative</u> analysis of the deterministic, cause-effect relationships that underpin the empirical observations. It is really only with this critical process understanding that we can generalize the findings, through synthesis and model development, to the various types of ecosystems that exist in the Great Lakes Basin. A quote from Hardy (1998) in regard to stream habitat modeling is especially relevant to this point; he says that the future of habitat modeling "remains an abstraction, in that integration of all the pieces has yet to be accomplished, field validation remains unproven, availability of an integrated analysis framework (*i.e.,* computer software system) is not yet available, and a clear framework for selection and application of specific tools has not been developed."

Meyer *et al.* (1999) reaches a similar conclusion. He points out that: "We are limited by availability of both data and models. More extensive data sets and better models are needed linking hydrologic regime with ecosystem processes (productivity,

nutrient dynamics, food web interactions), with ecological interactions (predation, species invasion), and with water quality." In view of these observations, we strongly recommend that future funding for research and development in this area be directed at "data mining" for both qualitative and quantitative stress-response relationships in this subject area. There should also be a concerted effort to **synthesize** and **model** the quantitative relationships between water withdrawals/diversions in various types of Great Lakes ecosystems (large lakes, inland lakes, streams and rivers, groundwaters) and potential ecological impacts of those water uses.

This synthesis and modeling effort is essential if we are to truly deal with the assessment and management of cumulative impacts from multiple withdrawals within a given watershed and the cumulative impacts of multiple watersheds on one of the Great Lakes or the St. Lawrence River. Another technical issue that demands an integrative approach is the confounding effects of multiple stressors acting in concert to produce a series of ecological responses; these confounding conditions make it difficult to isolate the hydrological → ecological cause-effect relationships.

Also, there are the issues related to time and space scales in making cause-effect assessments. Often, the time and space scales of the hydrologic/hydraulic stressors are very different than those for the ecological manifestation of those stressors. We have already seen that changes in flows or levels can be classified in three categories: 1) changes in mean values – annual or seasonal; 2) changes in frequency and amplitude of extremes – floods and droughts; and 3) changes in seasonal timing of levels or flows. Each of these categories of stressor may have its own time and space scale for a given system, and each may elicit a different ecological response with a different time lag (many years in some cases) and spatial extent. Any field or experimental characterization of cause-effect relationships should be done in the context of both stressor and response endpoint time and space scales.

Given the state of our understanding and the state of our data base on this issue, it makes sense to consider adopting an adaptive management approach in making and following up on water withdrawal decisions. Several authors, including Persat (1991) and Walters (1997), have pointed to the above multi-scale issues and data/understanding limitations as arguments for using an adaptive management approach.

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1. INTRODUCTION

The Great Lakes Commission is currently developing the framework for a decision support system that will provide the data, information and process required to ensure timely and well-informed public policy decisions concerning the use and management of ground and surface water in the Great Lakes Basin. The Great Lakes Protection Fund is supporting this effort, which is titled: *Development of a Water Resources Decision Support System for the Great Lakes/St. Lawrence System.* Project Element Four addresses the compilation of an inventory of information on ecological impacts of current and prospective water use. One Element Four task involves a literature review that may be used to contribute to a better understanding of ecological impacts. The outcome of this task will provide the policy/management community with a better understanding of the current state of the science related to ecological impacts of current and prospective water use (Great Lakes Commission, 2000).

1.1 BACKGROUND

Changing water levels (or flows) are just one stressor on wetlands and nearshore and instream communities. Degradation comes in many forms and degrees of severity, and is far more difficult to quantify than loss of area (Bedford, 1999). Documented examples of typical forms of degradation include: 1) fragmentation, partial filling and dyking of habitats; 2) toxic substances in water and sediments; 3) invasion by exotic species; 4) pollution, nutrient enrichment and other changes in the physical and chemical characteristics of a local environment; and 5) decrease in average area. In that context, it becomes very difficult to make a realistic assessment of the effects of just changes in levels or flows.

The biological effects of water level fluctuations in both lakes and rivers are greatest in shallow water, where even small changes in water levels can result in the conversion of a standing-water environment to an environment in which sediments are exposed to the air, or vice versa (International St. Lawrence River-Lake Ontario (ISLRLO) Plan of Study Team, 1999). The localized effects of this change in the environment are most evident in the relatively immobile plant communities that occur in wetlands. In fact, the patterns of water level change are the driving force that determines the overall diversity and condition of wetland plant communities and the habitats they provide for a multitude of invertebrates, amphibians, reptiles, fish, birds, and mammals.

Even in natural and unaffected river systems, cumulative changes in watersheds, although difficult to quantify, can often be tied to changes in parameters that control river behavior. They are the results of chain reactions that take place during relatively rare flood events, where the impact of an individual event makes it difficult to relate to the cumulative sum.

Changes in levels and flows can essentially be classified in three categories: 1) changes in mean values – annual or seasonal; 2) changes in the frequency and amplitude of extremes – floods and droughts; and 3) changes in seasonal timing of levels or flows. The sequence of flows, especially their magnitude, frequency and duration, also plays an important role in the geomorphologic processes of erosion, sedimentation and river channel evolution

There are also challenges in applying research assessments to other sites. Many assessments rely on site-specific links between level or flow and the geomorphology of various habitats, and the knowledge of the relationships between species and their preferred habitat. This poses a second level of major difficulty: space and time. The threshold sensitivity of any species is closely linked to the more critical phases of their life cycles.

Furthermore, since many impacts will take years to manifest, the assessment of such impacts should cover a long enough period of time. In the case of fluvial ecosystems, analyzing the condition of an ecosystem before a change and forecasting conditions afterwards raises formidable problems (Persat, 1991). Physically, fluvial ecosystems stand out by their spatial and temporal components; multiple longitudinal gradients are expressed throughout the forked branched fluvial network, where floods and low water levels alternate more or less regularly. These features greatly complicate the approach to the system. The Persat study focused on the space and time scale difficulties required to understand the function of such an ecosystem and stressed the uncertain value of former case studies as comparative material for predicting future conditions, thus raising the question of the reliability of forecasting.

1.2 OBJECTIVES

The objectives of the literature review were to:

- Identify and summarize literature that assesses the ecological impacts of water use, levels and flows; assesses ecological thresholds with respect to water supply; and presents indicators used to assess the ecological impacts of water use and the processes, functions and time scales of those indicators;
- Review literature related to the effects of water supply and use on the ecological systems. For example, the effects on water quantity and flow, water quality, water temperature, seasonal timing of water supply, vegetative patterns, flow velocity, and the geomorphologic characteristics of stream and lake shorelines; and
- Review frameworks that have been established to assess the ecological sensitivity of freshwater ecological systems to future water use and/or changes to water supply (e.g. under climate change).
- Prepare a report that presents a descriptive inventory and analysis of literature addressing the ecological impacts of water use, including:
  - A listing of all literature reviewed and abstracts of selected literature, appropriately categorized;
  - A series of findings, based on the literature review, addressing the state of knowledge and practice concerning ecological impacts of water use and

frameworks for defining the sensitivity of the freshwater ecological systems to future changes; and

- A series of recommendations as to: 1) how such findings might advance current and prospective water resource management efforts; 2) additional research needed to address gaps in knowledge and practice identified through the literature search; and 3) methodologies or approaches that hold promise as a means to assess individual and cumulative impacts of changes in water levels and outflows due to water use.

2. APPROACH

This section describes the methods that were used to review the literature, and provides explanations of the categories that were selected to organize the findings. Both the published and selected gray literature (government reports and documents published outside of the traditional peer review and publication process) were searched.

2.1 LITERATURE REVIEW METHODS AND SOURCES

A variety of methods were used to search the published literature and the gray literature, as described in the following sections.

2.1.1 Published Literature Review

Literature searches were conducted in the following databases: Aquatic Science and Fisheries Abstracts (1978-2000), Water Resources Abstracts (1967-2000), Water Resources Worldwide (1970-2000) and, for possible additions of recent articles, Current Contents (2000-2001). The searches used the following keywords individually or in combination: levels, water levels, flows, change, variation, fluctuation, impacts, effects, ecological, thresholds, and instream. The searches were extended to cover the complete table of contents of all titles appearing in journals such as Regulated Rivers, Hydrobiologia and Freshwater Biology. The abstracts were retrieved from the web when available. This approach probably covered most of the published scientific literature on this subject.

As the search produced hundreds of references, a manual review was made of all titles and abstracts to identify references of interest and literature relevant to the purposes of this report. Materials from beyond the Great Lakes-St. Lawrence system that might have an application to that system were accessed and reviewed. A number of visits to local university libraries at Laval University and INRS-Eau were made to verify the pertinence of the information. Document selection was limited to those articles that relate to levels and flows and their changes, and which focused specifically on ecological assessment related to potential changes. In that context, it should be realized that the author's perspective of what is relevant may have biased the results and that some important articles may have been missed.

The issue of climate change impacts was treated slightly differently. Recent literature on the subject is abundant, but mostly deals with global changes in precipitation and temperature. While some of it may address regional or local issues and impacts on levels or flows, the articles that look at the impact of those changes on ecological end points is very limited. Therefore, the few articles that have been retained deal with either direct impacts of temperature changes on the community structure of freshwater living organisms or look at the induced ecological impacts of changes in water levels. Only those articles specifically related to the Great Lakes-St. Lawrence basin have been retained and the few references dealing with impacts on the physiology of freshwater organisms are not listed.

In reviewing a preliminary draft of this report dated April 2001, anonymous reviewers suggested a list of possible additions to this literature survey. An analysis of some of these references made it possible to add them to the original list. It was also suggested at that time that the author look at the reports released in November 2000 by the World Commission on Dams (WCD). Unfortunately it was not possible to look at all this voluminous material in the time available. A limited time was spent examining a thematic review dealing with dams, ecosystem functions and environmental restoration and some contributing papers to that review.

After close examination of all available abstracts and further visits to the libraries at Laval University and INRS-Eau to check the relevance of some articles, this list was trimmed down to 121 articles for detailed review and analysis. The following criteria were used to exclude articles from further analyses: very short articles (1 to 2 pages) with no abstracts available, some foreign languages articles, very general content (general references, books) that might be of interest in a more general context and examples from outside the basin that seemed to have little relevance. It should be remembered that for some sources the review could only be carried out using the abstracts obtained from the database search or from online access to the table of contents, as it was impossible to access the full text for some references in the time available, especially technical reports and conference proceedings.

This shorter list was then used as a basis to try to answer the terms of reference of this report. Section 3 examines the results of the literature search, while section 4 presents short abstracts of the 121 articles, grouped in sub-sections. Section 5 presents a short summary of the author's analysis of the voluminous World Commission on Dams material that is available online. Section 6 presents conclusions and recommendations, while Section 7 lists all articles referenced in this review. Finally, Appendix 1 presents an in extenso version of the Executive Summary, Conclusions and Recommendations of the previously mentioned WCD thematic review, while Appendix 2 lists all contributing papers to the review and may provide interesting subjects for further examination.

2.1.2 Gray Literature Review

In addition to the peer-reviewed literature, focused literature searches of the "gray literature", *i.e.*, government (provincial, state, and federal agencies) and private sector publications, were conducted. A sampling of the gray literature was added to supplement the peer-reviewed literature in this survey, in response to comments expressed at the *Experts' Workshop on Ecological Impacts of Water Withdrawals in the Great Lakes-St. Lawrence System* in November 2001 (LTI and Great Lakes Commission, 2002).

Gray literature searches focused on following organizations: U.S. Army Corps of Engineers (US COE), U.S. Geological Survey (USGS), U.S. Fish and Wildlife

Service (US FWS), and The Nature Conservancy. However, other relevant material that was discovered during the search process was reviewed as well. On-line searches of the current public publications and the library holdings for these organizations were searched using key terms individually or in combination with a qualifying term:

- Key Terms: water level(s), (water) regulation, (water) diversion, water depth, water quantity, (water) discharge, flow(s), environmental flows, flow regimes, ecohydrology, hydrology/ecology, water export, water level regulation/control, water use, drawdown, and water withdrawal(s).
- Qualifying Terms: effect(s), impact(s), vegetation, wetlands, aquatic habitat, fish, and ecology/ecological.

This search strategy produced a number of documents of varying degrees of relevance. As was done with the peer-reviewed literature, search results were reviewed to identify the relevant literature for the purpose of this report. In addition, the Internet search engine *google.com* was used to identify other relevant documents from the gray literature.

The US FWS website and library holdings were not accessible in February-March 2002, due to a court order that restricted US FWS's internet access. For this reason, the Fish and Wildlife Reference Service was contacted, and they conducted a literature search for this literature survey. This search produced 273 records; search results primarily contained theses and dissertations from universities and documents published by state agencies. The relevance of each record was determined from the major/minor subject terms and from the record abstract, which was often limited or unavailable.

Although a large number of records were obtained through these search strategies, only a subset of key gray literature documents was collected for this review. Approximately 35-40 gray literature resources, spread across the same categories used to describe the peer-review documents (see Section 3), were obtained and are described in this report. These resources also include reports and materials from special focused studies (e.g., UNESCO's Ecohydrology Programme) as described in Section 4. Documents were collected during visits to federal government agency libraries and to university libraries located in Ann Arbor, Michigan: NOAA's Great Lakes Environmental Research Lab (GLERL), USGS's Great Lakes Science Center, and the University of Michigan. A number of documents were also downloaded from the Internet. In some instances, the document could not be obtained in full; the descriptions of such resources largely reflect published abstracts.

2.2 DESCRIPTION OF CATEGORIES

After reviewing all the potential references, useful references that assess cumulative ecological impacts in the context of this study were found to be practically non-existent. The problem of identifying ecological thresholds and indicators that could be used to assess the cumulative ecological impacts of water use, and their possible application to the Great Lakes-St. Lawrence system, has not been addressed in the context of water uses and changes in levels and flows. However as some of the references may have relevance to particular aspects of cumulative impact assessment, we have grouped the references in four broad categories to help narrow down possible areas of interest: 1) Effects on Physical Habitat; 2) Effects on Populations and/or Communities; 3) Ecosystem Effects; and 4) Synoptic Modeling Studies. It is recognized that some papers could be categorized in more than one of these categories.

2.2.1 Effects on Physical Habitat

This category includes literature describing the effects of changes in water levels/flows on physical habitat (substrate, flow, depth, and temperature). This category also includes papers describing assessments of physical habitat. Although climate change was not in itself a focus of this literature search, some references of interest have been included under this category. For example, climate change research that addresses changes in river flows, lake circulation, and waters levels and the ecological impacts of these changes is described.

2.2.2 Effects on Populations and/or Communities

This category includes literature describing the effects of water use and of changes in water levels/flows on biological populations and communities. The literature in this section has been subdivided into two categories: 1) Effects on Flora; and 2) Effects on Fauna. The Effects on Flora section includes literature that describes effects on phytoplankton, aquatic macrophytes, and tree species. The Effects on Fauna subcategory includes literature describing effects on fisheries populations, muskrats, turtles, and migrating birds; it also includes papers addressing minimum flow requirements for fish.

The literature on instream use of water is relatively abundant, yielding more than forty-six published articles in this category. It deals essentially with the effects on fisheries of abstractions and perturbations after diversions or withdrawals of stream flow, and the necessary minimum flow requirements to sustain available habitats and fishery resources. In this context, its relevance to the Great Lakes-St. Lawrence system should be adapted to specific conditions on some of the tributaries. The literature deals mostly with what proponents consider to be thresholds for various stream resources, but touches very little on the problem of sensitivity to threshold changes.

2.2.3 Ecosystem Effects

This category includes papers that describe ecosystem effects from water use or from changes in water levels/flows. This includes a subcategory that specifically focuses on Wetlands Ecology literature. Papers detailing wetland functions, wetlands stresses, and wetland assessments are described. In addition, this section includes a subcategory where Stream Ecology and Ecological Assessment Studies are described. This subcategory principally contains literature describing stream assessments and stream assessment techniques.

A number of articles in this category describe physical characteristics and ecological aspects of shore zone habitats, while others provide conceptual frameworks for describing impacts. They explore trends in alterations of freshwater ecosystems, discuss the ecological consequences of biophysical alterations and the need for an ecosystem approach, and identify some of the major scientific challenges to and opportunities for effectively addressing the changes. While the articles are in some aspects theoretical and useful for explaining the problem of ecological integrity, they offer little practical guidance for evaluating cumulative impacts. However, they may be useful in establishing an operational framework for impact analysis, monitoring protocols and agendas for scientific research evaluating the cumulative impacts of changes in level or flows.

2.2.4 Synoptic Modeling Studies

This category includes papers describing conceptual or mathematical models. Such models have been employed to predict the spatial distribution of vegetation, to investigate the impact of flow diversion on benthic communities, and to predict habitat suitability for fish. This section also includes literature describing conceptual frameworks for analyzing the ecological impacts of water use in the Great Lakes-St. Lawrence system.

Models that examine relationships with living organisms, and therefore attempt to predict possible impacts or changes, are just a very limited subset of the literature on modeling; this search did not include all types of models, including various hydraulic or hydrologic models.

2.3 SPECIAL FOCUSED STUDIES

This category highlights a number of relevant large-scale studies that target some aspect of the study question. These studies focus on water level issues in the Great Lakes, ecological impacts from dam and hydropower regulation, and conceptual frameworks for investigating ecological impacts of changing water levels and flows. These studies include work conducted by the International Joint Commission, World Commission on Dams, UNESCO’s Ecohydrology Programme, the Waterpower Project (Ontario, Canada), and The Nature Conservancy.

3. DESCRIPTIVE INVENTORY OF LITERATURE

This section contains a descriptive inventory of literature describing the effects of changes in water levels and flows on ecosystem components. The focus of the inventory is on the Great Lakes-St. Lawrence River system and other applicable freshwater environs. The literature is grouped into the following categories, as described in Section 2.2:

1. Effects on physical habitat
2. Effects on populations and/or communities
   - Effects on flora
   - Effects on fauna
3. Ecosystem effects
   - Wetland ecology
   - Stream ecology and ecological assessment
4. Synoptic modeling studies

3.1 EFFECTS ON PHYSICAL HABITAT

This section includes literature describing the effects of changes in water levels/flows on physical habitat (substrate, flow, depth, and temperature). This category also includes papers describing assessments of physical habitat. Although climate change was not in itself a focus of this literature search, some references of interest have been included. For example, climate change research that addresses changes in river flows, lake circulation, and waters levels and the ecological impacts of these changes is provided below.

Atkinson et al. (1999) investigate potential impacts of climate change on the Great Lakes through water quality and ecological modeling. Aside from changes in stratification, lake circulation patterns, timing and occurrence of overturns, etc., the main potential for changes in water quality is through changes in the temperature regime. This affects a number of processes of interest, including biochemical reactions, growth rates, partitioning coefficients for toxic organic contaminants, transfer of volatile materials across the air/water interface, and external loadings. Atkinson et al. (1999) describe two specific case studies of water quality models applied to the Great Lakes. Preliminary results show that under scenarios involving a doubling of CO_2 levels, early warming of Lake Erie waters could lead to increased uptake of nutrients by algae in early spring and prolonged algal production.

Bedford (1992) presents a summary of the physical effects of the Great Lakes on tributaries and wetlands, particularly through the effects of short and long-term water level fluctuations and accompanying transport disruptions, including flow and transport reversals. With there being few, if any, direct observations of these disruptions in the Great Lakes system based on velocity measurements, the possible physical effects can only be estimated by reviewing the current contributing physics known about the Great Lakes and contrasting possible marine estuary transport mechanisms with what little has been published about the Great Lakes. Lake Erie was chosen because that lake exhibits the strongest response to storms and the clearest measurable signals resulting from them.

Boulton *et al.* (1998) examine the functional significance of the hyporheic zone in streams and rivers. The hyporheic zone is an active ecotone between the surface stream and groundwater. Exchanges of water, nutrients, and organic matter occur in response to variations in discharge, bed topography and bed porosity. At the stream-reach scale, hydrological exchange and water residence time are reflected in gradients in hyporheic faunal composition, uptake of dissolved organic carbon, and nitrification.

Bult *et al.* (1998) propose a quantitative multi-scale technique based on frequency analysis and randomization to study habitat selection by fish in riverine habitats. The technique can be used over any range of spatial scales in an environment with irregular boundaries.

Bush & Larry (1996) assess habitat impairments impacting the aquatic resources of Lake Ontario. They estimate that from 1970-1990, Lake Ontario's ecosystem health was degraded by 58 percent. Impairments causes were almost equally divided among anthropogenic stresses from biological (loss of indigenous and introduction of exotic species), chemical (persistent toxins), and physical (dredge-fill, damming, and water-level regulations) sources.

Brunke & Gonser (1997) review the literature on the connections between river and groundwater systems, viewing them as linked components of a hydrological continuum. They further evaluate ecological processes that maintain the integrity of both systems and those that are mediated by their ecotones.

Cazaubon & Giudicelli (1999) analyze the impacts of residual flow on the physical characteristics and benthic community (algae, invertebrates) of a regulated Mediterranean river characterized by a greatly reduced residual flow. The main environmental consequences of residual flow were high daily and annual thermal amplitudes and a reduction in the diversity of available habitats.

Crowder *et al.* (1996) examine rates of natural and anthropogenic change in shoreline habitats in the Kingston Basin, Lake Ontario. Stresses from the lake cannot be controlled locally, whereas those arising from terrestrial activities are more easily managed. Slow rates of change are less likely to have dramatic effects than are rapid changes, but a small change can have catastrophic effects if it exceeds the threshold tolerance of an ecosystem. Dramatic alterations to the entire ecosystem can also occur if a single, important species (e.g., a macrophyte) is adversely affected, because of complex feedback responses among the various components of the system.

Gippel & Stewardson (1998) examine the use of wetted perimeter in defining minimum environmental flows. For the streams that were examined, the wetted perimeter relationships did not suggest an optimum environmental flow, nor did they suggest a flow level that would maintain the macro-invertebrate community in its unregulated state if it were applied for a long period of time. Fish habitat area does not necessarily increase with discharge, so the method of curve analysis suggested here for wetted perimeter may not be applicable to some fish habitat area data. Flowing water perimeter is preferable to wetted perimeter as a variable to define habitat suitable for macro-invertebrates.

The Great Lakes Regional Assessment (2000) investigates the effect of climate change on the Great Lakes. The Great Lakes Region Assessment (2000) is one of 16 regional assessments conducted in the US, as part of the US Global Climate Change Research Program (USGCRP). Previous assessments indicated that the 1.5-8 ft. drop in water levels would be observed with climate change—that is, a drop in lake levels would occur, on top of the monthly and seasonal fluctuations that occur in the lakes. Predictions of both wetter and drier futures demonstrated decreases in water levels and flows on all of the Great Lakes connecting channels. In this Assessment (2000), the Canadian Climate Center Model (CGCM1) simulations demonstrate a 1.5-3 foot drop in water levels within 3 decades. In contrast, the United Kingdom Hadley Center Model (HadCM2) demonstrates no change or a slight increase in water levels. Both models demonstrate a decrease in ice cover. In addition, both the CGCM1 and the HadCM2 models predict warmer conditions in the Great Lakes, which will be stable for longer periods of the year. This increased stability would result in less oxygen mixing down from the surface to greater depths. This, in turn, would effectively reduce biomass productivity by 20%. Coupled with other research this scenario indicates that fishery production would also decrease in the Great Lakes. Further research is required to quantify the magnitude of this decrease. Furthermore, the Assessment (2000) indicates that inland rivers that are primarily driven by snowmelt (e.g., peak flows in spring) may have earlier peaks because of less snow and more rain. Changes in stream flow will depend upon how future increases in precipitation are balanced by evapotranspiration. The Assessment (2000) also asserts that water regulation models need to incorporate some of the changes that are anticipated from climate change.

Hoover et al. (2000) evaluate the benefits of restoring riverine backwaters for fish habitat using weirs or other types of water control structures. Backwaters serve as important nurseries for riverine fishes. However, simple empirical techniques for quantifying their value prior to and following habitat restoration have not been established. In this study, plexiglas light-traps were used to effectively sample young-of-year fish assemblages in specific habitats of backwaters. This technique can be used to provide data for a wide variety of sampling regimes. Cases histories are presented from the lower Mississippi River Basin demonstrating that light traps may be deployed once, over an extensive range of habitats, or repeatedly within a narrower range of habitats, to provide data that adequately describe relationships between hydrologic conditions (habitat or stage) and fish abundance. Statistical models are readily developed between river stage, or individual habitat parameters, and fishery response variables. These models are easily modified for use in traditional habitat assessment techniques, such as Habitat Evaluation Procedure

(HEP) and cost-benefit analyses (Hoover et al., 2000). Unlike "off-the-shelf" habitat models, Hoover et al. (2000) assert that these models represent fish assemblages and physical habitat conditions distinctive to individual water bodies.

Hudon (1997) shows a strong negative relationship between seasonal water level and the percentage of emergent plant cover in Lake Saint-Pierre on the lower St. Lawrence River. At low water levels, the lake becomes a large marshland that could support a high plant biomass, whereas at high water levels the lake shifts to a vast, open-water body with a lower predicted plant biomass. Conceptual models of St. Lawrence River vegetation responses to water levels are shown, with respect to biomass allocation and species diversity, as a function of average level and the vertical range during the growing season.

Humphries *et al.* (1996) examine how littoral habitats in large rivers are influenced by changes in discharge. The macro-invertebrate assemblages of common littoral habitats in riffles, pools and runs in two reaches each of the Macquarie and Mersey Rivers, northern Tasmania, Australia, were compared from samples collected during the low flow and irrigation season. Differences in taxonomic composition, density and richness among habitats within reaches strongly imply the uniqueness of these habitats in terms of the invertebrate faunas that occupy them. They suggest that if maintenance of biotic diversity is an aim of instream flow management, water allocations that address low flows should place a high priority on the maintenance of a diversity of habitats.

Johnson *et al.* (1995a, 1995b) used IFIM to assess the impact of groundwater abstraction upon habitat suitability for trout and salmon at various life-stages in a chalk stream in southern England. Weighted usable area data and discharge relationships were combined with a twenty-year time series of mean monthly "historical" and "naturalized" flows. The resulting time series of historical and naturalized weighted usable areas were analyzed using a standard duration curve program. These habitat duration curves demonstrate the effect of the abstraction upon the availability of habitat for each species life stage that was considered. As the absolute value of the abstraction is relatively constant throughout the year, the relative effect increases rapidly at lower flows. For the summer months, discharge exceeding the 95-percentile level was depleted by 55 percent, representing a decline in the weighted usable area of 95 percent. The results provided by this analysis were used by the River Authority to negotiate a proposed 50 percent reduction in the levels of abstraction.

Johnson & Covich (2000) report on the importance of nighttime observations for determining habitat preferences of stream biota. Their results suggest that habitat models cannot be based only on daytime observations. Because the level of nocturnal activity is not known for most species of fish and invertebrates, studies of habitat preferences should include both day and night observations.

Jowett (1997) compares different approaches of instream flow methods; application of hydraulic and habitat methods suggests that the environmental response to flow is not linear; the relative change in width and habitat with flow is greater for small rivers than for large. Small rivers are more 'at risk' than large rivers and require a higher proportion of the average flow to maintain similar levels of environmental protection.

Magnuson *et al.* (1997) examine the physical changes that might come from climate change and would in turn affect phytoplankton, zooplankton, benthos and fishes. Annual phytoplankton production might increase but many complex reactions of the phytoplankton community – to altered temperatures, thermocline depths, light penetrations and nutrient inputs – would be expected. Zooplankton biomass would increase, but, again, many complex interactions are expected. Aquatic ecosystems across the region do not necessarily exhibit coherent responses to climate changes and variability, even if they are in close proximity. Lakes, wetlands and streams respond differently, as do lakes of different depth or productivity. Differences in hydrology and position in the hydrological flow system, terrestrial vegetation and land use, base climates, and aquatic biota can all cause different responses. Climate change effects interact strongly with the effects of other human-caused stresses such as eutrophication, acid precipitation, toxic chemicals and the spread of exotic organisms.

Meyer *et al.* (1999) review published analyses of the effects of climate change on goods and services provided by freshwater ecosystems in the United States. Climate-induced changes must be assessed in the context of massive anthropogenic changes in water quantity and quality resulting from altered patterns of land use, water withdrawal and species invasions; these may dwarf or exacerbate climate-induced changes. Water to meet instream needs competes with other water uses and that competition is likely to be increased by climate change. The study discusses potential ecological risks, benefits and costs of climate change and identifies information needs and model improvements required to improve the ability to predict and identify climate change impacts and evaluate management options. The ability to predict impacts on water resources is still hindered by the lack of good climate predictions on regional scales and by the lack of fundamental understanding of many of the effects of climate variability on the physical, chemical and biological characteristics of aquatic ecosystems. “We are limited by availability of both data and models. More extensive data sets and better models are needed linking hydrologic regime with ecosystem processes (productivity, nutrient dynamics, food web interactions), with ecological interactions (predation, species invasion), and with water quality”.

In modeling instream flow needs, Milhous (1998) examines the link between sediment and aquatic habitat. Instream flows are needed to remove undesirable accumulations of sediment. Fine sediments and sand accumulate on and in gravels during periods of low flow and must be removed (flushed) periodically for the gravel to remain suitable for aquatic habitat. Sediment of all sizes can also fill pools in the river and must be removed in order to maintain pool habitat.

Morin & Leclerc (1998) analyze the hydrologic evolution of Lake Saint-François, on the St. Lawrence River and its impact on wetland distribution. The Lake Saint-François area was drastically modified by a rise in water level after the river was dammed in 1849. New wetlands were created and pre-1849 wetlands, located on what are currently shoals in the central part of the lake, have totally disappeared.

Morrow (2000) asserts that freshwater fishes have evolved to occupy most freshwater habitats, some of which are naturally very harsh. This diversity allows freshwater fishes to occupy habitats that have been greatly altered and allows some altered habitats to support important recreational fisheries. Further, Morrow (2000) states that fish habitat assessment can be simplified by carefully examining project goals and anticipating potential habitat problems. Adequate assessments can often be accomplished by measuring certain water quality parameters and physical attributes such as, substrate size, amount and type of instream cover, amount and type of riparian vegetation, flow regimes, and stratification regimes (Morrow, 2000). A wide range of values can provide quality fish habitat in most regions; however the author asserts that well-stated project goals will probably considerably narrow the range of acceptable values and simplify the design process.

Mortsch (1998) examines how the magnitude and rate of climate change could alter the hydrology of the Great Lakes and affect wetland ecosystems. Wetlands would have to adjust to a new pattern of water level fluctuations; the timing, duration, and range of these fluctuations are critical to the wetland ecosystem response. Two "what if" scenarios were developed to assess the sensitivity of shoreline wetlands to climate change: (i) increased frequency and duration of low water levels, and (ii) changed temporal distribution and amplitude of seasonal water levels. Wetland functions and values – such as wildlife, waterfowl and fish habitat, water quality, areal extent, and vegetation diversity – are affected by these scenarios. Wetlands that are impeded from adapting to new water level conditions by man-made structures or geomorphic conditions are at a particular risk.

Rhodes & Wiley (1993) report that declining water levels may cause contaminated sediments to be resuspended and represents a potentially long-term environmental remediation problem.

Rozengurt (1999) examines the effect of water diversions on estuary coastal ecosystems where the seasonal alteration of runoff potential/kinematics energy input/output exerts a substantial force on deltaic, estuarine and coastal circulation patterns (e.g., a river plume, an estuarine hydrofront).

Shedlock *et al.* (1993) examine the interactions between ground water and wetlands on the southern shore of Lake Michigan. The results of this study suggest that wetlands in complex hydrogeologic settings may be influenced by multiple ground water flow systems that are affected by geomorphic features, stratigraphic discontinuities, and changes in sediment types. Discharge and recharge zones may occur in the same wetland. Multidisciplinary studies incorporating hydrological, hydrochemical, geophysical, and sedimentologic data are needed to identify such complexities in wetland hydrology.

Spink *et al.* (1998) investigate a range of river floodplain sites in North America and Europe to determine which factors determine nutrient richness and productivity. A principal component analysis revealed that phosphorus richness of the soil and plant growth were strongly associated with river size and site position, both in relation to the distance from the river's source and from the river channel. Nitrogen mineralization and available phosphorus were significantly correlated with river water quality. A phytometer experiment revealed that a large amount of the stress experienced by plants growing on the floodplain was due to other than soil factors, and fertilizer experiments showed that at several sites, production was not limited by nutrients. Climatic factors (temperature, latitude) also determined plant production. The hydrological regime that a floodplain is subjected to was found to be a vital factor for determining both nutrient dynamics and plant production, but is difficult to characterize due to the complex and variable nature of the flood pulse.

The US EPA Global Warming website (2002) presents a Great Lakes and Upper Midwest case study on climate change, wildlife and wildlands. Case study findings are as follows: Potential impacts of global warming on this region include the reduction of the habitat available for cold water fish such as trout and salmon in lakes and streams. In addition, lake levels in the Great Lakes may drop significantly with global warming, affecting wetlands, water quality, recreation facilities, and shipping. Habitat for waterfowl and other endangered species may also be impacted. Moreover, global warming may change the timing of migration and nesting of some birds, putting these birds out of sync with the life cycles of their prey species. In addition to this case study, the US EPA Global Warming website provides further information on water resource impacts and details state-specific impacts of global warming for all of the Great Lakes states.

Ward & Stanford (1995) examine the dynamic nature of alluvial floodplain rivers as a function of flow and sediment regimes interacting with the physiographic features and vegetation cover of the landscape. During seasonal inundation, the flood pulse forms a 'moving littoral' that traverses the plain, increasing productivity and enhancing connectivity. Flow regulation by dams, often compounded by other modifications such as levee construction, normally results in reduced connectivity and altered successional trajectories in downstream reaches. Flood peaks are typically reduced by river regulation, which reduces the frequency and extent of floodplain inundation. A reduction in channel-forming flows reduces channel migration, an important phenomenon in maintaining high levels of habitat diversity across floodplains. The seasonal timing of floods may be shifted by flow regulation, with major ramifications for aquatic and terrestrial biota.

The Water Science and Technology Board (1989) briefly reviews the importance of water level fluctuations and the importance of wetlands as habitat.

Wollmuth & Eheart (1999) explore several methods to control withdrawals from streams, examining each in detail and offering numerical examples comparing each on the basis of economic efficiency and effectiveness for maintaining critical streamflow standards. This work is part of a study to assess the vulnerability of midwestern streams to climate change and to surface-supplied irrigation spawned by such climate change in particular. The results suggest that it is possible to implement regulations that at once (i) are consistent with the riparian doctrine; (ii) control the hydrological and ecological impacts of offstream withdrawals effectively; and (iii) preserve the primary economic functions of those withdrawals, including minimizing economic risk.

3.2 EFFECTS ON POPULATIONS AND/OR COMMUNITY STRUCTURE

This section includes literature describing the effects of water use and of changes in water levels/flows on biological populations and communities. The literature in this section has been subdivided into two categories: Effects on Flora and Effects on Fauna. The Effects on Flora section includes literature that describes effects on phytoplankton, aquatic macrophytes, and tree species. The Effects on Fauna subcategory includes literature describing effects on fisheries populations, muskrats, turtles, and migrating birds; it also includes papers addressing minimum flow requirements for fish.

3.2.1 Effects on Flora

Hellsten (2000) investigates the environmental effects of water level regulation for purposes of hydropower production in the littoral zones of regulated lakes (northern Finland). Changes in the environmental conditions and aquatic macrophyte community were studied largely by comparing conditions in a regulated and unregulated lake. Hellsten's (2000) study reveals the sensitivity of the littoral against water level fluctuations. Rising water levels at the beginning of regulation caused long-term erosion process affecting aquatic macrophytes. The most obvious effect of regulation was the expanded area of extending ice, which caused an almost complete disappearance of large ice-sensitive isoetids. Enhanced erosion and unstable bottom especially limited the occurrences of emergent larges helophytes, and promoted the spread of small erosion-resistant isoetides. Apart from erosion, most of the *Carex* species were also limited by the delay of spring flood as a consequence of regulation. A model based on environmental factors was also used to roughly predict the vegetation types. In addition to the obvious changes in the distribution of aquatic macrophytes, Hellsten (2000) notes that the response of the littoral is slow and the effects may appear gradually over several decades. Hellsten (2000) also investigates restoration techniques based on mechanical protection of shorelines and revegetation.

Hudon *et al.* (1996) assess the longitudinal variations of phytoplankton biomass and composition in a 250 km-long section of the St. Lawrence River, which alternately runs through narrow river cross sections and wide fluvial lakes. Hudon (2000) observes that a discharge reduction of 12 percent in the St. Lawrence River and 46 percent in the Ottawa River between summer 1994 and summer 1995 coincided, for stations in both water masses, with lower biomass, greater species richness and an increase in taxa that generate noxious smells and odors. Phytoplankton is recommended for use in monitoring the biological impacts of changes in water characteristics resulting from human activities and climate change in the Great Lakes watershed.

Jean & Bouchard (1991, 1993) and Jean *et al.* (1993) evaluate the relative importance of small-scale abiotic factor variation and large-scale spatio-temporal variation on the distribution of wetland vegetation in a section of the Upper St. Lawrence River in Quebec. The time lag between a reduction in natural disturbances (water level fluctuations and fires) and the relative stabilization of species distribution could be a reason for the importance of spatio-temporal variables and account for the undetermined portion of species variation. Past history, particularly that of human interventions, becomes an important factor leading to the observed importance of large-scale spatio-temporal variables.

Jean & Bouchard (1996), using a dendrochronological analysis of three tree species colonizing a swamp along the St. Lawrence River, report on (i) the extent to which water-level fluctuations, as compared to climatic variations, impact tree growth; (ii) the responses of three species to hydrologic and climatic variations; and (iii) the duration of water-level fluctuation influences on tree growth. Response function analyses were used to measure the influence of climate (temperature and precipitation) and water level on tree growth.

Meeker and Wilcox (1989) investigate the effects of water-level regulation on aquatic macrophyte communities, individual plant species, and potential faunal habitat in a study of two regulated lakes and an unregulated lake in northern Minnesota. Water levels in Rainy Lake and Namakan Reservoir in Voyageurs National Park are regulated by dams. Natural annual fluctuations of 1.8 m are replaced with fluctuations of 1.1 m in Rainy Lake and 2.7 m in the five lakes that comprise Namakan Reservoir. In addition, springtime peaking of water levels in Namakan Reservoir is delayed by one month. After reaching the peak, water levels in the regulated lakes are held at that level through the summer and allowed to gradually decline through autumn and winter. Detrended correspondence analysis showed that the macrophyte communities at all depths of the regulated lakes differed from those in the unregulated lake. The differences were more profound in deeper parts of the littoral zone. Lac La Croix contained taxonomically and structurally diverse plant communities at all depths, maximizing faunal habitat. The greatest effect of the regulation on Rainy Lake was along transects at the depth that is never dewatered. There were only four taxa present. The greatest effect of regulation on Namakan Lake was along transects at the depth where drawdown occurs in early winter and disturbance results from ice formation in the sediments. Rosette and mat-forming species were dominant, providing minimal faunal habitat. The hydrologic regime at Lac La Croix results in intermediate disturbance that maintains high diversity. There is too little disturbance from water-level fluctuations in Rainy Lake and too much disturbance in Namakan Reservoir, resulting in reduced diversity in both cases.

Minc (1997) examines the vegetative responses in Michigan coastal wetlands and marshes to interannual fluctuations in Great Lakes levels. Data was collected as part of the Michigan Natural Features Inventory (MNFI) sampling program of Michigan's

Great Lakes shorelines in 1987-98, when extreme high water levels occurred, and in 1994, when near normal water levels occurred. Project objectives were to examine the changes in species composition between sampling events, to relate the changes to differences in water level fluctuations, and to explore the implications of vegetation variability for developing a Great Lakes marsh classification system. Minc (1997) found year-to-year continuity is low (<50%) in Great Lakes marshes, possibly reflecting the continual stress and response of wetlands systems. Minc (1997) also found indicator species of marsh types are generally stable, but experience a shift in abundance and in relative dominance in response to lake level changes. In addition, a classification system with four divisions was developed for emergent marsh types and for herbaceous zone types. In this study, the effect of changing water levels is also discussed for the emergent marsh types and the herbaceous zone types.

Stromberg & Patten (1990) describe a methodology that allows determination of instream flow requirements for maintenance of riparian trees. Tree-ring data revealed strong relationships between tree growth and stream flow volume for riparian species at Rush Creek, an alluvial stream within an arid setting; these relationships allowed the development of models that predict growth rates from hydrologic variables. Simple linear regression models were used to determine the relationship between the annual growth of cottonwood and pine trees and a number of seasonal hydrologic variables. The models can be used to assess instream flow requirements under the assumption that certain levels of growth are necessary to maintain the population. There is a critical need to develop and use instream flow methodologies for riparian vegetation, since present methodologies focus on needs of aquatic animals (e.g., fish) and may underestimate needs of the entire riparian ecosystem.

Wilcox & Meeker (1991) investigate the effects of water level regulation on aquatic macrophyte communities by comparing two regulated lakes in northern Minnesota with a nearby unregulated lake. The unregulated lake supported structurally diverse plant communities at all depths. In the lake with reduced fluctuations, only four taxa were present along transects that were never dewatered; all were erect aquatics that extended through the entire water column. In the lake with increased fluctuations, rosette and mat-forming species dominated transects where drawdown occurred in early winter and disturbances resulted from ice formation in the sediments.

3.2.2 Effects on Fauna

Aadlland (1993) examines the selection of target species for instream flow studies, reviewing a study of 114 combinations of fish species and life stage in six Minnesota streams. Each stream had been assigned membership in one of six habitat-preference guilds based on the habitat type supporting their highest densities. Exclusive use of pool-oriented game fish as target species in instream flow studies may result in recommendations that do not protect species occupying flow-sensitive riffles. To preserve fish community diversity and integrity, instream flow assessments should include target species that occupy flow-sensitive habitat types.

Auer (1994) examines how migratory lake sturgeon which spawn below a small hydroelectric facility on Michigan's Sturgeon River have responded to a change in facility operation negotiated during recent relicensing. Spawning characteristics of this fish have been monitored for six years. The change in facility operation, and therefore water discharge patterns, created changes in several characteristics of the spawning lake sturgeon population. There has been a reduction in the times when adult lake sturgeon are observed on-site, an increase in the total number and size of adults, an increase in spawning-ready fish, and a change in capture locations. Constant and nonfluctuating water flows produced by run-of-the-river operations appear to be reproductive readiness triggers and allow more and larger fish to move onto spawning grounds.

Research during the 1980s (Bain & Travnichek, 1996) on fish communities and habitat in flow-regulated rivers of the northeastern U.S. provides the basis for a general hypothesis of regulated stream flow effects on riverine fishes. This hypothesis predicts that flow regulation would most strongly affect fish restricted to shallow shoreline microhabitats, that species composition would be dominated by habitat generalists in flow-altered reaches, and that a gradient of change in community composition would be found below hydroelectric dams. These predictions were largely confirmed in studies of a large southeastern U.S. river with extensive hydroelectric development.

Bellrose & Low (1943) report on the influence of flood and low water levels on muskrat survival. Too little water, like too much water, resulted in the muskrats attempting to relocate to more favorable habitats. This movement was sometimes within the area but more often to adjacent areas with much stress on the affected populations. Fortunately such forced exoduses occurred at a time when the muskrat habitats were generally underpopulated.

Bergeron *et al.* (1998) examine winter geomorphologic processes in the Ste. Anne River (Quebec) and their impact on the migratory behavior of Atlantic tomcod. The data in this paper suggest that channel morphology and flow dynamics, controlled both by the tidal regime and the ice cover, influence the tomcod's migratory behavior.

Bickerton *et al.* (1993) investigate the invertebrate communities and environmental characteristics of three English chalk streams to determine the effects of groundwater abstraction. A variety of analytical techniques, including a novel multivariate analysis (co-structure analysis), and the use of species profiles, showed significant physical and biotic differences among the three rivers and between impacted and natural sites on each river. A decrease in macrophytes was the major difference between sites and changes in discharge, depth and substrate composition were seen to a lesser extent. All can be attributed at least in part to groundwater abstraction.

Blinn *et al.* (1995) use five in situ experiments to test the influence of fluctuations in river discharge on the structure and function of tailwaters benthos associated with cobble substrata in the Colorado River downstream from Glen Canyon Dam, Arizona. Periods of daily desiccation and freezing during river fluctuation significantly limited community biomass and energy. The permanently submerged channel supported four times as much macro invertebrate mass as the zone affected by level fluctuation.

Dickerson (1995a-e), in a series of Technical Notes, reports that changing water levels or other operations at U.S. Army Corps of Engineers (USACE) reservoirs may impact critical habitat parameters for turtle species (i.e., mud, musk, snapping, softshell, terrestrial, and wetland turtles). These turtle species and habitats have been identified by resource managers as potentially impacted by USACE reservoir or other water-control projects. Life-history summaries and habitat requirement descriptions are provided for each potentially-impacted turtle species. Current state and/or Federal legal protection status is summarized for each turtle species, as is the distribution of USACE Districts and reservoir projects potentially impacted by specific turtle species conservation issues. This work has been accomplished as part of the “Reservoir Operations—Impacts on Habitats of Target Species” study initiated in FY98 under the Ecosystem Management and Restoration Research Program (EMRRP) (Dickerson et al., 1999).

Englund & Malmqvist (1996) examine the effects of flow regulation, habitat area and isolation on the macroinvertebrate fauna of rapids in north Swedish rivers. An analysis of the relationship between the effects and the regulation-related variables indicates that the occurrence of large and rapid discharge changes was the most important factor. Habitat size and isolation were not found to have an effect on overall species richness, suggesting that extinction and re-establishment of subpopulations are not prominent processes on the scale considered in this investigation. The data suggest that avoiding large and rapid flow changes can increase both the abundance and the diversity of vertebrates. Increasing the flow will decrease flow variability but also expand the habitable area and thus the production of invertebrates. The best effect is expected at sites where a considerable proportion of the flow has been diverted.

Fjellhiem *et al.* (1993) study benthic animal densities, biomass and production in a regulated west Norwegian river in 1988 and 1989. The change in flow regime resulted in reduced biomass and faunal changes. A great part of the biomass reduction was due to reduced densities of the chironomids caused while an increase in biomass was recorded for rheophilic insect larvae such as the stoneflies. The faunal change was attributed to the altered physical environment and destruction of lentic habitats.

Gehrke *et al.* (1999) analyze within-catchment effects of flow alteration on fish assemblages in the Hawkesbury-Nepean River system, Australia. This study identifies differences in fish assemblages between reaches of the river system affected by dams, flow diversion and regulation, and rivers unmodified for water supply. Seven fish assemblages were identified by multivariate analyses, which revealed a separation of assemblages in habitats affected by dams or flow alteration.

Gippel & Stewardson (1995) examine the impact of flow abstractions of Australia’s upper Thomson River, which was dammed in 1983 creating an impoundment to provide a reliable water supply to Melbourne for up to 20 years. Despite profound modification of the river's hydrology, there is no evidence of severe or irreversible environmental impacts from the interim environmental flows in the upper river. Macroinvertebrate populations have recovered from disturbances during the construction phase and the diversity of fish has not changed; a population of blackfish and grayling is still maintained. However, there is concern that a lack of floods will result in a contraction of the channel. This would probably mean a loss of available habitat area in the long term. Abstraction of water from the lowland section of the Thomson River began in 1957. Unfavorably low flows have occurred since regulation, but wetland inundation floods still occur with the same frequency. Although current management practices do allow unfavorable flow conditions to occur occasionally, the regulated flow regime has not reduced the diversity of native fish present in the lower river.

Gregory *et al.* (1983) investigates goose population trends and the effects of water level fluctuations on Canada goose and brood habitat, as a result of releases from Kerr Dam. Twenty-eight percent of all nests were below the high water mark and were potentially vulnerable to flooding. Observations of broods indicated broods fed on aquatic vegetation and developing wheat. Geese used the river less and reservoirs more as the post-fledging period progressed.

Grossman *et al.* (1998) analyze the effects of environmental variation and interspecific interactions on the assemblage organization of stream fishes inhabiting Coweeta Creek, North Carolina. The study encompassed a 10-year time span (1983-1992) and included some of the highest and lowest flows in the last 58 years. Habitat availability data was classified on the basis of year, season and hydrologic period (pre-drought, drought and post-drought). Hydrologic period explained a greater amount of variance in habitat availability data than either season or year. Total habitat availability was significantly greater during post-drought than in pre-drought or drought, although microhabitat diversity did not differ among either seasons or hydrologic periods. There were significantly fewer high-flow events during drought than in either pre-drought or post-drought periods.

Heggenes & Saltveit (1996) studied hypothesized critical minimum flows, habitat availability and habitat selection by young Atlantic salmon and brown trout on selected stream reaches in a spatially and temporally heterogeneous Norwegian west coast river. They conclude that there is no such a thing as “the” suitable minimum flow; the effect of reduced flows varies with stream structure, the hydro-physical variables in question and fish species. More studies are needed to elucidate spatial, and in particular temporal, variations in fish habitat selection. Care must be taken in aggregating habitat suitability data into single-valued functions.

Kallemeyn et al. (1988) examine a single hydropower facility and two small regulatory dams located outside Voyageurs National Park that regulate water levels in the four large lakes, which compose 96% of the park’s water area. The present water management program utilizes greater-than-natural fluctuations on the second reservoir. Additionally, the regulated lake levels differ from natural levels by usually peaking later, remaining relatively stable throughout the summer rather than slowly declining and, on one reservoir, by declining 1.8 m rather than 0.6 m over the winter. This regularly system was found to have an adverse effect on northern pike, common loon, red-necked grebe, beaver, and muskrat populations of the littoral zone and adjacent wetlands of the park. An alternative water management program is presented that would meet the biological requirements of these species by resorting to more natural lake-level fluctuations. It is hypothesized that it would also have a positive effect on the other members of the aquatic community.

Koehn (1993) examines changes to key habitat factors that are responsible for the general decline in fish species. A detailed account is given of such factors, including: water and its condition; the surrounding land which helps determine that condition; conditions that the water creates within the stream; and instream objects.

Leonard & Orth (1988) examine the use of habitat guilds of fishes to determine instream flow requirements. Cluster analysis of depth, velocity, substrate, and cover use identified four primary habitat-use guilds, which were distinguished largely on the basis of water velocity. Habitat-suitability criteria were developed for each species and life stage combination, and these criteria were used in physical habitat simulations to determine relations between weighted usable area (WUA) and discharge for three streams in the upper James River basin, Virginia.

Mathur *et al.* (1985) present a review and reanalysis of the published literature that shows that several assumptions are violated in the application of the Instream Flow Incremental Methodology (IFIM) without considering the implications of doing so. The fundamental assumption of a positive linear relationship between "potential available habitat" (WUA) and biomass of fish has neither been documented nor validated, particularly in warm water streams. Absence of correlation precludes prediction of changes in fish populations. In some studies the test of this assumption appears to be equivalent to a calibration operation. The other assumption violated includes independent selection of habitat variables by fish. The presence of significant interaction among habitat variables can affect stream flow recommendations. Care should be taken to distinguish real behavioral preferences of fishes (based on distributional occurrence) from abundance (relative or absolute size) in a stream.

Meador (1996) looks at the role of fisheries biologists in water transfer projects, as the movement of water from one area to another may have broad ecosystem effects, including on fisheries. Results from some case studies suggest that fisheries biologists have provided critical information regarding potential ecological consequences of water transfer. If these professionals continue to be called for information regarding the ecological consequences of water transfer projects, it may be necessary to develop a broader understanding of the ecological processes that affect the fish species they manage.

Mitchell et al. (2000) address the interior populations of the piping plover (*Charadrius melodus*) and least tern (*Sterna antillarum*), which are shorebirds that breed along coastal beaches and major interior river systems within North America. The interior population of the least tern and the Great Lakes populations of the piping plover, for example, are federally listed as threatened. These birds are known to be highly dependent on riparian areas associated with large rivers systems and may be potentially impacted by USACE Reservoir operations.

Rao *et al.* (1992) examine flows required for sustaining fish populations in a stream. The IFIM that has been developed for estimating these flows requires data that are not commonly available and are expensive to acquire. Other methods to estimate instream flows, based only on flow rates, do not consider the characteristics of the fish population in the stream and hence are unrealistic. A modification of IFIM is proposed in this study. Various factors that are involved in the modification are investigated. Based on these investigations, a method which is much less data-intensive than IFIM but which gives results of the same order of magnitude is proposed. The method is illustrated by using data from streams in Indiana.

The US Fish and Wildlife Service (1963) provides an appraisal of the effects on fish and wildlife of a US Army Corps of Engineers Plan to regulate the Great Lakes (Plan 57-E0-1 of Plan G). This is the first report of this scope produced by the Bureau of Sport Fisheries and Wildlife, Fish and Wildlife Service. The report also highlights the importance of marshes in western end of Lake Erie and the Upper Niagara River to waterfowl. In addition, the Saginaw Bay region of Lake Huron and the St. Clair Flats are of Lake St. Clair as areas of wildlife importance; the gradient in these marshes is extremely gradual and they are affected by relatively small water-level changes. The US FWS did not find any major effects on fisheries resources.

3.3 ECOSYSTEM EFFECTS

This section includes papers that describing ecosystem effects from water use or from changes in water levels/flows. This section includes a subcategory that specifically focuses on Wetlands Ecology literature. Papers detailing wetland functions, wetlands stresses, and wetland assessments are described. In addition, this section includes a subcategory where Stream Ecology and Ecological Assessment Studies are described. This subcategory principally contains literature describing stream assessments and stream assessment techniques.

Wlosinski and Koljord (1996) produced an annotated bibliography on the effects of water levels on ecosystems, principally freshwater ecosystems. The bibliography contains annotations from 846 papers includes both peer-reviewed and “gray” literature. The annotated bibliography was written as part of the Upper Mississippi River System Long Term Resource Monitoring Program (LTRMP). Major goals of the Upper Mississippi River LTRMP were to predict the effects of natural and human inducted actions on various ecosystem components, and to recommended management actions to ameliorate undesirable natural and human-induced effects on the ecosystem. A number of Great Lakes-St. Lawrence River system citations are included. A subject index containing key works is also contained in the report to facilitate the location of references on certain subjects; key words are also grouped into general categories.

3.3.1 Wetlands Ecology

Adamus *et al.* (2001) review the literature from North American inland freshwater wetlands published between 1989-2000. Their literature survey was written for wetland managers, researchers and monitoring specialists. Over 1500 publications, principally from peer-reviewed journals, were reviewed as part of their effort. The survey is structured around 11 categories of human-related disturbances to which wetlands are commonly exposed including dehydration and inundation. This document describes the literature on effects of the human-related disturbances, or "stressors", on the following biological groups: microbes, algae, vascular plants, invertebrates, fish, amphibians, and birds. The work by Adamus et al. (2001) updates a previously published review on the same subject sponsored by US EPA (Adamus and Brandt, 1990), see: http://www.epa.gov/owow/wetlands/wqual/introweb.html.

Adamus & Stockwell (1983) review main wetland functions. Functions covered include: groundwater recharge and discharge, flood storage and desynchronization, shoreline anchoring and dissipation of erosive forces, sediment trapping, nutrient retention and removal, food chain support (detrital export), habitat for fish and wildlife, and active and passive recreation. Cumulative impacts and social factors affecting wetland significance are discussed. Effects of the following factors on wetland function are documented: contiguity, shape, fetch, surface area, watershed and drainage area, stream order, gradient, land cover, soils, depositional environment, climate, wetland system, vegetation form, substrate, salinity, pH, hydroperiod, water level fluctuations, tidal range, scouring, velocity, depth, width, circulation, pool-riffle ratio, vegetation density, flow pattern, interspersion, human disturbance, turbidity, alkalinity, dissolved oxygen, temperature, and biotic diversity.

Jaworski et al. (1979) discuss field data collected over a 2-year period, which focuses on the interrelationships between coastal landforms, wetlands, and lake levels in Lakes Michigan, Huron, St. Clair, and Erie. The geomorphology of seven study areas was mapped, and descriptive models of four coastal wetland types were developed. With the aid of areal photography and field bisects, plant communities were identified, historical vegetation distributions mapped, and transects reconstructed. As the Great Lakes presently oscillate from one extreme to another over a hydroperiod of 8 to 12 years, water levels fluctuate 1 to 2 m and the total wetland area increase or decrease by 12.9%. A field model was developed that predicts the displacement of wetland plant communities on Dickinson Island as lake levels change periodically. Fluctuating water levels not only disrupt hydrarch succession, but also inhibit senescence, which contributes to the high primary productivity so characteristic of freshwater wetlands.

Maynard and Wilcox (1997) provide a focused synthesis of the state of the Great Lakes coastal wetlands, addressing such topics as major threats to coastal wetlands, and the best ways to determine ecosystem health. The paper is part of a series of background papers developed for the State of the Lakes Ecosystem Conference 1996 (SOLEC 96). The importance of water level changes, both historic and seasonal, to the stress-driven coastal wetlands is also discussed. Maynard and Wilcox (1997) also note that water level fluctuations affect sediment supply and transport and ice conditions, which are major stressors affecting coastal wetlands. The authors also assert that water-level control and regulation, such as implemented on Lake Ontario and Lake Superior, reduce the range of natural water levels, reducing the occurrence of extreme high and low levels. This regulation reduces the extent, diversity, function, and value of wetlands in the nearshore.

3.3.2 Stream Ecology and Ecological Assessment

Annear et al. (2002) present instream flow concepts for resource managers in *Instream Flows for Riverine Resource Stewardship*. This book stresses the importance of addressing instream flow issues in terms of hydrology, biology, geomorphology, water quality, and connectivity within the legal and institutional constraints of states and provinces. The book contains 44 position statements related to program development and study design and includes descriptions and critical opinions of 29 instream flow methods.

Allan & Johnson (1997) note that aquatic ecologists are making significant progress toward understanding how landscape variables influence the physical, chemical and biological properties of freshwater systems. The type and scale of data found to have the strongest influence depends on the variable measured and on study design. As aquatic scientists develop experience with spatially scaled studies, increasing attention should be paid to temporal vs. spatial distribution of effort and the hierarchical structure of spatial data.

Barbour *et al.* (2000) show how the development of biological criteria (biocriteria) to serve as regulatory program thresholds for judging the attainment of designated aquatic life conditions of surface waters, is a major focus of U.S. states and Indian tribes. The derivation of reference conditions for the nation's surface waters (*i.e.*, streams. rivers, lakes, wetlands, estuaries, and marine waters) across different physiographic regions is a critical element in the design of biocriteria and is currently a primary initiative in the U.S.

Blanch *et al.* (1999) use selected water regime indices to describe the flooding and exposure tolerances of littoral and floodplain plants of the River Murray, South Australia. The cover and abundance of 26 perennial species were surveyed at 12 sites along a reach where water levels were influenced by weir operations. Half of the 26 species occurred in at least four of seven regimes suggested by cluster analysis of water regime indices, thus indicating a broad tolerance to flooding and exposure. Preferred water regimes are summarized using minimum and maximum values and quartiles for the six indices. A model based on minimum spanning tree techniques illustrates similarities between preferences.

Bovee et al. (1998) update the concepts and ideas used to describe the Instream Flow Incremental Methodology (IFIM). This document is intended to serve as the official guide to IFIM in publication. The document is aimed at the decision makers who manage and allocate natural resources priorities; and to those who design and implement studies to inform the decision makers. Background on model concepts, data requirements, calibration techniques, and quality assurance is presented, to help the technical user design and implement a cost-effective application of IFIM that will provide policy-relevant information.

Bundi *et al.* (2000) present how stream assessment, in Switzerland, should produce sound data suitable for characterizing the ecological condition of streams and supporting their sustainable management. Such methods should include a system approach as the basic unit, along with sound scientific principles of ecological integrity that emphasize habitat connectivities. The methods should allow: (1) rational descriptions and judgments of stream condition, (2) identification of different types of impacts on a stream, (3) verification of the effects of water protection measures, and (4) identification of suitable future actions in the context of a whole stream system. In order to cover the various requirements, a modular concept for stream system-oriented analysis was developed.

Bunn & Davies (2000) evaluate the ultimate success of biomonitoring approaches that depend on understanding the biophysical processes that influence the structure and dynamics of stream and river systems and the way they function. Although biomonitoring approaches are increasingly used in the measurement of stream and river health, critical assumptions about the nature of biological populations and communities that underpin them are often ignored. Many approaches based on pattern detection in plant and animal communities assume high temporal persistence in the absence of anthropogenic disturbances. However, this has rarely been tested with long-term data sets and there is evidence that this assumption is not true in some river systems.

Cohen *et al.* (1998) describe the partitioning of France's Loire basin (105,000 km^2) into hydro-ecoregions tested at the mesohabitat scale to comply with the 1992 French Water Act, which aims to preserve the biotic and ecological integrity of aquatic ecosystems. The following null hypotheses were examined in the four largest hydro-ecoregions of the basin: (1) differences in mesohabitat types distribution do not exist between regions; (2) the longitudinal structure of mesohabitat type distribution is not different between regions; and (3) the factors governing distribution and longitudinal evolution of mesohabitat distribution are not different between regions. It was found that the four regions behaved in different ways in terms of distribution and longitudinal evolution of mesohabitats. Valley slope and stream order, the two tested control variables, do not play the same role in each region. If the region contains mainly alluvial rivers, slope and/or order do explain or predict mesohabitat distributions. If the region contains rivers with largely cohesive sediments, these factors do not, or poorly explain, mesohabitat distributions.

Extence *et al.* (1999) propose a method linking qualitative and semi-quantitative change in riverine benthic macroinvertebrate communities to prevailing flow regimes. The Lotic-Invertebrate Index for Flow Evaluation (LIFE) technique is based on data derived from established survey methods incorporating sampling strategies considered highly appropriate for assessing the impact of variable flows on benthic populations. Hydroecological links have been investigated in a number of English rivers by correlating LIFE scores obtained over a number of years with several hundred different flow variables. This process identifies the most significant relationships between flow and LIFE which, in turn, enables those features of flow that are of critical importance in influencing community structure in different rivers to be defined. Summer flow variables are thus highlighted as the most influential factor in predicting community structure in most chalk and limestone streams, whereas invertebrate communities colonizing rivers that drain impermeable catchments are much more influenced by short-term hydrological events. Biota present in rivers with regulated or augmented flows tend to be most strongly affected by non-seasonal, interannual flow variation. An example is presented to show how this might be accomplished. Key areas of further work include the need to provide robust procedures for setting hydroecological objectives, the investigation of habitat quality and LIFE score relationships in natural and degraded river reaches, and the evaluation of potential links with other biological modeling methods.

Foulger & Petts (1984) analyze water quality implications of artificial flow fluctuations in regulated rivers. The determination of instream-flow needs for river ecology must consider the acceptable range, rate and frequency of flow fluctuation, as well as minimum and optimum flows. Due consideration must not only be given to the immediate destructive effects of large magnitude fluctuations but also to the cumulative effects of repeated, relatively low-magnitude pulses which, although sublethal, could eliminate a species over time by adversely affecting reproduction or growth, or by favoring a competitor or predator.

Gasith & Resh (1999) examine abiotic influences and biotic responses to predictable seasonal events in streams in the Mediterranean-climate regions. They present 25 testable hypotheses that relate to the influence of the stream hydrograph on: faunal richness, abundance, and diversity; species coexistence; seasonal changes in the relative importance of abiotic and biotic controls on the biotic structure; riparian inputs and the relative importance of heterotrophy compared to autotrophy; and the impact of human activities on these seasonally water-stressed streams. They list and describe the sequence of physical, chemical and biological events that are shaped by sequential, predictable and seasonal events of flooding and drying over an annual cycle.

Gore & Hamilton (1996) compare flow-related habitat evaluations downstream of low-head dams on small fluvial ecosystems. The physical habitat simulation (PHABSIM), a software package used in IFIM, was used to evaluate stream enhancement activities on a low-order stream, with the placement of a series of three-log weirs on Brushy Branch – a second-order stream in Tennessee – and compared with published results of a hydraulically similar concrete structure on a large-order system used to regulate flows downstream of a peaking hydropower facility on the Cumberland River, Tennessee. On Brushy Branch, the simulation demonstrated that benthic macroinvertebrate habitat could be dramatically increased at low flows (up to five times higher) after the placement of structures that improve hydraulic conditions to sustain maximum diversity of the benthic community.

Habersack (2000) discusses the river-scaling concept as a basis for ecological assessments. Since river morphology is a result of two major boundary conditions, transport of water and sediments, the size of project areas and the analysis procedure are found to be critical. Restricting the assessment of abiotic and biotic river components and their variability to a certain scale neglects the fact that ecological integrity depends on the process scale of boundary conditions. The paper presents a newly developed two-step procedure for assessing the ecological integrity at various temporal and spatial scales.

Hardy (1998) examines emerging trends in applied instream flow assessment methods within the context of an ecologically based assessment framework and in light of the challenges imposed by the spatial and temporal domains of aquatic ecosystems. The paper touches on measurement techniques and technologies used to characterize the spatial domain of river systems, analysis tools for characterization of the hydrodynamic elements of rivers in both the spatial and temporal domains, and finally tools and approaches which integrate the biological elements at the individual, population and community levels. However much of this view of the future of habitat modeling "remains an abstraction, in that integration of all the pieces has yet to be accomplished, field validation remains unproven, availability of an integrated analysis framework (*i.e.* computer software system) is not yet available, and a clear framework for selection and application of specific tools has not been developed".

Innis *et al.* (2000) summarize scientific knowledge concerning methods for assessing ecological integrity in wetlands and riparian zones, with an emphasis on riparian areas. The article examines which indicators (abiotic parameters, species, faunistic and floristic communities, and functional assemblages) are used, how they are applied (single or integrative indicator), and which assessment algorithms and models have been successful to date. Overall, the review shows that despite the relatively recent emergence of riparian ecology, riparian assessments are better developed than the wetland functional assessments currently employed. In general, it recommends that:

- Useful methods be updated and cross-calibrated;
- New rapid-assessment methods provide reasonable levels of accuracy for a variety of users in a variety of situations;
- Assessments be developed for specific applications (with identified users);
- Uncertainty be explicitly acknowledged;
- Policy implications of specific assessments methods be openly discussed; and
- Methods to be formally tested for accuracy, cost and practicality.

Johnson & Gage (1997) examine how new perspectives in stream ecology are made possible by developments in hierarchy theory, patch dynamics, and the refinement of tools used to quantify spatial and temporal heterogeneity. Geographical information systems (GIS), image processing technology and spatial statistical techniques allow quantitative assessment of lateral, longitudinal and vertical components of the landscape which interact at several spatial and temporal scales to influence streams.

When GIS is used in concert with geostatistics, multivariate statistics or landscape models, complex relationships can be elucidated and predicted.

Karr (1991) looks at the need for operational definitions of terms like "biological integrity" and "unreasonable degradation," and for ecologically sound tools in order to measure divergence from societal goals that have generated an increased interest in biological monitoring. Assessing water resource quality by sampling biological communities in the field (ambient biological monitoring) is a promising approach that requires expanded use of ecological expertise. One such approach, the Index of Biotic Integrity (IBI), provides a broad-based, multiparameter tool for assessing biotic integrity in running waters. IBI based on fish community attributes have now been applied widely in North America. The success of IBI has stimulated the development of similar approaches using other aquatic taxa.

Karr & Chu (2000) examine the condition, or health, of aquatic biota as the best means of understanding and controlling human impact on the Earth's watercourses and on the whole water cycle. Biological monitoring, especially multimetric approaches such as the IBI, acknowledges the importance of a river’s biotic integrity and offers one of the strongest available tools for diagnosing, minimizing, and preventing river degradation. The broad perspective offered by biological evaluations stands a better chance of sustaining living rivers than do narrow chemical criteria or conventional measures of urban development.

Kevern et al. (1984) use the Instream Flow Incremental Methodology (IFIM) for the first time in a Michigan stream. The objective was to test the method's applicability to the Midwest, and to detail the impacts of irrigation withdrawals on a typical Lower Michigan marginal trout stream. The IFIM was able to accurately simulate the hydraulic characteristics of a Midwestern stream and to predict brown trout (*Salmo trutta*) habitat locations within the stream. Brown trout habitat losses were most critical in the month of July, with reductions of up to 19 percent. A greater percentage of the remaining fish experienced negative growth rates as a result of reduced habitat availability. Benthic macroinvertebrate habitat was less impacted by irrigation withdrawals. This study also described a method for assessing the impacts of withdrawing water from the stream channel for crop irrigation.

Kleynhans (1996) assesses the riparian zone and instream habitat integrity of the Luvuvhu River (in Kruger National Park) based on a qualitative rating of the impacts of major disturbance factors such as water abstraction, flow regulation, bed and channel modification, *etc.* A system was devised to assess the impact of these factors on the relative frequency and variability of habitats on a spatial and temporal scale gauged against habitat characteristics that could have been expected to occur under conditions not anthropogenically influenced. It was found that deterioration of habitat integrity could be ascribed primarily to water abstraction. This has resulted in the cessation of surface flow in a naturally perennial river during the dry season and during droughts with consequent tree deaths and a loss of fast flowing instream habitat types in the main stem of the river.

Kondolf *et al.* (1987) describe methods for collecting relevant hydrologic data for predicting the impacts of flow reductions on riparian vegetation and report the results of such studies on seven stream reaches proposed for hydroelectric development in the eastern Sierra Nevada, California. Because the extent and density of riparian vegetation depend largely on local geomorphic and hydrologic settings, site-specific geomorphic and hydrologic information is needed. The methods described are: (i) preparing geomorphic maps from aerial photographs, (ii) using well level records to evaluate the influence of streamflow on the riparian water table, (iii) taking synoptic flow measurements to identify gaining and losing reaches, and (iv) analyzing flow records from an upstream-downstream pair of gages to document seasonal variations in downstream flow losses. In the eastern Sierra Nevada, the geomorphic influences on hydrology and riparian vegetation were pronounced. For example, in a large, U-shaped glacial valley the width of the riparian strip was highly variable along the study reach and was related to geomorphic controls, whereas the study reaches on alluvial fan deposits had relatively uniform geomorphology and riparian strip width. Flow losses of 20 percent were typical over reaches on alluvial fans. In a mountain valley, however, one stream gained up to 275 percent from geomorphically controlled groundwater contributions.

Lorenz *et al.* (1997) aim to develop river ecosystem indicators, in particular for the River Rhine, on the basis of theoretical concepts describing natural rivers. The study includes river ecology concepts on zonation, stream hydraulics, river continuum, nutrient spiralling, serial discontinuity, flood pulse, riverine productivity and catchment hierarchy. The abiotic steering variables describing the hydrology, geomorphology and water quality act as a template for ecosystem functioning. Functional processes are characterized by the flux of matter, which is affected by input, processing and retention of organic matter and nutrients. Spatial and temporal variation of input, retention of matter and the flow along the length of the river cause shifts in species distribution. These are reflected in gradients of macroinvertebrates and zonation of fish and benthic fauna, which form a dominant structural characteristic of the river ecosystem. Proposed indicators are retention of matter as an indicator for functional characteristics and zonation of species as an indicator for structural characteristics of the river ecosystem. Present river ecosystems are far from undisturbed. To allow efficient management of the Rhine ecosystem, indicators and variables are required that reflect the cause-effect chain of human disturbance. River ecologists have developed a more spatially integrated and interdisciplinary view on rivers. Accordingly, the design, implementation and ecological assessment of monitoring programs should reflect such an integrated spatial view. Finally, the study presents some recommendations for monitoring, in particular for the Rhine monitoring program.

Muhar *et al.* (2000) investigate fifty-two of the largest Austrian rivers with catchment areas greater than 500 km2 (Danube River excluded) providing a national estimate of the ecological status of Austria's rivers and an example of the current status of European alpine rivers. Emphasis is placed on evaluation criteria, such as morphological character, instream structures, longitudinal river corridor, lateral connectivity and hydrological regime, as compared with original conditions. This assessment and evaluation of nearly 5,000 river kilometerss identifies the remaining river stretches with high habitat quality as well as those stretches that have been altered by systematic channelization or hydropower development.

Naiman & Descamps (1997) discuss the unusually diverse array of species and environmental processes in riparian zones. Ecological diversity is related to variable flood regimes, geographically unique channel processes, altitudinal climate shifts, and upland influences on the fluvial corridor. Riparian zones play essential roles in water and landscape planning, in restoration of aquatic systems, and in catalyzing institutional and societal cooperation for these efforts. Innovations in riparian zone management have been effective in ameliorating many ecological issues related to land use and environmental quality.

Naiman *et al.* (2000) briefly review the traditional view of hierarchical physical controls on stream structure and dynamics, showing how this viewpoint is changing due to the emerging recognition of strong biological influences on physical structure. Natural stream characteristics that reflect variations in local geomorphology; climate; natural disturbance regimes and the dynamic features of the riparian forest, including interactions among individual components; as well as recognizing the importance of biotic feedbacks on physical structure; combine to form the basis for establishing effective conservation strategies.

Naiman & Turner (2000) explore trends in alterations to fresh-water ecosystems, discuss the ecological consequences of biophysical alterations expected to occur in the next 20-30 years, and identify some of the major scientific challenges and opportunities involved in effectively addressing the changes. Topics discussed include altered hydrological regimes, biogeochemical cycles, altered land use, riparian management, life history strategies and the relationship between climate change and water resource management. Considering the magnitude of the changes that have already taken place and those that are projected to occur in the next two decades they focus their discussion on processes at the watershed and landscape scales that require better understanding. A basic need is to incorporate ecological principles into use and management decisions for aquatic resources. Specifying ecological principles – such as those related to time, place, species, disturbance, and scale – and understanding their environmental and social implications are essential steps on the path to sustainability.

Nestler & Long (1997) present a hydrological analysis of historic stream data collected on the Cache River at Patterson, Arkansas, as the basis for cumulative impact analysis of riverine wetlands. Subtle, long-term changes in hydroperiod (length of one wet and dry cycle), which could collectively have major effects on wetland function, are quantified. Harmonic analysis, time-scale analysis and conventional methods of hydrological analysis of gauge data (at decade intervals) are employed, showing a steady decline in the magnitude and predictability of the base flow during low flow periods, beginning with the 1920s and becoming increasingly more pronounced into the 1980s. Complementary information suggests that hydroperiod alterations are associated with increased groundwater pumping to support rice agriculture in the basin. These hydrological methods are simple enough for routine application (when adequate data are available) but sufficiently sophisticated to identify subtle changes in hydroperiod associated with cumulative effects. The changes in hydroperiod identified using these methods may have potential to explain changes in biotic communities or wetlands structure as part of comprehensive wetlands studies.

Nestler & Sutton (2000) propose new methods for quantitative description of spatial patterns that are often at the heart of ecological research in aquatic systems, particularly for investigations of how biota respond to physical habitat.

After describing the effects of dams and regulation on a global scale, both upstream (inundation of habitats, creation of new riparian zones) and downstream (hydrologic and geomorphologic changes, changes in riparian communities, invasion by exotic species), Nilsson & Berggren (2000) look at future needs and directions. They stress the need for a better understanding of the effects of hydrological alterations in order to evaluate the changes caused by existing projects and predict the outcomes of planned projects. Such knowledge is also a prerequisite for ecological restorations that are now becoming increasingly common. There seems to be no example of a water-regulation project for which the effects on riparian processes were described in reasonable detail before construction; all developments have been pursued with little understanding or appreciation of the ecological consequences to riparian zones. To alleviate this discrepancy, there is a need to increase both the spatial and temporal scales at which regulated riparian systems are studied. In other words, the effects of regulated riparian systems on local and regional scales, over short and long time periods, should be disentangled. The studies of large-scale effects of hydrological alterations on riparian processes can take three directions: studies of effects within catchment areas, differences in effects between catchment areas, and changes with time. In addition to these three types of studies, long-term monitoring will be the only reliable method to detect, assess, and validate predicted changes in riparian ecosystems and thus provide a useful basis for adaptive management of riparian systems. More complete assessments of the effects of hydrological alterations on riparian ecosystems, however, will be difficult to achieve because hydrological alterations usually displace riparian zones. To regain a riparian vegetation structure in the new location, riparian trees have to complete at least one life cycle; this period will be long enough to make it difficult to distinguish between natural dynamics, succession initiated by river regulation, and succession initiated by global change.

Petts (1996) presents an approach for determining “ecologically acceptable” flow regimes and volumes for regulated rivers that affects (i) changes in the seasonal flow regime below dams and reservoirs and (ii) reduction in flow caused by water abstraction and diversion, upon lotic and riparian ecosystems for rivers in a range of geographical regions. The approach is founded on a set of fundamental scientific principles concerning longitudinal connectivity, vertical exchanges, floodplain flows, channel maintenance flows, minimum flows and optimum flows. Several judgmental decisions are needed in setting an ecologically acceptable flow regime and further research is required to improve the capability for modeling the roles of different flows and patterns of flows in sustaining river ecosystems.

Poff *et al.*, (1997) define the natural flow regime and the role it plays in organizing and defining the river ecosystem and its natural functions. Human alterations and ecological responses to altered flow regimes are examined and some recent approaches to streamflow management and strategies for managing toward a natural flow regime are discussed.

Pouilly & Souchon (1995) discuss the applicability of IFIM, presently the most-used tool for evaluating stream carrying capacity, by crossing information from biological and hydraulic models. It is used in negotiation for minimum instream flow determination in regulated rivers. However, the biological validity of the methodology remains its main uncertainty. Hypotheses and experimental conditions for validation are presented and discussed. The discussion of each model explains its present development and future research necessary to improve the methodology.

Rabeni (2000) evaluates the relation of physical habitat to benthic invertebrate communities in Missouri streams at both reference quality and habitat altered sites. Six common within stream habitats were delineated from each of 45 reference-quality streams in three ecoregions. Biological responses to habitat alterations were readily documented by taking into account the presence or absence of particular habitats and the quality of each habitat type. Distinctive assemblages of invertebrates were associated with each habitat type. A spatial hierarchy of the influence of habitat was evident. At the largest scale, physical attributes unique to ecoregions were more influential than local conditions in structuring invertebrate communities. Physical habitat integrity, while a necessary condition for ecological integrity, is not well defined and rarely examined in relation to the biological potential of a stream. The relationship of physical habitat to the biota needs to be quantified so as to establish better reference conditions and to document physical habitat alterations that actually impact the biota.

Raven *et al.* (2000) describe how the attributes of a method for determining the physical quality of rivers are well suited for use in environmental assessment and catchment planning in the U.K. The system, known as River Habitat Survey (RHS), uses a standard field survey method with quality controls and a computer database for rapid analysis, along with outputs that quantify habitat quality and channel modification. Further refinement of the system is needed because of the inherent limitations of the data collected, specifically assumptions that were made about species' habitat requirements and the impact of channel modification. By taking full account of catchment characteristics, historical influences, geomorphologic processes and other information, the system can help in the conservation and rehabilitation of rivers

Reid & Brooks (2000) recommend a range of physical, chemical and biological indicators for use in monitoring changes in wetland health in response to environmental water allocations (EWAs) designed to redress some of the damage caused by regulation by partially restorating the natural hydrological regime of associated floodplain wetlands. Monitoring and scientifically rigorous adaptive management practices are the key to the long-term success of EWAs, and successful monitoring relies on the well-informed selection of a variety of hydrological sensitive indicators. Physical and chemical variables suggested include wetland depth, area and salinity. Aquatic macrophytes and macroinvertebrates are recommended as the primary biological indicators for monitoring changes within the Murray-Darling Basin, although the indicator potential of macroinvertebrates still has to be confirmed by planned and ongoing research. Information is also presented for a variety of other components of wetland ecosystems, including biofilms, zooplankton, birds, fish, mammals, reptiles, amphibians and fringing vegetation. The current knowledge of the relationships of these variables to wetland hydrology and ecosystem health is relatively limited. Further research is required to investigate the nature of these relationships and determine the utility of these parameters as indicators within wetlands of the Murray-Darling Basin.

Richter *et al.* (1997) introduce a new approach for setting stream flow-based river ecosystem management targets. The proposed approach derives from aquatic ecology theory concerning the critical role of hydrological variability and the associated characteristics of timing, frequency, duration, and rates of change in sustaining aquatic ecosystems. The method is intended for application on rivers where the conservation of native aquatic biodiversity and protection of natural ecosystem functions are primary river management objectives. The method uses as its starting point either measured or synthesised daily stream flow values from a period during which human perturbations to the hydrological regime were negligible. This stream flow record is then characterized using 32 different hydrological parameters and methods described in Richter *et al.* (1996). Richter *et al.* (1998) demonstrate the use of this approach for assessing hydrologic alteration at stream gauge sites throughout a river basin and illustrate a technique for spatially mapping the degree of hydrologic alteration for river reaches at and between stream gauge sites.

Rogala et al. (1999) estimate the likelihood of 1- or 2-foot drawdowns, and the areas affected by such alternative drawdowns, for Pool 13 on the Upper Mississippi River. Areas that would be affected by two drawdown scenarios were predicted by overlying maps of water surfaces with depths using a geographic information system. The Fish and Wildlife Interagency Committee requested the drawdown as an experiment to evaluate alternative regulation effects on moist soil plant production, sediment oxidation and compaction, and the photic zone for submersed vegetation. The work was accomplished through collaborative efforts of The Upper Midwest Environmental Sciences Center (UMESC) and the Rock Island District of the U.S. Army Corps of Engineers. This work is a continuation of efforts by UMESC to determine the effects of water levels and discharges on the Upper Mississippi River. Although the drawdown effects of most physical and biotic components of Pool 13 are unknown, Rogala et al. (1999) present some general drawdown effects likely to occur because of the changes in water surface elevation.

Rogers & Biggs (1999) propose the integration of value system endpoints with indicators of ecosystem health and integrity as the cornerstone of a consultative management process for the rivers of the Kruger National Park. In trying to apply the notion of sustainable ecosystem health, ecologists have focused on identifying sets of indicators that can be used to assess river conditions relative to some normative, undegraded condition. Recognition and description of this normative state has proved elusive, particularly in highly variable semi-arid ecosystems. Without an operational definition of the desired system condition that reflects scientific rigour and broader societal value systems, effective river management is unlikely. Managing river health should not be confused with measuring it. Many monitoring or assessment programs become ends in themselves rather than the means to achieving specific management goals. The absence of a test of monitoring results further introduces the risk of management by observation and "pseudo-fact". Health "end points" provide a scientific description of management goals while "values" provide a societal perspective. They propose a concept of "Thresholds of Probable Concern" that represent statements or hypotheses of limits of acceptable change in ecosystem structure, function and composition and thereby provide an inductive and strategic approach to adaptive management in a data poor situation that could be used as a guide to establish monitoring protocols.

Schmutz *et al.* (2000) propose a multi-level concept for fish-based assessment of the ecological integrity of running waters. This concept is designed for large-scale monitoring programs such as are required for the proposed Water Framework Directive of the European Union. For five different biological organization levels (fauna, community, guild, population and individual), they propose seven criteria: river-type-specific species, species with self-sustaining populations, fish region, number of guilds, guild composition, population size, and population age structure.

Shelby *et al.* (1990) analyze the resource values for Gulkana National Wild River, Alaska, and make instream flow recommendations to identify the amount of water necessary to preserve and protect the natural values in the river and its immediate corridor environs. They also recommend a legal mechanism, through which those recommended flow regimes would be recognized and protected,

Stalnaker *et al.* (1995) present a primer on IFIM. Stalnaker (1980) summarizes the effects of stream flow perturbations from a fisheries viewpoint and identifies pertinent recent literature documenting such effects. Methods for evaluating instream flow requirements for fisheries are reviewed and presented in three categories: (i) those suitable for early planning and general guidance, usually based upon hydrologic data; (ii) those used in water allocation processes and flow regulation schemes, usually based upon stream channel by hydraulic measurements; and (iii) those suitable for detailed ecological evaluations of impacts, usually based upon regression analyses of stream attributes vs. fish population attributes.

Stanford *et al.* (1996) propose a general protocol for the restoration of regulated rivers. They examine the four-dimensional nature of the river continuum and the propensity of riverine biodiversity and bioproduction to be largely controlled by habitat maintenance processes, such as cut and fill alluviation mediated by catchment water yield. Stream regulation reduces annual flow amplitude, increases baseflow variation and changes temperature, mass transport and other important biophysical patterns and attributes. As a result, ecological connectivity between upstream and downstream reaches and between channels, ground waters and floodplains may be severed. Native biodiversity and bioproduction usually are reduced or changed and non-native biota proliferate. The protocol requires: restoring peak flows needed to reconnect and periodically reconfigure channel and floodplain habitats; stabilizing base flows to revitalize food webs in shallow water habitats; reconstituting seasonal temperature patterns (**e.g.**, by construction of depth-selective withdrawal systems on storage dams); maximizing dam passage to allow recovery of fish metapopulation structure; instituting a management belief system that relies upon natural habitat restoration and maintenance, as opposed to artificial propagation; installing artificial instream structures (river engineering) and predator control; and practicing adaptive ecosystem management.

Tarlock (1991) examines two emerging challenges to the instream flow community's efforts to integrate flow protection: (1) the predicted consequences of global warming and (2) the growing use of water transfers to meet new water demands.

Vincent & Godson (1999) use examples from the St. Lawrence River to identify environmental pressures on large rivers that would greatly benefit from an integrated "whole ecosystem" approach toward their understanding and management. These pressures include hydraulic control, channel modification, contaminant discharge, eutrophication, climate change and community shifts, and invasion by exotic species. The downstream reach of such environments, in particular the freshwater-saltwater transition zone (FSTZ), is a critical ecotone for the entire river system and is highly sensitive to each of these anthropogenic effects. The FSTZ integrates upstream and downstream processes, is one of the most biologically productive sections of the river, and is a prime site for monitoring fluvial and estuarine health.

Walker & Thoms (1993) analyze the environmental effects of flow regulation on the Lower River Murray, Australia. Regulation has limited exchanges between the river and its floodplain, changed the nature of the littoral zone and generally created an environment inimical to many native species, notably fish. The key to rehabilitation may be to restore a more natural balance of low and medium flows, but this may be unrealistic given the needs of irrigators and other water users. Despite its evolutionary history of wide spatial and temporal variations, the Murray river-floodplain ecosystem evidently cannot accommodate these forms of disturbances.

Walters (1997) examines why many case studies in adaptive-management planning for riparian ecosystems have failed to produce useful models for policy comparison or good experimental management plans for resolving key uncertainties. Riparian and coastal ecosystem modeling efforts have been plagued by difficulties in representing cross-scale effects (from rapid hydrologic change to long-term ecological response), lack of data on key processes that are difficult to study, and the confounding of factor effects in validation data. Experimental policies have been seen as too costly or risky, particularly in relation to monitoring costs and risk to sensitive species.

The Water Resources Division of the Geological Survey Madison, Wisconsin (1982) investigate the effect of a floodwater-retarding structure (FRS) on the hydrology and ecology of Trout Creek, Wisconsin. During the study period (1975 to 1979), the FRS reduced flood peaks from 58 to 91%. An inverse relationship was observed between sediment concentration and outflow from the FRS during floods. Furthermore, bank full capacity of the channel was reduced from 154 cubic feet per second (cfs) upstream from the FRS to 65 cfs second downstream. Due to the sedimentation of materials transported from the FRS during reduced flows, mean bankfull depth downstream from the FRS was adjusted to a value 45% less than upstream. The FRS was not found to have any significant adverse effect on the arthropod fauna or trout reproduction in Trout Creek from 1975 to1979. During 1960-1979, winter floods seem to have had the greatest adverse effect on the survival of brown trout eggs and sac fry.

Ward *et al.* (1999) propose a hierarchical framework for examining diversity patterns in floodplain rivers, as various river management schemes disrupt the interactions that structure ecotones and alter the connectivity across transition zones of the floodplain river ecosystems.

Welcomme (1995) addresses the problem of river system integrity relative to fisheries for food, as human uses of rivers and their floodplain complexes have grown and intensified considerably in the last century, with associated higher demand for water through industrial and agricultural technologies. This intensification process has impacted rivers and resident organisms. The review paper examines the importance of the integrity of channel floodplain systems for fish and includes an evaluation of the impacts of the integrity of fish assemblages on other human uses of the shared ecosystem, such as fishing activities and management.

Wloanski et al. (2000) report on an experiment to improve ecological conditions while maintaining a 9-ft navigation channel initiated in 1994 and continued in 1995 and 1996 on the three pools of the Upper Mississippi River managed by the St. Louis District, U.S. Army Corps of Engineers. Water levels were held from 1-3 ft lower than maximum regulated elevations at the dam from mid-June though July in Pools 24-25 and Melvin Price Pool, and then were gradually raised as discharge allowed. In Pool 22, no drawdown occurred. Vegetation was surveyed along an elevation gradient in eight areas in 1995 and six areas in 1996 and was found in 30-90% of the sites. A geographic information system model was also used to predict areas that would be dewatered under various water-level management options. Minnow seining data collected on the three pools from 1986 to 1996 were also analyzed. The total numbers of fish per haul and Simpson's Diversity Index showed no significant detrimental effects during years when water levels were held on the low side of the operating band. Wloanski et al. (2000) assert that this management experiment was successful and that continuation, as conditions allow, would be beneficial.

3.4 SYNOPTIC MODELING STUDIES

This section includes papers describing conceptual or mathematical models. Such models have been employed to predict spatial distribution vegetation, to investigate the impact of flow diversion on benthic communities, and to predict habitat suitability for fish. This section also includes literature describing conceptual frameworks for analyzing the ecological impacts of water use in the Great Lakes-St. Lawrence system.

Allan *et al.* (1997) present a case study of a river basin in southeastern Michigan. A distributed parameter model, using twenty-two spatially distributed variables linked to a geographical information system, predicted that an increase in forested land cover would result in dramatic declines in runoff and sediment and nutrient yields to the stream. Habitat quality (MDNR, 1991) and an index of biotic integrity (IBI: Karr, 1991) varied widely among individual stream sites in accord with patterns of land use/cover. The extent of agricultural land at the sub-catchment scale was the best single predictor of local stream conditions. Local riparian vegetation was uncorrelated with overall land use and was a weak secondary predictor of habitat quality and biotic integrity.

Auble *et al.* (1994) present a direct gradient method to predict the vegetation change resulting from a proposed upstream dam or diversion. The method begins with the definition of vegetative cover types, based on a census of the existing vegetation in a set of 1 x 2 m plots. A hydraulic model determines the discharge necessary to inundate each plot. The hydrologic record, as defined by a flow duration curve, was used to determine the inundation duration for each plot; this allowed cover types to be plotted along a gradient of inundation duration. A change in river management results in a new flow duration curve, which is used to redistribute the cover types among the plots. Changes in vegetation are expressed in terms of the area occupied by each cover type. This approach was applied to riparian vegetation of the Black Canyon of the Gunnison National Monument along the Gunnison River in Colorado. This analysis defined three vegetative cover types that were distinct in terms of inundation duration. Quantitative changes in the extent of cover types were estimated for three hypothetical flow regimes: two diversion alternatives with different minimum flows and a moving average modification of historical flows. Our results suggest that (i) it is possible to cause substantial changes in riparian vegetation without changing the mean annual flow, and (ii) riparian vegetation is especially sensitive to changes in minimum and maximum flows. The principal advantages of this method are simplicity and reliance on relatively standard elements of plant community ecology and hydrologic engineering. Limitations include the use of a single environmental gradient, restrictive assumptions about changes in channel geometry, the representation of vegetation as quasi-equilibrium cover types, and the need for model validation.

Austin *et al.* (1979a, 1979b) present a mathematical simulation model describing shoreline vegetative succession in response to flooding. Plant species were grouped into ecologically similar compartments. Differential equations describing compartment intrinsic growth, intraspecies competition, interspecies competition and other growth-limiting factors were solved numerically. The model was used to evaluate the impacts of various operating policies on plant succession for a new reservoir in Central Iowa.

Baker and Coon (1995a) diverted approximately 50% of the summer stream flow from a 0.7 km section of Hunt Creek to simulate the impacts of flow withdrawal for irrigation on the benthic macroinvertebrate assemblage. They also simulated the impacts of the withdrawal on the benthic macroinvertebrate habitat in the treatment section by use of the Physical Habitat Simulation System (PHABSIM), and compared the changes in habitat with observed densities of benthic macroinvertebrates in the treated section of Hunt Creek. A habitat suitability criteria (HSC) from benthic macroinvertebrate samples collected in the treated section of Hunt Creek was then developed. The withdrawal of 50% of stream flow did not decrease the benthic macroinvertebrate habitat of most of the taxa examined, but did reduce habitat of riffle dwelling taxa (*e.g. Heptageniidae*) by up to 38%. The total density of benthic macroinvertebrates in the treatment section of Hunt Creek did not change as a result of the reduced flow in relation to the total density of benthic macroinvertebrates in a control section. However, the densities of *Heptageniidae* in a riffle sampled in 1994 did decrease in relation to a control riffle (p=0.05), indicating that reduced flow may have resulted in a reduction of *Heptageniidae* density.

Baker and Coon (1995b) withdrew approximately 50% of the summer stream flow from Hunt Creek, MI, to simulate the impacts of a water withdrawal for irrigation on the brook trout *Salvelinus fontinalis* population and to evaluate the Physical Habitat Simulation System (PHABSIM) under controlled conditions. They then used bioenergetic modeling to derive diurnal foraging habitat suitability criteria for mean column water velocity and depth for brook trout *Salvelinus fontinalis*. These were compared to diurnal foraging habitat suitability criteria derived from frequency-of-use data from brook trout in Hunt Creek, MI. Baker and Coon (1995b) also formulated hypotheses concerning the impact of the withdrawal on the brook trout population based on the PHABSIM model output and tested these hypotheses using Before-After-Control-Impact (BACI) analysis. The PHABSIM model also predicted that a summer withdrawal equal to approximately 88% of summer baseflow would be needed to produce a statistically detectable reduction in brook trout density in the treatment section of Hunt Creek and that yearling and older brook trout habitat would be reduced more than young of the year habitat at that level of flow reduction.

Bloczynski *et al.* (2000) analyze the question of how to manage a lacustrine wetland, given the uncertain potential for long-term lake level changes resulting from global warming and the uncertain biological processes involved in creating wetlands. The paper develops a model to evaluate an investment decision made under uncertainty. The model considers the best available information on the role of wetlands as habitat, the role of lake level variation in determining the extent of wetlands and the potential for climate change to alter the historic pattern of lake levels. A stochastic dynamic program (SDP) was used to optimize wetland protection decisions under a variety of management objectives. The SDP was applied to the question of how to best manage Metzger Marsh, a Lake Erie coastal wetland near Toledo, Ohio.

Burkata *et al.* (1998) presents mathematical expressions that relate changes in persistent water levels to the disappearance or re-emergence of marshlands in terms of the onshore and offshore slopes of the wetlands, the change in water level, the initial marsh area, and the maximum marsh depth beyond which emergent vegetation becomes indiscernible in a synoptic overview. Their computer program (in IBM PC BASIC) is intended to enable workers concerned with particular marshland regions to use the predictive (both for conditions of total vegetative regeneration and total vegetative nonregeneration) capabilities of the conceptual mathematical marsh model to evaluate the impacts of either naturally occurring or anticipated man-made changes in persistent ambient wetland water levels. The impact of prolonged water level changes on the areal extent of shoreline marshlands is also discussed.

Cardwell *et al.* (1995) examine ways to balance human water uses with instream releases for environmental values. To meet the need for planning-level tools for instream flow determination, they developed a flexible multiobjective optimization model. The model considers both the extent and frequency of water supply shortages, and the habitat available for fish species as they progress through life stages. It uses a habitat capacity metric to combine expected mortality, the fraction of a life stage in a particular month, and the areal habitat needs per individual fish. The model incorporates human water supply concerns such as monthly variations in human water demand, water-year types, and flood control restrictions. They apply this monthly optimization model to a west-slope Sierra Nevada stream used for municipal and agricultural supply and for supporting an anadromous fish population. Results identified a range of alternative solutions that involve trade-offs between water shortage levels and fish population capacity.

Hill *et al.* (1998) propose a model, based on the species richness of shoreline vegetation along unregulated lakes in Nova Scotia, Canada, to compare the vegetation and hydrological regimes of regulated and unregulated systems. Hydrological regimes of regulated systems deviated from natural systems of similar catchment area by being either hypovariable or hypervariable for both within-year and among-year fluctuations in water level. Plant communities of dammed systems were less diverse, contained more exotic species and were, with one exception, devoid of rare shoreline herbs. Data from "recovering" or previously dammed systems indicate that shoreline communities could be restored upon return of the appropriate hydrological regime. Using observed within-year and among-year water level fluctuation data, they propose a general model for the maintenance or restoration of diverse herbaceous wetlands on shorelines of temperate lakes or reservoirs.

Harpman *et al.* (1993) propose a methodology for quantifying and valuing the impacts of flow changes on a fishery. A quasi-population model, termed the effective habitat model, is used to predict the effects of changing the timing and quantity of reservoir releases on downstream fish populations of brown trout. An anglers' survey was used to develop a willingness-to-pay economic valuation model. The economic impact of the change in brown trout population, arising from different flow regimes, is dependent on the resulting change in anglers' catch. The predicted change of population of two different flow release patterns were compared with the predicted population for the current reservoir operation regime and found to be relatively small. As a result the impact on the economic value of the fishery was limited.

Hart & Finelly (1999) propose a conceptual framework for investigating the multiple causal pathways by which flow influences benthic biota, with particular attention to the local scales at which these organisms respond to flow. Flow (especially characteristics linked to the velocity field) can strongly affect habitat characteristics, dispersal, resource acquisition, competition, and predation; creative experiments will be needed to disentangle these complex interactions. Benthic organisms usually reside within the roughness layer, where the unique arrangement of sediment particles produce strongly sheared and highly three-dimensional flow patterns. Thus, accurate characterization of the local flow environments experienced by benthic organisms often requires the use of flow measurement technology with high spatial and temporal resolution. Because flow exhibits variation across a broad range of scales, it is also necessary to examine how organism-flow relationships at one scale are linked to those at others. Interdisciplinary approaches are needed in the study of physical-biological coupling; increased collaboration between ecologists and experts in fluid mechanics and hydraulic engineering is particularly desirable. A greater understanding of physical-biological coupling will not only yield deeper insights into the ecological organization of streams and rivers, it will also improve our ability to predict how flow alterations caused by various human activities affect these vital ecosystems.

Hellsten *et al.* (1996) look at an ecologically based regulation practice in Finnish hydroelectric lakes. The regulated lakes in northern Finland were subjected to intensive ecological research during the 1980s. Heavy geomorphologic changes have taken place in lakes with raised water levels and a lowering of the ice cover during the winter causes rapid changes in the littoral benthos and vegetation. The scale of harmful effects depends on both the range of regulated water level fluctuations and water quality; clear-water lakes are more resistant to water level regulation than humic lakes. As a result of these studies, the principles of so-called ecologically based regulation practices (ERP) have been applied to several lakes used for hydropower production. This procedure is based on underwater light climate and water level fluctuation data, which make it possible to calculate the proportion of frozen littoral area to total littoral area. Another procedure calculates the biomass of benthic fauna from data on water level fluctuation and Secchi depth. The ERP could be used as a guide in identifying ecologically preferable water levels that could then be used whenever economically and hydrologically possible. It offers a simple way to illustrate to regulation permit owners the differences among various regulation practices.

Hudon (1997) proposes a conceptual model of the major structuring forces acting upon the St. Lawrence River wetlands; it describes aquatic plant biomass allocation and species diversity as a function of the average level and vertical range during the growing season.

Hudon *et al.* (2000) examine the maximum depth of macrophyte colonization and depth distribution of macrophyte biomass assessed, over 3 years, in late summer at six sites in the St. Lawrence River and two sites in the Ottawa River. The study relates the above-ground and total biomass of macrophytes to a variety of environmental variables, as follows in descending order of importance: exposure to wind and waves, plant growth forms, water depth, and light intensity. These environmental variables were used to elaborate hierarchical predictive models of above-ground and total biomass of emergent and submerged macrophytes. The empirical relationship linking St. Lawrence River and Ottawa River aquatic plants to environmental variables may eventually allow the forecasting of wetland responses to changes in water levels and clarity resulting from climate variability and/or discharge regulation.

Lamouroux *et al.* (1998) present a new model to predict habitat suitability for lotic fish. While most habitat studies of lotic fish use a deterministic hydraulic model and univariate suitability curves, the alternative method presented in this paper relates statistical hydraulic models to multivariate habitat use.

Leclerc *et al.* (1994) propose a numerical approach to simulate habitat displacement by using a two-dimensional hydrodynamic model combined with a hydrological analysis of temporal changes in discharge. This model circumvents one of the weaknesses of IFIM and its physical habitat simulation model, which do not consider the displacement of habitat positions within a river that accompany discharge changes. This methodology was employed in a preliminary evaluation of the eventual impact of a peaking hydropower project on the juvenile habitats of landlocked salmon.

Madsen & Wright (1999) propose a framework for analyzing the ecological impacts of water use in the Great Lakes St. Lawrence system. Their approach for assessing cumulative effects is based on the physical changes and processes that determine the configuration and size of a series of shore zone habitats. They relate lake levels and fluctuation cycles to habitat conditions, using GIS data on the location and morphology of habitats and knowledge of shore zone geomorphic processes. A conceptual model integrating lake levels, shore zone morphology and geomorphic processes could provide a cumulative assessment of changes that have occurred or could occur, in individual lakes or the entire Great Lakes ecosystem. The ecological effects of forecasted physical changes can be added using knowledge of species-habitat relations. Their analyses begins this process by presenting a dual overview of habitats and taxonomic group responses in the context of general approximations of changing lake levels. No details are presented as to the structure of the model.

Marttunen (1992) proposes a system model for the effects of lake regulation on European whitefish stocks. It is based on assumed functional relationships and specified causal connections among a great number of factors. The main emphasis is on changes in reproduction and food resources, and subsequent effects on fish stocks and catches. The model consists of four components: food, growth, reproduction, and population.

Milhous (1999) presents two examples of the application of the Physical Habitat Simulation System (PHABSIM). PHABSIM was developed as a water management tool to assist in the establishment of instream flow requirements (environmental flows) to support water control and water allocation activities. The fist PHABSIM example was part of the water development planning studies of the late 1970s, and the second is the development of an instream flow need for a hydroelectric project. Analysis of the relation between physical habitat and the populations of aquatic animals shows the physical habitat is a necessary but not sufficient condition for a viable population of aquatic animals. Future developments in physical habitat analysis require improvements in the analysis of the substrate and in the approach to how the substrate is included in the physical habitat. Also needed are improvements in understanding the time dimension of physical habitat. A significant limitation is that there are many interactions between species, life states, and other variables that influence the state of the ecosystem that are not modeled by PHABSIM.

Richards *et al.* (1997) use catchments and reach-scale physical properties to predict the occurrence of life history events and behavior traits for specific aquatic insects across 58 catchments in a mixed-use land basin. Catchment-scale attributes were derived using a geographical information system (GIS). Logistic regression techniques were used to model the relationships. The reach-scale properties were highly predictive of species traits. Catchments features, in particular surficial geology, influence macro invertebrate assemblages through their control over channel morphology and hydrologic patterns. The effects of land use were masked by geology, lack of detail in land-use data and the aggregation of the species data.

Rodier & Norton (1992) describe basic elements, or a framework, for evaluating scientific information on the adverse effects of physical and chemical stressors such as global climate change, habitat loss, acid deposition, reduced biological diversity and the ecological impacts of pesticides and toxic chemicals on the environment. The framework offers starting principles and a simple structure as guidance for current ecological risk assessments and a foundation for future EPA risk assessment guideline proposals.

Rousseau *et al.* (2000) present an integrated modeling system prototype designed to assist decisionmakers in assessing various river basin management scenarios in terms of standard physical and chemical parameters of water and standards for its various uses. The model provides a user-friendly framework to examine the impact of agricultural and industrial uses and municipal management scenarios on water quality and yield. A database (including spatial and attribute data) and physically based hydrological, soil erosion, agricultural chemical transport and water quality models comprise the basic components of the system. A geographical information system and a relational database management system are also included for data management and system maintenance. This paper illustrates potential uses by presenting two sample applications applied to the 6680 km2 Chaudiere River basin in Quebec, Canada: (i) a timber harvest scenario and (ii) a municipal clean water program scenario. Results from the simulatedtimber harvest scenario showed how clear-cutting could lead to earlier and larger spring runoff than in the investigated reference state. Results of the municipal clean water scenario revealed that substantial reductions in coliform counts and total phosphorus could be made by constructing and operating wastewater treatment plants.

Shipley *et al.* (1991) present a regression model of vegetation species density (number of species per unit area) on a local (0.25 m2) scale for freshwater shorelines in southwestern Quebec. The model was then tested against independent data from shoreline vegetation in southeastern Ontario. There were no significant differences in the two data sets in their response to the two independent variables (the amount of aboveground biomass and the proportion of vegetation composed of obligate perennial species) in the full model. However, only 42% of the variance in species density was explained in the combined data set.

Toner & Keddy (1997) use logistic regression models and the composition of shoreline plant communities to describe the distribution of wooded wetlands as a function of all possible combinations of seven hydrological variables. The variables were chosen to reflect the depth, duration and time of flooding and were calculated for four different time intervals (3, 7, 12, and 18 growing seasons, defined as the period which starts when the mean daily temperature exceeds 5.5°C for five of seven days and ends when it fails to exceed 5.5°C for five of seven days). The results suggest that models based on a few key environmental variables, such as the last day of the first flood and the time of the second flood can be valuable tools in the conservation management of the vegetation in temperate and boreal zone wetlands.

Waddle *et al.* (1997) provide the aquatic biology component of a decision support system being developed by the by U.S. Bureau of Reclamation for water operations planning and day-to-day management. In an attempt to capture the habitat needs of Great Plains fish communities, Waddle et al. (1997) looked beyond the traditional habitat modeling approaches that rely on one-dimensional hydraulic models and on lumped compositional habitat metrics to describe aquatic habitat. Waddle et al. (1997) assert that two-dimensional hydrodynamic models have advanced to the point that they may provide spatially explicit description of physical parameters needed to address this problem. Waddle et al. (1997) report on the progress to date on applying two-dimensional hydraulic and habitat models on the Yellowstone and Missouri rivers and use examples from the Yellowstone River to illustrate the configurational metrics as a new tool for assessing riverine habitats.

Wiley *et al.* (1997) examine how rapidly advancing geographical information systems (GIS) technologies are forcing a careful evaluation of the roles and biases of landscape and traditional site-based perspectives on assessments of aquatic communities. Decomposition of variances by factorial ANOVA into time, space and time-space interaction terms can provide a conceptual and analytical model for integrating processes operating at landscape and local scales. Using this approach, long-term data sets were examined for three insects and two fishes common in Michigan trout streams. Each taxon had a unique variance structure and the observed structure was highly dependent upon sample size. Both spatially extensive designs with little sampling over time (typical of many GIS studies) and temporally extensive designs with little or no spatial sampling (typical of population and community studies) are biased in terms of their view of the relative importance of local and landscape factors. The necessary but often costly solution is to develop and analyze data sets that are both spatially and temporally extensive.

4. SPECIAL FOCUSED STUDIES

This section highlights a number of relevant large-scale studies that are targeting some aspect of the study question. These studies focus on water level issues in the Great Lakes, ecological impacts from dam and hydropower regulation, and conceptual frameworks for investigating ecological impacts of changing water levels and flows. These studies include work conducted by the International Joint Commission, World Commission on Dams, UNESCO's Ecohydrology Programme, the Waterpower Project (Ontario, Canada), and The Nature Conservancy.

4.1 INTERNATIONAL JOINT COMMISSION

The International Joint Commission has a longstanding involvement with water quantity issues in the Great Lakes, which first emerged through concern related to lake levels. In response to References from the US and Canadian Governments under the Boundary Treaty of 1909, the IJC was requested to conduct a number of studies:

- Regulation of Great Lakes Water Levels (October 1964 Reference);
- Great Lakes Diversions and Consumptive Uses (February 1977 Reference); and
- Levels Reference Study Great Lakes-St. Lawrence River Basin (August 1986 Reference).

The International Great Lakes Levels Board (IGLLB, 1973 a,b) investigated the effects of changes in lake level regimes on fisheries, wildlife, beaches, and recreational boating in *The Regulation of Great Lakes Water Levels*; the board also studied the economic effects of changes in flows and water levels on these resources. As part of this study, a detailed inventory survey of existing conditions and developments was conducted along the entire Great Lakes-St. Lawrence shorelines to develop a baseline data set for this study.

The Commission's Report on the 1977 Reference on *Great Lakes Diversions and Consumptive Uses* is contained in two parts (IJC, 1985). Part One examines the effects of existing diversions, the potential to improve extremes in Great Lakes levels by changing existing diversion flow rates, and existing and projected consumptive uses in the Great Lakes basin. Part Two provides a broader and more appropriate context within which to address the longer-term prospects for the use of Great Lakes water. The report states that the environmental evaluation was limited by inadequate ecological and other relevant data (IJC Great Lakes Diversions and Consumptive Use Study Board, 1981a,b). Nonetheless, the Board examined fisheries, wildlife/wetlands and water quality issues.

The August 1986 Reference from the US and Canadian Governments under the Boundary Waters Treaty of 1909 asked the International Joint Commission (IJC) to examine the effects of any measure it proposes on fish, wildlife and other environmental aspects (IJC, 1993).

The above Reference studies incorporate findings from a number of working group studies, functional group studies, and workshop proceedings related to ecological impacts from changes in water levels and flows. For the most part, the IJC studies have approached cumulative ecological impact assessment from a relatively narrow point of view. The References from the U.S. and Canadian governments, as well as the IJC directives to the study boards, were directed at measures that could be taken to regulate the waters of the Great Lakes to reduce the extremes in experienced water levels so damages can be alleviated. A number of criteria were imposed on possible regulation plans in terms of the maximum and minimum levels and flows that need to be preserved. The possible impacted sectors of activities were also specified and these stayed more or less the same for most study boards from the late 1960s to the early 1990s. The impacts of various regulation alternatives were assessed by comparing a particular plan with a basis of comparison (BOC). For this reason, it is important to recognize BOC has already integrated the historical changes in the baseline (diversions, consumptive use, channel modifications, *etc.*) and that the measured and evaluated impacts are therefore incremental rather than cumulative.

In the next sections, important findings the References and related studies are presented. These are related to erosion, fisheries/wildlife, wetlands, and water quality. Some of these findings are included in a working paper (Working Group 4, 2000) that summarizes the results of the Cumulative Impacts and Risk Assessment component of the 1977 IJC reference on Consumption, Diversion and Removal of Great Lakes Water (IJC, 1985).

The second working paper, prepared in November 1999, summarizes the workshop on Cumulative Impacts in the Great Lakes-St. Lawrence River Ecosystem. This summary paper includes *A Literature Review on Cumulative Impacts in the Great Lakes-St. Lawrence River Ecosystem From Factors Affecting Water Levels and Flows*.

4.1.1 Erosion

The Levels Reference Study Board (1993) carried out extensive studies of beach erosion processes to try to resolve the controversy over the difference between long- and short-term erosion. Overall, it was found that recession rates are completely independent of lake levels for some shore types and that there is a direct, although small, relationship between changes in lake level ranges and recession rate for others.

4.1.2 Fisheries and Wildlife

As part of the environmental portion of International Great Lakes Levels Board's study (IGLLB, 1973a,b), the effects of lake levels regulation on fish stocks were investigated, by looking at the relationship between water levels and commercial catch in pounds; this approach was recognized to be inadequate and the study reverted to a qualitative assessment by polling the expertise of fishery biologists and administrators using a letter of inquiry. In addition, an experiment performed in the St. Marys River rapids in 1971 provided information on the effects of operation of regulatory structure on the aquatic environment (water quality and benthic community) for this study. This study also computed the acreage of marshland under basis-of-comparison conditions and under regulation plans; this measure was used to evaluate losses or benefits to wildlife. This report (IGLLB, 1973a,b) also stated that fish and wildlife are best served by high water levels.

Manny (1984) investigated the potential impacts of water diversions on fishery resources in the Great Lakes. Using the reports of the International Great Lakes Diversions and Consumptive Uses Study Board (1981) and the International Lake Erie Regulation Study Board (1981), Manny examined the impact of water withdrawals (water diversions and consumptive water withdrawals) on fish, and the economic impact of water diversions on Great Lakes fish resources. He noted, for example, that in 1979 an estimated 1.2 billion fish larva and 98 million juvenile and adult fish were drawn into the water intakes of the 90 power plants on the shores of the Great Lakes. Meador (1996), after examining the results from five case studies presented in a 1995 symposium, concluded that these studies reveal important clues about the status of knowledge and the need for information related to the ecological consequences of water transfer. Understanding the fundamental ecological processes of managed fish species is crucial to future water transfer studies.

In addition, The New York State Department of Environmental Conservation (1997) investigated the effect of water regulation on fisheries, as part of an IJC effort. The study reported that healthy northern pike populations exist throughout Lake Champlain wetlands, but tend to be more dominant in the low-gradient wetlands located near the northern portions of the lake. Flooded terrestrial vegetation such as grasses and grass-bush-tree combinations and emergent aquatic plants were preferred substrates for spawning. Water levels above elevation 30.0 m during the spawning period were required for access to, and flooding of, preferred substrates for egg deposition. If lake-level regulation is implemented, inundation of this habitat for 40-50 days at least once every 3 years should ensure egg and fry survival. Dropping water levels during the critical egg and spawning period would have an adverse effect on northern pike production. Reduction of lake elevations from 31.0 to 29.5 m would eliminate about 42% of the 37,500 mapped wetlands.

4.1.3 Wetlands

Wetlands were used as the primary indicators of the overall health of the system's aquatic environment (Levels Reference Study Board, 1993). The impacts upon wetlands of lake level regulation plans were assessed and research was oriented toward two goals: 1) to better understand the response of wetland communities to fluctuation in water levels; and 2) to apply this knowledge generally and to predict the response of wetland plant communities to proposed water level regulation schemes. The environmental effects were evaluated based on qualitative assessments; that is, descriptive rather than numerical data were used to rate impacts as either positive, neutral or negative. It was found that fluctuations in water levels are important to maintain the extent of coastal marshes. The smaller the fluctuation in water levels, the smaller the extent of wetlands (Wilcox *et al.*, 1992, Wilcox, 1995, Wilcox and

Meeker, 1992). The environmental evaluation of all regulation plans found that environmental impacts were negative on all wetlands, lakes and connecting channels. Fish association and wetlands subsystems were perceived by this study to be "integrative indicators" of the aquatic consequences of human activities, including regulation, in a river basin. Such an approach treats the integrative indicator as a surrogate of the whole ecosystem and if the surrogate manages to sustain its integrity under external stress then the whole ecosystem is expected to do so. However, such a working assumption should be tested (Regier, 1999).

The Wetlands Summary Workshop (January 24-25, 1989), sponsored by the IJC Water Levels Reference Functional Group 2, also examined the impact of changing water levels as a result of further regulations and modifications of existing regulations (IJC, 1989b). Results from the workshop are as follows:

- Major changes in water-level fluctuation will affect the lake influence wetlands through impacting the size of some of these wetlands, the plant community and the functions performed by these wetlands.
- Fluctuating water levels, as exhibited in the Great Lakes, have provided conditions for wetlands such that the actual wetland area as significantly larger and more productive than if the water levels had been stable.
- The impacts of a reduction in the range of fluctuations on wetland area can be quantified but mitigation is anticipated to be difficult because of the size of the impacted area.
- Changes in fluctuations though regulations that may affect the timing of the highs and low, and such changes could have significant detrimental impacts on the wetland vegetation.
- Impacts caused by changes to the timing of highs and lows can be described but not easily quantified.
- Changes in the amplitude would have system-wide impacts on plant species diversity and on area. In general, scrub-shrub, Typha and exotics could increase at the expense of other species.
- Recommendations for water level profiles were also developed for the Great Lakes at the workshop.

Studies under the 1986 Water Levels Reference found that the wetlands of the Great Lakes-St. Lawrence Basin and the habitats they support are, to a large, degree, dependent on water level fluctuation (e.g., IJC Water Levels Reference Study, 1989a,b,c). The Levels Reverence Study Board concluded that the reduction in the range of water level fluctuations resulting from regulation has adversely affected the extent and diversity of Lake Ontario's wetlands. The Study Board also concluded that altering natural water level conditions on Lake Ontario resulted in the appearance of many undesirably plant species in its wetland habitats. In addition, the Study Board concluded that regulation of Lake Ontario has caused losses of flood planning forests also the St. Lawrence River through flooding and erosion. The Commission noted that the Study Board relied heavily on qualitative assessments of environmental impacts. From this work, the IJC recommended that the inventory of the location, extent and quality of existing wetlands be completed and that long-term monitoring and evaluation of the effects of water level fluctuations on wetlands be carried out.

4.1.4 Water Quality

Water quality characteristics were examined in detail in two studies (International Lake Erie Regulation Study Board, 1981 and International Great Lakes Diversions and Consumptive Uses Study Board, 1981). These included hypolimnion volume and oxygen resources, general lake water quality, total phosphorus budget and near-shore turbidity concentrations, Cladophora production, embayment water quality and waste dispersion capability.

Water quality evaluations were based on the water quality studies of the International Lake Erie Study Board and therefore deal mostly with Lake Erie, based on a one-foot lowering. Very little pertinent information is available for the other lakes. However the Board's conclusion is that "implementation of the 'maximum-effect' (Long Lake /Ogoki: 0 cfs, Chicago: 246 cms, Welland: 255 cms) diversion scenario would not significantly affect the lower lakes water quality." A summary of the impacts (International Lake Erie Regulation Study Board, 1981) states that except for a reduction of turbidity (2 - 11 percent) and increase in *Cladophora* production (0.5 - 2.7 percent), all other impacts are negligible for the ranges of level variations resulting from implementation of the three regulation plans.

4.2 REPORT OF THE WORLD COMMISSION ON DAMS (WCD)

In November 2000, the World Commission on Dams released its final report, "Dams and Development - A New Framework for Decision Making" (WCD, 2000), the result of a multi-year, multi-stakeholders and multi-million dollar study. To finalize its report, the WCD drew on the WCD Knowledge Base consisting of seven case studies, two country studies, one briefing paper, seventeen thematic reviews of five sectors, a cross-check survey of 125 dams, four regional consultations and nearly 1,000 topic-related submissions. All these reports are available on CD-ROM or can be downloaded from the web site *http://www.dams.org*.

Among the seventeen thematic reviews, the 200-page "TRII.1" (Berkamp *et al.*, 2000) deals with the subject of "Dams, Ecosystem Functions and Environmental Restoration." Chapters 3 and 4, respectively, deal with the ecosystem impacts of large dams and with responding to the ecosystem impacts of dams. While making for interesting reading on this complex and controversial subject, the review contributes little in terms of this literature survey, as it is written in a very general and descriptive way. Little information is presented linking specific changes in levels and flows to specific effects and impacts on ecosystem variables. Moreover, much of the existing and available literature on the subject was not reviewed.

In Appendix 1 of this report, we present an in extenso copy of the Executive Summary, Conclusions and Policy Recommendations of this thematic review to the WCD.

It should be noted that the TRII.1 review is a working paper of the World Commission on Dams, and was prepared for the Commission as part of its information-gathering activity. This document is based on contributions from a wide range of sources and comments received from a review panel and a WCD Forum. Appendix 2 lists the titles and authors of the sixteen contributing papers, which can be downloaded in PDF format from the WCD web site.

The following summarizes some of the contributing papers that seemed most relevant to this study, based on a limited review of this very comprehensive study.

King *et al.* (1999) present an extensive review of instream flows definitions and implementations. The review looks at types of environmental flow methodologies applied worldwide and their limitations, global trends in the application and advancement of environmental flow methodologies, the position of environmental flow assessments in the planning process, and points of linkage and summary of features vital to successful implementation of environmental flow requirements.

In Annex 1 of their report, King et al (1999) examine in detail the various types of flow assessment methodologies, looking at state-of-the-art methodologies, data requirements and expertise, and strengths and weaknesses. The following are analyzed in depth:

- Hydrological type methodologies
- Hydraulic rating methodologies
- Habitat simulation methodologies
- Methodologies for the maintenance of channel form, and fluvial geomorphological and sedimentological processes
- Environmental flow methodologies for water quality purposes
- Methodologies addressing the ecological flow requirements (EFR) of riparian vegetation
- Methodologies addressing ecological flow requirements of wildlife
- Methodologies addressing the ecological flow requirements of wetlands, floodplains and estuaries. While consideration of EFRs have, to date, focused very little on wetlands in a broad context (including floodplains and estuaries), the need to address problems pertaining to reduced or altered hydrology of wetlands, or reduced freshwater inflows to estuaries, has been recognized for some time.
- Methodologies addressing groundwater and its links with surface flow in rivers. The international literature on this topic has yet to be intensively reviewed, as it is evident that methodologies that explicitly assess EFRs for groundwater, particularly in terms of links with surface flows in the river channel and conditions in the riparian zone, wetlands and floodplain, are virtually absent.

In Annex 2 of their report, King *et al.* (1999) list relevant information on environmental flow assessments available on Internet web sites, while in Annex 3 presenting a summary list of Internet sites that provide further information on issues surrounding shared watercourses. Finally, after a full list of references they include in Appendix A comments received from the eleven members of the panel that reviewed a July 1999 draft.

King & Brown (1999) look at eight steps to informed decision-making, such as situation assessment, specialist reviews, selection of representative components, developing predictive capacity of biophysical responses to dam-related flow changes, predicting the social impacts of biophysical responses and creating scenarios. They stress that the kinds of environmental data needed on rivers cannot be provided from a week or two of effort. With present knowledge, for instance, river scientists could probably only describe trends in river ecosystem response to management actions and not predict the timing and severity of the response, even after a considerable research effort.

McAllister *et al.* (2000) review the biodiversity impacts of large dams. In this highly descriptive document the authors examine the status of the world's freshwaters, the status of the world's biodiversity, the large dams, the value of biodiversity and the patterns of freshwater biodiversity. Under impacts of dams on biodiversity, they look at species movements and movement of matter up and down stream. Finally in a number of tables they summarize the impacts on the biodiversity of mollusks, fishes and waterfowl that have been reported in the scientific literature.

McCartney *et al.* (2000) present a review of the ecosystem impacts of large dams. The report gives a rationale for considering the environmental impacts caused by dams within the context of ecosystems. It provides baseline data on the broad spectrum of both upstream and downstream impacts and offers an initial attempt to link differences in impact with variation in geographical location. A review of economic issues associated with dam impacts is presented and there is a brief overview of current environmental standards that relate to large dam construction and operation. Finally, a distillation of the arguments used by both sides in the large dam debate is given.

4.3 UNESCO STUDIES

The understanding of evolutionary established links between hydrology-biota-water quality and quantity is the basis for the sustainable water management. For this reason, Ecohydrology has been the subject of a project launched by UNESCO, during the Fifth Phase of its International Hydrological Programme (IHP-V). The Project is supported by the UNESCO Division of Water Sciences, the UNESCO Venice Office for Science & Technology for Europe (UVO-ROSTE), and the United Nations Development Programme (UNDP). Its main goals are:

- To collate and review information on the interactions between hydrological and ecological processes.
- To review their predictive potential and to define the most important directions for future research.

- To identify a hierarchy of environmental problems associated with ecohydrological processes.
- To create a background of transition toward operational procedures aimed at sustainable development and generate a new way of thinking among scientists, policy-makers and decisions-makers.

The activities to be undertaken within the framework of the project have been organized in four main phases distributed between 1997 and 2001.

Ecohydrology has been defined by the IHP as the science of hydrological processes with biota dynamics over varied spatial and temporal scales. Zalewski (1996) has asserted that Ecohydrology is a principal factor accelerating the transition from descriptive ecology, restrictive conservation, and over-engineered management of aquatic ecosystems to analytical/functional ecology, creative management, and conservation of fresh waters. The conceptual background, working hypotheses, and rationale and scientific guidelines for the implementation of the IHP-V Projects 2.3/2.4 are discussed in *Ecohydrology: A New Paradigm for the Sustainable Use of Aquatic Resources* (Zalewski et al., 1997). A brief description of the projects is given in IHP (1997).

In May 1997, the International Symposium on Ecohydrology was held in Salzburg, Austria, to launch a network of international pilot projects for the preparation of guidelines on ecologically sound water resources planning and management. The pilot projects involve research in the following areas:

- Functioning of buffer zones between the catchment and the river;
- Timing of biological and hydrological processes and interactions;
- Changes in flow regime and opportunities to restore ‘natural’ flow regime;
- Range of modifications of hydrological processes by biotic structures in catchments and aquatic systems; and
- Range of modifications of biological responses to hydrological processes.

A List of Scientific Activities of IHP-V Projects 2.3/2.4, including preliminary results, is given in Zalewski and McClain (1998). In addition, the IHP has been involved in regional studies where the environmental effects of water use have been significant—e.g., the Aral Sea (IHP, 2000). Documents are available for download or to order from IHA and Ecohydrology website.
http://www.uni.lodz.pl/ulan/ecohyd.htm/index.htm

4.4 WATERPOWER PROJECT (ONTARIO, CANADA)

The Waterpower Science Strategy (WPSS) serves to provide sound scientific research to characterize hydrologic regimes in ecologically meaningful ways to support water management planning in Ontario. The WPSS includes a short-term research program that focuses on the development of methods immediately required for the production of Water Management Plans. This strategy also establishes the framework for a long-term research program of process-oriented field studies and experimental adaptive management. Longer-term research initiatives will provide important preliminary information during the course of the Waterpower Project (i.e. up to 2004); it is expected that continued funding will be required to complete these projects and to address further science needs identified through this work. The Waterpower Science Committee (Ontario Ministry of Natural Resources) oversees the development and implementation of the WPSS in support of Water Management Planning in Ontario.

Short-term objectives of the Waterpower Science Strategy are as follows:

- To complete a synoptic analysis of flow regimes and in some cases, their degree of alteration, to better understand the relationship between the hydrograph and the ecological integrity of the total riverine ecosystem and facilitate meaningful operational flow and level recommendations; and

- To develop quantitative methods for monitoring river ecosystem integrity, focusing on the response of Valued Ecosystem Components (VECs) to altered flow and level regimes related to waterpower generation.

Long-term objectives of the Waterpower Science Strategy follow:

- To quantitatively describe the full range of inter- and intra-annual variation in hydrologic regimes, and associated characteristics of magnitude, timing, duration, frequency and rate of change, and their role in sustaining biodiversity and ecological integrity of riverine ecosystems; and

- To establish a broad-scale framework to evaluate hydrologic variability and change likely to be associated with alternative water management scenarios.

Within the context of the Waterpower Science Strategy, Valued Ecosystem Components (VECs) refers to organisms and biological processes within the aquatic and terrestrial environment that are functionally linked to the river and can be used as broad indicators of ecosystem integrity. VECs that will generally be prominent in water management planning include fish, aquatic invertebrates, aquatic vegetation (e.g. wild rice), furbearers and nesting waterfowl. Additionally, vulnerable, threatened, and endangered species (VTEs) as well as ecosystem functions unique to specific areas may be considered during the planning process. The focus of the Science Strategy is to improve existing knowledge about the spatial and temporal scales at which VEC's are effected and the range of their tolerance to flow regulation.

The WPSS web site (http://www.trentu.ca/wscproject/wpscinfo/wpschome.htm) disseminates information about the strategy and is maintained through a collaborative effort between the Waterpower Science Committee (WPSC), Waterpower Project, Ontario Ministry of Natural Resources, and the Watershed Science Centre (WSC), Trent University. The website includes information about WPSS research projects in

Ontario. It also provides information about established and potential field locations that have been identified for the intensive study component of the WPSS.

The Waterpower Project—Science Information Report (House, 2001), contained on the WPSS website, is also of note. This document serves to highlight information for consideration in planning waterpower research and management strategies focused on aquatic ecosystem protection. This document investigates information pertaining to a) fluctuating water levels and winter de-watering in reservoirs; b) hydropeaking activity; and c) peak and minimum flows (i.e., instream flow requirements, IFR); and d) hydrological modeling/ regionalization approaches. In the report, House (2001) indicates that information on waterpower planning and aquatic ecosystem management objectives does exist; however, limited information is available on some issues (e.g., effects of winter de-watering and reservoir fluctuations) and limited research is conducted in Ontario and in northern-temperate rivers. In addition, House (2001) highlights the importance of developing instream flow requirements (IFRs) for individual rivers, the need to assess the interaction between rivers, their channels and surrounding watersheds when considering flow requirements below dams, the need to generate sufficient "baseline" data before IFR methods are widely applied. House's (2001) assessment includes peer-reviewed literature, gray literature, and major waterpower related reports, reviews, and bibliographies. In the report, House (2001) also notes that a number of government and/or scientific research organizations have excellent information sources at their websites. A list of relevant web pages and some selected websites is given in Appendix A of the report.

4.5 THE NATURE CONSERVANCY

The Nature Conservancy launched its Freshwater Initiative in 1998, with the goal of increasing freshwater conservation in the United States, Latin America, and the Caribbean. As part of the Initiative, the Conservancy staff developed, and are now applying, an aquatic community classification system. Using this system, the Conservancy can map existing locations of freshwater animals and their habitats across broad regions and assess their relative conservation priority. A list of supporting documents/tools related to the aquatic community classification framework is given below. The documents and tools are available for download from the website: http://www.freshwaters.org/science.html.

- Aquatics and Ecoregional Planning. This document provides guidance for individuals and teams engaged in large-scale conservation planning. The primary focus of this document is assisting ecoregional planning teams to adequately consider aquatic biodiversity in the selection of priority sites for future conservation focus.

- Threats Guide. This guide identifies data sources helpful when evaluating the quality of and threats to natural biodiversity of freshwater systems. Most of these sources are national or regional data sources, available through internet web sites. (Where possible, links to these data sources are incorporated). The guide was developed primarily to assess streams and lakes, although much of the information could be applied to wetland and riparian areas.

- Aquatic Community Classification Framework. This document describes the development and application of an aquatic community classification framework for the Great Lakes Basin.

- Watershed Characteristics and Aquatic Ecological Integrity: A Literature Review. This document is a review of empirical research on the relationship between watershed characteristics and indexes of biotic integrity for aquatic species.

- GIS Tools for Aquatic Macrohabitat Classification. GIS Tool Tutorial Dataset. This zip file contains GIS tools intended for experienced GIS users who are interested in implementing Strategy One's aquatic macrohabitat classification. The tools use EPA's RF3 hydrography dataset to generate attributes of streams and lakes.

In addition, The Nature Conservancy's Biohydrology program has focused on the role of hydrologic regimes in determining the biotic composition, structure, and function of aquatic, wetland, and riparian ecosystems. Scientists at The Nature Conservancy's Biohydrology Program have developed a statistical method to characterize environmental regimes, namely Indicators of Hydrologic Alteration (IHA); the IHA software package was developed by Smythe Scientific Software (Boulder, CO). IHA allows hydrologists and ecologists to examine historical changes in stream flow regimes. The IHA method is discussed in Richter et al. (1996). Richter et al. (in press) have also used the "Range of Variability Approach" (RVA) for setting streamflow-based river ecosystem management targets and for assessing hydrologic alterations at available stream gauge sites in a river basin. Publications by Richter and others from The Nature Conservancy are available from the IHA website (http://www.freshwaters.org/iha.html).

5. FINDINGS AND RECOMMENDATIONS

The thrust of this literature review was to compile the body of research relevant to the identification and quantification of ecological impacts that might arise from water withdrawals/diversions in the Great Lakes Basin. Because this topic really encompasses the entire body of knowledge on the effect of physical, chemical, and biological conditions in a freshwater ecosystem on its structure and function, we had to be reasonably selective in the inclusion of literature in this document. Also, in an effort to organize the included literature in a logical and understandable way, we have grouped the literature in four broad categories: 1) effects on physical/chemical habitat; 2) effects on populations and/or communities; 3) ecosystem effects; and 4) synoptic modeling studies. There were also a number of large, focused studies that have or are making significant contributions to these four categories. We have dealt with each of these studies individually.

The over-arching hypothesis in organizing this body of literature has been that alterations in flow, water levels, or system geometry and hydrology in the course of withdrawing or diverting water for human use produces ecological effects ecosystem in a serial manner. First the perturbation effects the physical and/or chemical environment, which in turn causes effects on specific populations or groups of populations (*i.e.,* communities). Finally, the ecosystem structure and functioning is affected through ecosystem processes such as competition, predator-prey interactions, energy flow, nutrient cycling, and habitat quality and quantity. Of course, ecosystem effects can lead to feedbacks on the physical, chemical, or individual population or community components of the ecosystem. Indeed, these feedback processes are a crucial part of ecosystems in that they provide the homeostasis of ecosystems that is a measure of their stability and resilience in the face of perturbations. We recognize all of these levels of effects as ecological effects and, therefore, have categorized them as listed above. The final category – synoptic modeling studies – includes those studies that have made an effort of demonstrating the coupling among the first three effects and thereby include the process understanding and feedbacks that allow a more generic application of site-specific observations.

5.1 FINDINGS

Many of the papers that were reviewed describe the impacts of regulation, withdrawals, and dam construction and operation on biota, landscape ecology, environmental flows, geomorphologic processes and vegetation landscape, without specific information relating these impacts to changes in flows or levels. Other articles make comparisons between regulated and non-regulated rivers, and a limited number propose assessment methodologies. Some papers describe physical characteristics and ecological aspects of shore zone habitats, while others provide conceptual frameworks for describing impacts. In general, the studies explore trends in alterations of freshwater ecosystems, the ecological consequences of biophysical alterations, and the need for an ecosystem approach. A few discuss the major scientific challenges and opportunities involved in effectively addressing the changes.

While some papers are theoretical and relevant, they offer few practical approaches for evaluating cumulative impacts of changes in levels and flows, though they may be useful as guides to establishing monitoring protocols and agendas for scientific research.

What is striking at first is the diversity of key ecological end points used in the various publications: shoreline and near-shore vegetation, inland or riverine/lacustrine wetland vegetation, macrophytes and submerged vegetation, aquatic insects, plankton, benthos and various species of fishes. The end points are species-specific, and practically any kind of living organism can be found in these publications. This concept not only has a very strong social value representation and perspective, but is often site-specific, making it difficult to find an integrative concept that can be applied to management objectives (Rogers & Biggs, 1999).

The words and concepts of measurements, indicators and thresholds are often used interchangeably. Sometimes, even the concept of a threshold becomes more of a descriptive value than something that can be used in a cumulative impact evaluation. Lack of precision in the use of terminology is common; for example, some authors recognize a distinction between "effects" and "impacts." This distinction reflects an intentional separation between scientific “assessment” of facts (effects) and the “evaluation” of the relative importance of these effects by the analyst or the public (impacts). While the analytical component or the scientific part of an analysis is often termed “assessment”, the term “evaluation” applies to the significance or importance of an impact and is often value-laden.

The following sections describe our findings by the four categories described above.

5.1.1 Physical and Chemical Habitat Effects

Studies of the impacts of global climate change in the Great Lakes have great relevance to the assessment of potential impacts of large-scale withdrawals that might impact the water levels in the lakes themselves. Depending on the model that is used, global climate change models predict a potential drop in average water levels in the Great Lakes of from 1.5 to 8 feet. This change in the hydrology of the Great Lakes basin will, of course, have a concentrating effect on all materials (nutrients, toxic chemicals, salinity, plankton, etc.) being carried by the water bodies. Studies have also produced forecasts of a systematic reduction in ice cover. But perhaps one of the major impacts of a decrease in average water levels will be it effect on the temperature regime of the lakes. We expect to see a deepening of the location of the thermocline and a lengthening of the stratified period in the lakes. Although the center of the thermocline will be deeper on average, the temperature gradient through the metalimnion will likely be steeper. A deeper thermocline with a steeper metalimnion gradient will exacerbate the hypolimnetic oxygen depletion problem in the lakes, a problem that manifests itself most evidently in the central basin of Lake Erie. This problem will probably be exacerbated by what will likely be an increased flux of oxygen-demanding material to the hypolimnion from temperature-induced increases in phytoplankton production in the epilimnion of the system. Another significant effect of this change in the temperature regime of the lakes is its potentially significant impact on the movement, feeding and spawning habits of fish in the lakes. This of course can have widespread impacts on the reproductive success and resulting population dynamics of fish, a significant ecological endpoint in the Great Lakes.

Many of the other studies in this category focused on identifying the effects of flow and geometry changes in river and lake physical/chemical habitats in the watersheds that drain into the Great Lakes. A great many studies dealing with stream habitats identified flow reduction effects on the area and quality of benthic habitats. One of the main observations was that minimum flow rates are required to prevent excess sedimentation in stream reaches that are providing quality fish spawning habitat. Another observation of alterations in flow and resulting water levels in inland lakes and river-impoundments (especially those impoundments in the St. Lawrence River) is that it affects light penetration, thereby causing a change in the littoral area available for macrophyte growth, which in turn causes a shift in the distribution of primary production between open-water, phytoplankton and nearshore macrophytes.

5.1.2 Population/Community Effects

The population/community effects studies could be divided into those that focused on impacts on flora versus those that focused on fauna. Studies on the impacts of flow water level changes on flora were generally restricted to nearshore areas, rivers, and impoundments. For example, in the St. Lawrence River phytoplankton biomass decreased in response to flow reduction but species diversity increased. With regard to macrophytes, it was found in a number of studies that unregulated water levels led to more diverse plant communities, while communities in regulated lakes or impoundments were less diverse.

Studies of flow effects on fauna included both aquatic fauna (fish and benthic invertebrates) and terrestrial species (muskrats and turtles). Studies were found that could connect flow or water levels changes to some impacts on fish, benthos, muskrats and turtles. In general, these impacts were very subtle and not connected directly with the flow/level change but rather indirectly through various pathways. However, there were some direct mortality or spawning effects on fish that resulted in capture of fish larvae and juveniles in water intake systems and impeding of fish migration by dams in river systems. For example, Manny (1984) estimated that in 1979 1.2 billion fish larvae and 98 million juvenile and adult fish were drawn into the water intakes of 90 power plants on the shores of the Great Lakes.

5.1.3 Ecosystem Effects

With regard to ecosystem effects, the bulk of available literature relative to effects of flow/level changes was directed at wetland and stream ecosystems. There is a very good review of recent literature on North American freshwater wetlands that was compiled by Adamus, et al. (2001). This work agrees with the bulk of the literature that extols the virtues of the many important functions that wetlands ecosystems provide, including: groundwater recharge and discharge, flood storage, shoreline anchoring and dissipation of erosive forces, sediment trapping, nutrient retention and removal, food chain support through primary and secondary production, habitat and refuge for fish and wildlife, and active and passive recreation (Adamus and Stockwell, 1983). While there are a great many factors that affect wetland function, it is clear that fluctuating water levels, as exhibited in the Great Lakes under unregulated conditions, are good for wetland diversity and productivity that support their many valuable functions.

There have been an enormous number of studies on stream ecology that are relevant to our topic. And virtually every study recognizes the importance of flow (or velocity) and stream depth on the structure and function of the ecosystem. Unfortunately, there have been few really systematic studies that have been able to control for the many other stressors (both natural and anthropogenic) that can confound our ability to quantitatively link a stream ecosystem response to a change in the flow regime. Of course, such factors as land use in the watershed, watershed size, and stream geomorphology are among the primary factors that lead to varied responses to flow alterations. Because of these and other complexities of stream ecosystems, there has been a movement in the direction of using data-based adaptive management approaches such as the Instream Flow Incremental Methodology (IFIM) (Bovee, et al. 1998) and the Index of Biotic Integrity (IBI) (Karr, 1991). While the application of these methods has great value, we are far from developing a process-oriented knowledge base that allows for development of a generic, predictive framework to aid in decision-making.

5.1.4 Synoptic Modeling Studies

There have been a great many conceptual and mathematical models developed to relate receiving water and habitat quality to land use/cover in the watershed. However, in general these modeling exercises have used a baseline hydrology/hydraulics regime to examine how changes in land use or pollutant loadings impact the system. While many of them have the capability to examine how changes in hydrology may impact the system, these applications remain largely undeveloped.

There are a number of other models that predict changes in riparian vegetation as a function of drying and inundation cycles of stream shorelines (Auble et al. 1994, for example). These methods generally indicate, similarly to wetland studies on water levels, that it is not the mean annual stream flow that causes the impact, but the variability in flow and, in particular, the minimum and maximum flows.

A model development and field testing study that was directly aimed at quantifying the effects of stream flow was the study conducted by Baker and Coon (1995a, 1995b). They diverted about 50% of the summer stream flow around a 0.7 km reach of Hunt Creek, Michigan and compared the observed response of benthic macroinvertebrates and Brook Trout to predictions of their model (PHABSIM – Physical Habitat Simulation System). They found no change in the total density of benthic macroinvertebrates; however, they found significant reductions in riffle dwelling taxa (*e.g.,* Heptageniidae). With regard to Brook Trout, the model and the experiment suggested that measurable negative impacts are not seen until a greater flow reduction than what was implemented.

5.2 SUMMARY AND RECOMMENDATIONS

While there have been a great many studies that are relevant to assessment of ecological impacts of water withdrawals/diversions, most of these studies have been site-specific and descriptive in nature. Often they test a hypothesis that there is or is not a significant response of the system, but do not collect sufficient information for quantitative analysis of the deterministic, cause-effect relationships that underpin the empirical observations. It is really only with this critical process understanding that we can generalize the findings, through synthesis and model development, to the various types of ecosystems that exist in the Great Lakes Basin. A quote from Hardy (1998) in regard to stream habitat modeling is especially relevant to this point; he says that the future of habitat modeling "remains an abstraction, in that integration of all the pieces has yet to be accomplished, field validation remains unproven, availability of an integrated analysis framework (*i.e.,* computer software system) is not yet available, and a clear framework for selection and application of specific tools has not been developed."

Meyer *et al.* (1999) reaches a similar conclusion. He points out that: "We are limited by availability of both data and models. More extensive data sets and better models are needed linking hydrologic regime with ecosystem processes (productivity, nutrient dynamics, food web interactions), with ecological interactions (predation, species invasion), and with water quality." In view of these observations, we strongly recommend that future funding for research and development in this area be directed at "data mining" for both qualitative and quantitative stress-response relationships in this subject area. There should also be a concerted effort to **synthesize** and **model** the quantitative relationships between water withdrawals/diversions in various types of Great Lakes ecosystems (large lakes, inland lakes, streams and rivers, groundwaters) and potential ecological impacts of those water uses.

This synthesis and modeling effort is essential if we are to truly deal with the assessment and management of cumulative impacts from multiple withdrawals within a given watershed and the cumulative impacts of multiple watersheds on one of the Great Lakes or the St. Lawrence River. Another technical issue that demands an integrative approach is the confounding effects of multiple stressors acting in concert to produce a series of ecological responses; these confounding conditions make it difficult to isolate the hydrological → ecological cause-effect relationships.

Also, there are the issues related to time and space scales in making cause-effect assessments. Often, the time and space scales of the hydrologic/hydraulic stressor are very different than those for the ecological manifestation of those stressors. We have already seen that changes in flows or levels can be classified in three categories: 1) changes in mean values – annual or seasonal; 2) changes in frequency and amplitude of extremes – floods and droughts; and 3) changes in seasonal timing of levels or flows. Each of these categories of stressor may have its own time and space scale for a given system, and each may elicit a different ecological response with a different time lag (many years in some cases) and spatial extent. Any field or experimental characterization of cause-effect relationships should be done in the context of both stressor and response endpoint time and space scales.

Given the state of our understanding and the state of our data base on this issue, it makes sense to consider adopting an adaptive management approach in making and following up on water withdrawal decisions. Several authors, including Persat (1991) and Walters (1997), have pointed to the above multi-scale issues and data/understanding limitations as arguments for using an adaptive management approach.

Some additional specific recommendations follow:

- Large amounts of basic field data and expertise in hydroecological and hydraulic modeling will be required in order for the majority of present-day habitat simulation methodologies to be applied to the Great Lakes-St. Lawrence system. The basic field data requirements are similar for the majority of present-day habitat simulation methodologies. Typically, the channel morphology and hydraulics of each river site are described at one or more discharges using data from a number of cross-sections, which together represent all the types of in-channel conditions and microhabitats found within the study site, and thus the relevant section of the river. Hydraulic variables include depth, velocity, substratum, cover, benthic shear stress and other near-bed indices. Similar microhabitat point data are required to describe the habitat requirements of the biota for use as input to the habitat simulation programs. The hydraulic simulation programs require both fundamental hydraulic information and program-specific parameters. Average daily hydrological data over the whole period of record are required for time series analyses.

- In certain areas methodologies are virtually absent, such as for addressing groundwater in terms of links with surface flows in the river channel and conditions in the riparian zone, wetlands and floodplain. Also, specialized knowledge of the flow-related ecology of the biota under investigation will have to be developed.

- The most difficult issue (and the one that will require the most scientific research) relates to linking changes in habitat to effects and impacts on the ecological end points. Once a site-specific (and social value-laden) ecological end point has been agreed upon, the effects due to changes in levels and flows must be separated from effects due to other stressing agents, if any. Then, the sensitivity of ecological end points to changes in hydrological or hydraulic variables has to be resolved, as it is often the most critical link in the chain of cumulative effects. A number of authors point to the non-linear nature of the relationships linking various stressors to ecological effects, and they highlight the practical and theoretical difficulties in defining adequate ecological responses.

- All pertinent data and knowledge on the subject should be acquired, especially as it relates to species-habitat linkages and the development of mathematical models. This approach could generally follow the framework proposed for the Great Lakes Basin by Madsen & Wright (1999) and consist essentially of the following steps:
  - Ensure that a complete description of shoreline habitat types in the Great Lakes St.-Lawrence River basin is available. It appears that these shoreline types have already been encoded for the Great Lakes; one would have to ensure that similar information is available for all stretches on the St. Lawrence River, with adequate vertical and horizontal resolutions;
  - Evaluate the potential ecological impacts of changes in levels and flows on those shorelines;
  - Evaluate the effects of habitat changes that may affect the various biotic communities (plants, invertebrates, fishes and other vertebrates) in the Great Lakes-St. Lawrence River Basin, with special attention to the ecological processes essential for life (*i.e.*, reproduction, survival, growth and habitat);
  - Develop appropriate habitat simulation models for all reaches of interest; and
  - Update and cross-calibrate useful methods as soon as possible and develop assessments for specific applications that include identified ecological end points and explicit acknowledgement of uncertainties.
- An in-depth review of the World Commission on Dams report, *Definition & Implementation of Instream Flows*, should be carried out by experts in the field of habitat assessment, with the objective of possibly implementing of some of the methodologies in the Great Lakes St. Lawrence River Basin.

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APPENDIX 1
EXECUTIVE SUMMARY, CONCLUSIONS AND POLICY RECOMMENDATIONS OF THE WCD'S THEMATIC REVIEW II.1: *DAMS, ECOSYTEM FUNCTIONS AND ENVIRONMENTAL RESTORATION*

Executive Summary, Conclusions and Policy Recommendations of the World's Commission on Dams Thematic Review II.1: Dams, ecosystem functions and environmental restoration, (Berkamp *et al.*, 2000). Available on line in PDF format from http://www.damsreport.org/docs/kbase/thematic/tr21main.pdf. (2,041k)

Introduction. The impact of dams upon natural ecosystems and biodiversity has been one of the principal concerns raised by large dams. Over the course of the past 10 years in particular, considerable investments have been made in the development of measures to alleviate these impacts. Yet today widespread concern remains that despite improvements in dam planning, design, construction and operation, they continue to result in significant negative impacts to a wide range of natural ecosystems and to the people that depend upon them for their livelihood. WCD Thematic Reviews I.1, Social Impacts of Large Dams Equity and Distributional Issues; I.2, Dams, Indigenous People and Vulnerable Ethnic Minorities; and I.3, Displacement, Resettlement, Rehabilitation, Reparation and Development; examine this complex set of issues. They do so by first reviewing the importance of natural river basin ecosystems and examining the impact of dams on these ecosystems. They then examine the current status of approaches being taken to address these impacts through the continuum of "avoidance-mitigation-compensation-restoration." Based upon this analysis, the reports conclude with an assessment of the areas of convergence and divergence on these issues within the dams debate and provide a set of recommendations to the Commission.

River Basin Ecosystems and Biodiversity. Each river basin contains many natural ecosystems that include not only the aquatic habitats associated with water in the river channel, but all of the elements of the river catchment that contribute water, nutrients and other inputs to the river. These ecosystems include: the headwaters and the catchment landscapes; the channel from the headwaters to the sea; riparian areas; associated groundwater in the channel/banks and floodplains; wetlands; the estuary and any near shore environment that is dependent on freshwater inputs.

These ecosystems perform functions such as flood control and storm protection, yield products such as wildlife, fisheries and forest resources, and are of aesthetic and cultural importance to many millions of people. The total global value of ecosystem goods and services is estimated at $33 trillion (U.S.) per year, of which roughly 25 percent relates directly to freshwater ecosystems. With widespread and still-growing recognition of these ecosystem values, **river basin development** needs to determine how much water is required for the maintenance of ecosystems to provide environmental goods and services, and how much water should be used to support agriculture, industry and domestic services.

Ecosystem Impacts of Large Dams. The current state of knowledge indicates that the impacts of dams on ecosystems are profound, complex, varied, multiple and mostly negative. By storing or diverting water dams alter the natural distribution and timing of stream flows. This in turn changes sediment and nutrient regimes and alters water temperature and chemistry, with consequent ecological and economic impacts. Reduction in downstream annual flooding in particular affects the natural productivity of floodplains and deltas.

These ecosystem impacts mean that dams have a significant impact on freshwater biodiversity, which is already under special threat. Global estimates of endangered freshwater fish reach 30 percent of the known species. In North America, detailed studies indicate that dam construction is one of the major causes of freshwater species extinction. Dramatic reductions in bird species are also known, especially in downstream floodplain and delta areas. Some reservoirs also provide habitat for birds and other fauna but this often does not outweigh the loss of habitat downstream.

Multiple dams on a river significantly aggravate the impact on ecosystems. Sediment entrapment can reach 99% if a cascade of dams is developed. Fish migration is affected by even a single dam, and multiple dams worsen this situation dramatically. In the Northern hemisphere dams affect 77% of the largest rivers, and on many rivers fully natural reaches are restricted to headwaters. The global impacts of dams on the global water cycle are increasingly recognized.

The review highlights the complexity of the processes that occur when a dam impacts an ecosystem. It is therefore extremely difficult and rarely possible to predict in precise detail the magnitude and nature of impacts arising from the construction of a dam or a series of dams. The precise impact of any single dam is unique and depends not only upon the dam’s structure and operation, but also upon local hydrology, fluvial processes, sediment supplies, geomorphic constraints, climate, and the key attributes of the local biota. There is therefore no normative or standard approach to address ecosystem impacts, which have to be looked at on a case-by-case basis. In addition the acceptability of ecosystem changes will vary with the nature of human societies, cultures, and expectations.

The Economic and Social Implications of Ecosystem Impacts. Because natural ecosystems perfrom functions and yield a range of services that are of substantial economic and cultural value to society, the ecosystem changes that result from dam creation lead in turn to substantial economic and social impacts. Entire communities depend on the functions provided by freshwater wetlands, yet it is still difficult to translate the value into monetary terms. As a result the value of ecosystem functions is not properly accounted for in conventional market economics and the value of these functions and the cost of their loss, is excluded from the economic decision-making process.

This externalization of costs is a major factor leading to the loss of natural ecosystems. By reducing or eliminating access to resources flooded by the reservoir, through degradation and loss of agricultural and grazing resources on downstream floodplains, and through loss of riverine and coastal fisheries dependent upon the river flood, many dams have very high external costs. Policy-makers need to identify the value of these losses and implement financial and institutional mechanisms to assimilate these costs into the accounting structure.

However, the review stresses that, even when these steps are taken, the valuation of ecosystems and consideration of development options are not straightforward accounting exercises. It needs to be recognized that not all ecosystem values can be expressed in economic terms. Ethical and societal considerations also need to be included. The monetary value serves as an input to multicriteria decision making and raises awareness of costs that are currently hidden and negated in the accounting exercise.

Responding to the Ecosystem Impacts of Dams (EIA). There are four principal categories of measures that may be incorporated into dam design or operating regime in order to respond to the environmental impacts identified through an EIA. These are: i) measures that avoid anticipated adverse effects of a dam; ii) mitigation measures that are incorporated into a new or existing dam design or operating regime in order to eliminate, offset or reduce ecosystem impacts to acceptable levels; iii) measures that compensate for existing or anticipated adverse effects that cannot be avoided or mitigated; and iv) decommissioning the dam and restoring the riverine ecosystem.

Within this framework of avoidance, mitigation, compensation and restoration, there are wide ranges of specific measures that can be taken and are appropriate to the specific circumstances of each dam. The thematic review evaluates experiences with each approach and reveals that the most widely used approach – mitigation – is problematic. It concludes that there are always residual impacts that cannot be mitigated, simply by the nature of the dam's impact on ecosystems. Whether these impacts are significant varies from case to case.

While there have been good mitigation experiences, this success is nevertheless contingent upon stringent conditions of:

- a good information base and competent professional staff available to formulate complex choices for decision makers;
- an adequate legal framework and compliance mechanisms;
- a cooperative process with the design team and stakeholders;
- monitoring feedback and evaluating mitigation effectiveness; and
- adequate financial and institutional resources.

If any one of these conditions is absent, the ecosystem values are likely to be lost. In practice the extent to which these conditions are met varies enormously from country to country and dam to dam. The review therefore concludes that mitigation, though often possible in principle, has many uncertainties attached to it in field situations and therefore is not a credible option in all cases and all circumstances at present. In addition the weaknesses of the EIA process (cf Thematic Review V.2) reduce the possibilities for positive outcomes for many projects. This would tend to encourage a strategy of avoidance and minimization rather than one of mitigation if the aim is to maintain biodiversity and ecosystem functions and services for the foreseeable future. Therefore, alternative tools for maintaining ecosystem health need to be pursued.

The review argues that improving scientific predictive capacity and institutional and human capacity will take several decades. In the short term therefore, focused attention needs to be given to the development and application of effective tools that can allow environmentally sound development of river water resources and the management of dams within this context. Three such tools are described: 1) indicators for hydroproject selection; 2) indicators of ecological integrity; and 3) environmental flow requirements.

Trends in the International Debate/Approach to Dams. The thematic review examines current trends in the international debate over dams and their environmental impacts. It concludes that considerable steps have been taken to address the environmental concerns and that there are many areas of broad agreement between those who are generally supportive of building dams and those who are generally philosophically opposed to large dams. However, differences remain. At the most general level these differences concentrate on the value systems adhered to by the different groups involved, especially the value to be attached to the intrinsic value of nature. This highlights the importance of ensuring that project approval be based on multicriteria decision making, not just on economic cost-benefits analyses or a purely ecocentric view of the world. Techniques also need to be improved to offer better methods of economic valuation that are acceptable to both proponents and opponents of dams. Clearer guidelines on how costs and benefits can be distributed among those people affected by a dam may require the establishment of appropriate institutions to promote equitable water use, especially between upstream and downstream ecosystems and livelihoods.

The review argues that success in bridging the outlined differences is most likely to be made by strengthening options assessments and evaluating the true cost and benefits of projects for the short and medium term. Discrepancies are likely to remain on value systems and development paradigms for decades to come. Therefore, efforts to deal with the environmental impacts of dams should concentrate on developing legitimate and accepted processes for dam planning, design and management within the river basin context. Second, much effort could be invested in improving the economic tools for analysis and improving incentives for better dam design and operation.

Policy Recommendations. The review concludes by providing ten policy recommendations to the WCD.

Conclusions and Policy Recommendations for WCD

Conclusions

This review has highlighted the value of natural ecosystems to human society, giving particular attention to the specific goods and services provided by those ecosystems that are most impacted by dams. While some of these ecosystem values are non-monetary in nature, such as the aesthetic, cultural and heritage value of specific habitats and landscapes, their direct and indirect economic value is highly significant to local, national and regional economies. In most cases one or more sectors of society depend upon these values (***e.g.***, fisheries, grazing) while in some the total value of the benefits of natural ecosystems can exceed the value of the benefits derived from dams and associated investments in agriculture (Barbier 1996). In the past, the failure to take into account the cost of dam consequences has resulted in the benefits of many dams being overstated. The importance of these natural ecosystems is today widely recognized by national governments and the importance of efforts to preserve these ecosystems and harness their values sustainably is enshrined in a series of international agreements, notably the Convention on Biological Diversity and the Ramsar Convention on Wetlands of International Importance. See section 5.3.6.

The review has illustrated that dams have a wide range of major impacts upon natural ecosystems, that most of these are negative, many are irreversible, and they are manifest in economic and social costs. Perhaps surprisingly, the review has noted that there is widespread, but not complete, agreement as to the reality and importance of these impacts and their costs. The review has also recognized the growing understanding of the threats to the world's biodiversity and the particularly acute threats to those species that are dependent upon freshwater. By altering the quantity and quality of water available to natural riverine ecosystems, dams add to these already significant threats.

In response to the identified impacts of dams on natural ecosystems and species, four principal approaches – avoidance, mitigation, compensation and restoration – have been developed and are now promoted as solutions to these impacts. However, a review of these approaches illustrates that while there is good evidence that each of the individual measures can be successful in specific cases, there are problems with them all. The most widely used approach, mitigation, is particularly problematic. As with any kind of human development, whatever amelioration measures are utilized, dam building will always result in some environmental and ecosystem impacts. While there is experience of good mitigation, this success is nevertheless contingent upon stringent conditions of:

- a good information base and competent professional staff able to formulate complex choices for decision-makers;
- an adequate legal framework and compliance mechanisms;
- a cooperative process with the design team and stakeholders;
- monitoring feedback and evaluating mitigation effectiveness; and
- adequate financial and institutional resources.

If any one of these conditions is absent, then the ecosystem values will be lost. In practice the extent to which these conditions are met varies enormously from country to country and dam to dam. The review therefore concludes that mitigation, though often possible in principle, will rarely be successfully implemented under present political, economic and institutional conditions. Alternative approaches to maintaining ecosystem health therefore need to be pursued.

Recommendations

In light of the above, ten recommendations are submitted to the WCD.

1. **Recognize the important role of natural ecosystems in contributing to sustainable development**. If river basin development is to be truly sustainable, the wide range of goods and services that are provided to human society by natural ecosystems need to be recognized. All major development investments, including dam construction, should seek to conserve and enhance these ecosystems and their value to society. Actions that diminish these values should be minimized.
2. **Recognize the importance of biodiversity and promote its conservation.** Biodiversity is recognized internationally as a uniquely important, but endangered, feature of our planet. In the face of unprecedented rates of species extinction in recent decades, every effort needs to be made to minimize threats to biodiversity. In the past, dams have contributed significantly to endangerment and extinction of species. In the future, no dam should proceed if it is shown to have a high probability of having a significantly detrimental effect on species diversity.
3. **Dams must be considered within a framework of river basin management plans and international/national/regional policies**. They must be evaluated alongside other options for water supply, irrigation and electricity production. In any situation, the environmental costs and benefits of the full "life-cycle" of the various options must be compared. This must include the costs of decommissioning dams that have come to the end of their useful lives.
4. **Recognize and manage for uncertainty**. There is enormous variation among river basins, rivers, ecosystems, dams and associated projects. This diversity – together with the seriously limited quantity and quality of information on the functions of specific natural ecosystems and on species diversity and resilience in different habitats affected by dams – contributes to a very limited capacity to predict the precise impact of dams on natural ecosystems and biodiversity. Such a high degree of uncertainty and limited predictive capacity argue forcefully for adoption of a precautionary approach to dam development. Wherever possible dams and their impacts should be avoided. Where avoidance is not possible, the capability to manage the dam in a flexible manner and adapt to improved understanding of ecosystem requirements should be incorporated into dam design. This precautionary approach should be recognized as a central feature of planning, design and management of dams, especially as many are probably irreversible.
5. **Ensure effective multi-sector participation in dam planning, design and management**. In order to help recognize and reduce uncertainty, it is essential that all dam projects and their impacts are subject to intensive analysis during planning and design. This needs to be pursued through open processes that

ensure that there is full sharing of available information and recognition of areas where that information is not sufficient to predict the impact of dams or design successful mitigation measures with any confidence. This participatory process also needs to identify who should assume responsibility for the ecosystem impacts of dams and therefore take on their true costs, ensure their mitigation or compensation (as appropriate) and restore, where possible, the river at the end of a project's life.

6. **Maximize adaptive capacity**. When the participatory design processes recommended above lead to a decision to construct a dam as the best option for sustainable development in the river basin, design features should include the capacity to adjust operation to adapt to the lessons of experience, improved knowledge or changing ecological requirements. Such design features include, in particular, sluices or gated spillways that will allow environmental flow releases of appropriate water quality. This approach needs to be accompanied by a program of independent environmental monitoring that will allow continuous tracking and regular assessment of the impact of the dam and its operation upon downstream ecosystems. This information needs to be fed back into to an adaptive decision making process. Mechanisms must be established to ensure compliance with recommendations for dam operation from monitoring bodies.
7. **Promote the incorporation of environmental management features into dam design**. In addition to features that provide for adaptive management as a permanent element of dam operations, dams should also be designed to include all appropriate environmental features for improving water quality. These include variable-level off-takes, shallow plunge pools, fish passes, regulating weirs *etc.*
8. **Promote the development of national legislative frameworks**. Ultimately, the measures recommended here, together with recognition of the need to fulfil international commitments in regard to ecosystems and biodiversity, need to be enacted in national legislation governing dams and river basin development. This should be promoted along with measures to strengthen enforcement, such as the use of environmental bonds, direct compensation revenue sharing (hydropower), or environmental trust funds as guarantees of compliance.
9. **Promote application of tools to foster ecosystem health**.

(I) Environmental Flow Releases. EFRs are used in 25 countries and serve as the single most important tool for managing the ecosystem and associated impacts of dams. EFRs should be a requirement for all future dams. Blanket minimum flow requirements, such as "10 percent minimum flow" do not address the needs of riverine ecosystems. Taking account of the dynamic nature of rivers requires optimum flows, often including periodic managed floods. An intensive investment should be made in further developing the knowledge-base required to improve this tool, adapting it to local needs and extending it to include explicit support for social downstream needs.

(II) Ecosystem Health Indicators. In order to engage in a proactive discussion on the requirements for maintaining (or restoring) healthy ecosystems, greater investment should be made in developing indicators of ecosystem health. These can be used to set targets for mitigation, compensation and restoration of ecosystems impacted by dams.

(III)Site Selection Indicators. The World Bank has identified six key indicators of site selection that help minimize ecosystem impacts: reservoir surface area, water retention time in the reservoir, biomass flooded, length of river impounded, number of inflows to mainstream from undammed downriver tributaries and access roads through sensitive areas. The use of these indicators should be promoted and refined on the basis of experience.

10. **The role of every dam should be periodically reviewed and its value to society re-evaluated.** Consideration should be given to decommissioning, retrofitting with modern technologies and altering dam operations so that, where feasible, dams are improved to comply with up-to-date standards of environmental care.

APPENDIX 2
LIST OF CONTRIBUTING PAPERS TO THE WCD'S THEMATIC REVIEWS
II.1 *DAMS, ECOSYSTEM FUNCTIONS AND ENVIRONMENTAL RESTORATION*

List of contributing papers to the thematic review II.1: Dams, Ecosystem Functions and Environmental Restoration (Berkamp et al, 2000).

All of the following documents can be downloaded in PDF from the following site: http://www.dams.org/thematic/tr21.htm.

1. Managed Flood Releases from Reservoirs: Issues and Guidance, Mike Acreman (577k).
2. Capacity and Information Base Requirements for Effective Management of Fish Biodiversity, Fish Stocks and Fisheries Threatened or Affected by Dams During the Project Cycle, Garry Bernacsek, (203k).
3. International Mechanisms for Avoiding, Mitigating and Compensating the Impacts of Large Dams on Aquatic and Related Ecosystems and Species, John R. Bizere (363k).
4. Large Dams and Freshwater Fish Biodiversity, John Craig (173k).
5. Biodiversity Impacts of Large Dams: Waterbirds, Nick Davidson and Simon Delany, (82k).
6. Fundamental Legal and Ethical Principles in Adjudicating the Merits of Development Projects, Charles DiLeva (118k).
7. The Influence of Dams on River Fisheries, Donald Jackson and Gerd Marmulla (159k).
8. Definition and Implementation of Instream Inflows, Jackie King, Rebecca Tharme, and Cate Brown (547k).
9. Information Needs for Appraisal and Monitoring of Ecosystem Impacts, Jackie King and Cate Brown (70k).
10. Dams and Fish Migration, Michel Larinier (160k).
11. Biodiversity Impacts of Large Dams, Don McAllister, John Craig, Nick Davidson, Diane Murray and Mary Seddon (1,123k).
12. Ecosystem Impacts of Large Dams, M.P. McCartney, C. Sullivan and M.C. Acreman (399k).
13. A Review of Guidance and Criteria for Managing Reservoir and Associated Riverine Environments to Benefit Fish and Fisheries, Steve Miranda (276k).
14. Report on Hydrological and Geochemical Processes in Large Scale River Basins, 15-19 November 1999, Manaus, Brazil, Leonard Sklar (113k).
15. Molluscan Biodiversity and the Impact of Large Dams, Mary Seddon (227k).