The Great Lakes Commission

# A Literature Review on Cumulative Ecological Impacts Of Water Use and Changes in Levels and Flows

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## Executive summary

Searches of various databases were undertaken for literature that assesses cumulative ecological impacts of water use and levels and flows. Particular attention was paid to possible literature that assesses ecological thresholds with respect to water supply and presents indicators (and their processes, functions and time scales) that have been used to assess the cumulative ecological impacts of water use. The literature related to water supply and use that will impact the ecological system was also covered. This approach probably covered most of the scientific published literature on this subject, but it should be realised that the "grey literature", i.e. the numerous government (provincial, state, federal) as well as private sector, were not covered in this search.

A list of possible addition for this review, submitted by anonymous reviewers, with the comments on a preliminary draft of this report was also examined and some additional articles were included for further analysis. A brief examination was further conducted of the World Commission on Dams 1999 report; particular attention was paid to the thematic review on environmental issues "*Dams, Ecosystem Functions and Environmental Restoration*" as well as some of the thematic reports.

This search produced a list of some 200 references that appears in the references section at the end of the report. This list, with all pertinent information, including extended abstracts when available, is indexed in Procite, a bibliographic software database program, by ISI ResearchSoft. This approach made it easy to conduct more detailed analyses and searches. After close examination of all available abstracts and a check for relevance of number of full articles, this list was further trimmed down for the detailed review and analysis to some 120 articles, which are summarized in section 4. These 120 references have been regrouped in five broad categories to help in narrowing down the possible areas of interest. While all classifications have strength and weaknesses we feel that the following five categories might be helpful: i) modelling, ii) climate change, iii) inventories, iv) ecological river integrity, v) instream uses.

Changing water levels or flows are just one stressor on wetland, near shore and instream communities. Degradation comes in many forms and degrees of severity and degradation is far more difficult to quantify than loss of area. For instance number of documented examples of typical forms of degradation include: i) fragmentation, partial filling and dyking of habitats, ii) toxic substances in water and sediments, iii) invasion by exotic species, iv) pollution and nutrient enrichment and changes in physical and chemical characteristics of the local environment, v) decrease in average area. In that context it becomes very difficult to make a realistic cumulative effect assessment of just changes in levels or flows.

The biological effects of water level fluctuations in both lake and river are greatest in shallow water where even small changes in water level can result in conversion of a standing water environment to an environment in which sediments are exposed to the air, or vice versa. 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 some changes in some parameters that control river behaviour. They are the results of chain reactions that take place during relatively rare flood events, and the impact of an individual event makes it difficult to relate to the cumulative sum. The sequence of flows and especially their magnitude, frequency and duration play an important role in geomorphological processes, of erosion, sedimentation and river channel evolution.

The knowledge of the relations between the species and their preferred habitat poses a second level of major difficulties: space and time. The threshold sensitivity of any species is closely linked to the more critical phases of their life cycles. Further more as number of the impacts will take number of years to be felt, the assessment of the impacts should cover a long enough period of time. When applied to fluvial ecosystems, the analysis of the condition of the ecosystem before the change, and the forecast of future condition after the change raise formidable problems.

Useful and specific references that directly assess cumulative ecological impacts in the context of the terms of reference of this study are practically non-existent. The problem of ecological indicators that could be used to assess the cumulative ecological impacts of water use and changes in levels and flows, and their possible applications to the Great Lakes-St. Lawrence system, have never been specifically addressed.

While the search produced a number of possibly useful references it is very difficult for the author to pass a judgement on the relative value or merit of any specific articles as they lie in the most part behind the area of expertise. Some of the most promising methods or frameworks to assess ecological effects and impacts are based on habitat simulation methodologies (instream and others) and holistic methodologies (King *et al.*, 2000; Madsen & Wright, 1999). However as mentioned in some publications, knowledge just does not exist presently to move beyond the description of effects.

Linking specific changes in levels and flows to specific changes in biota will require much better data and models. Many current habitat simulation approaches are still in fairly early stages of development, and require further research, as well as rigorous testing tested for accuracy, cost and practicality and validation. In certain areas like for instance, methodologies addressing ground water in terms of links with surface flows in the river channel, as well as with conditions in the riparian zone, wetlands and floodplain are virtually absent.

Large amounts of basic field data will be required for the application of the majority of present-day habitat simulation methodologies and expertise in hydroecological and hydraulic modelling, as well as specialist flow-related ecological knowledge on the biota under investigation will have to be developed

Particular efforts should made in defining the critical and significant time frame of the site specific problems relating changes in habitats to changes in levels and flows. Are they linked to changes in average or seasonal mean hydrologic values or in the frequencies and magnitudes of extremes (high and low flows)?

An assumption common to the majority of habitat simulation methodologies is that modelling biological response to changes in physical microhabitat, as described by various hydraulic variables is an adequate level at which to make assessments about the environmental flow requirements of instream biota. Such an assumption is likely to be highly limited or even inappropriate.

Overall, the review shows that despite the relatively recent emergence of habitat simulation methodologies a large amount of work remains to be done. The following is recommended as the next possible steps:

An in depth review of the World Commission on Dams Thematic Report on *Definition & Implementation of Instream Flows* should be carried out by experts in the field of habitat assessment with an objective of possible implementation of some of the methodologies in the Great Lakes S. Lawrence River Basin.

The next steps should consist in acquiring all pertinent data and knowledge especially on species-habitat linkages and development of mathematical models. This approach could follow the framework described by Madsen & Wright (1999) and consist essentially in the following items:

- Ensure that we have a complete description of shoreline habitat types in the Great Lakes St. Lawrence River Basin. Apparently these shoreline types have already been encoded for the Great Lakes and one would have to ensure that similar information is also 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 these shorelines;

- Evaluate the effects of changes of habitats as they may affect the various biotic communities (plants, invertebrates, fishes and other vertebrates) in the Great Lakes St. Lawrence River Basin and pay special attention to the ecological processes essential for life i.e. reproduction, survival, growth and habitat;

- Develop appropriate habitats simulation models for all reaches of interest;

- It is further recommended that useful methods be updated and cross calibrated as soon as possible, that assessments be developed for some specific applications (with identified ecological end points) and that uncertainties be explicitly acknowledged.

# Contents

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## 1 - Introduction

The objective of the present study was to undertake searches of various databases including Water Resources Abstracts and the Aquatic Sciences and Fisheries Abstracts.

The search was:

- To place an emphasis on literature that assesses cumulative ecological impacts of water use and levels and flows, assesses ecological thresholds with respect to water supply and presents indicators (and their processes, functions and time scales) that have been used to assess the cumulative ecological impacts of water use.
- To review literature related to water supply and use that will impact the ecological system. For example, literature related to the effects of water supply and use on water quantity and flow, water quality, water temperature, the seasonal timing of water supply, vegetative patterns, flow velocity, and the geomorphologic characteristics of the stream/lake/shoreline.
- To review frameworks that have been established to assess the ecological sensitivity of the ecosystem to future water use and/or changes to water supply (e.g. under climate change).

The report should present a descriptive inventory and analysis of literature addressing the ecological impacts of water use and include:

- A listing of all literature reviewed and abstracts of all relevant literature, appropriately categorised.
- 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 system to future changes.
- A series of recommendations as to 1) how such findings might advance current and prospective water resource management efforts; 2) what additional research is necessary to address gaps in knowledge and practice identified through the literature search; and 3) what methodologies or approaches hold promise as a means to assess individual and cumulative impacts of changes in water levels and outflows due to water use.

## 2 - Approach

Literature searches were conducted in the following databases: Aquatic science and fisheries abstracts (1978-2000), Water Resources Abstracts (1967-2000), Water Resources World-wide (1970-2000) and Current Contents (2000-2001) for possible additions of recent year articles. The searches used the following keywords single 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 the 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 scientific published literature on this subject, but it should be realised that the "grey literature", i.e. the numerous government (provincial, state, federal) as well as private sector, were not covered in this search.

As the search produced hundreds of references, a manual review was made of all titles and abstracts to identify possible references of interest and literature pertinent and relevant to the purposes of this report; materials beyond the Great Lakes-St. Lawrence system that might have an application to that system was 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 focussed specifically on ecological assessment related to potential changes. In that context it should be realised that the author perspective of what is relevant may have biased some of the results and that the search is not complete as some important articles may have been missed.

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

This search produced a list of some 200 references, which appear in the references section at the end of this report. This list, with all pertinent information, including extended abstracts when available, is indexed in Procite, a bibliographic software database program by ISI ResearchSoft. This approach made it easy to conduct more detailed analyses and searches.

Further to the review of 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 to the original list. It was also suggested at that time that the author looks at the recent 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. Some limited time was spent examining the thematic review dealing with dams, ecosystem functions and environmental restoration and some contributing papers to this thematic review.

After close examination of all available abstracts and visiting the local university libraries at Laval University and INRS-Eau to check for relevance of some articles, this list was further trimmed down for the detailed review and analysis to some 121 articles. The following criteria were used to exclude the articles from further analyses: very short articles (1 to 2 pages) and no abstracts available, some articles in foreign languages, very general content (general references, books) that might be of interest in a more general context, examples from outside the basin that from the abstracts seemed to have little relevance. It should be reminded that for some sources the review had to be carried out only from the available abstracts when available either as a direct result of the database search or from online access to the table of contents as it was impossible to access the full texts, in the time frame available, for some references and 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. In section 3 we will examine the results of this literature search, while in section 4 we will present short abstracts of these 121 articles grouped in different sub-sections and section 5 will present a short summary of my analysis of the voluminous World Commission on Dams material that is available on line. Section 6 will present conclusions and recommendations while section 7 will list all articles referenced in this review. Finally Annexe 1 presents an *in extenso* version of the Executive Summary, Conclusions and Recommendations of the WCD's Thematic Review mentioned previously and Annex 2 lists all contributing papers to this thematic review that might be an interesting source for further examination.

## 3 - Ecological cumulative impacts

### *3.1 General framework of analysis*

Before going into the analysis of the results of the literature search it is necessary to examine the general context of cumulative impacts due to water uses and changes in levels of flows.

By defining cumulative impacts as long term effects that accumulate over many years in a particular watershed and represent the sum of past present and future activities, the nature of the cumulative impacts may be substantially different from the impacts caused by any one of the activities; determining the contribution of an individual stressor to the cumulative impact has proven to be an elusive and politically contentious goal.

One should also not forget that changing water levels or flows are just one stressor on wetlands, near shore and instream communities. Degradation comes in many forms and degrees of severity and degradation is far more difficult to quantify than loss of area (Bedford, 1999). For instance, a number of documented examples of typical forms of degradation include: i) fragmentation, partial filling and dyking of habitats, ii) toxic substances in water and sediments, iii) invasion by exotic species, iv) pollution and nutrient enrichment and changes in physical and chemical characteristics of the local environment, v) decrease in average area. In that context it becomes very difficult to make a realistic cumulative effect assessment of just changes in levels or flows.

The biological effects of water level fluctuations in both lake and river are greatest (International St. Lawrence River-Lake Ontario (ISLRLO) Plan of Study Team, 1999) in shallow water where even small changes in water level can result in conversion of a standing water environment to an environment in which sediments are exposed to the air, or vice versa. 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 some changes in some parameters that control river behaviour. They are the results of chain reactions that take place during relatively rare flood events, and the impact of an individual event makes it difficult to relate to the cumulative sum.

Changes in levels and flows can essentially classified in three categories: i) changes in mean values – annual or seasonal, ii) changes in the frequency and amplitude of extremes – floods and droughts and iii) changes in seasonal timing of levels/flows. Also the sequence of flows and especially their magnitude, frequency and duration play an important role in geomorphologic processes, of erosion, sedimentation and river channel evolution

While the assessment framework proposed by Madsen & Wright (1999) seems interesting it poses a number of relatively important application difficulties. It essentially relies on i) the links between level/flow and the geomorphology of various habitats and ii) the knowledge of the relations between the species and their preferred habitat.

The knowledge of the relations between the species and their preferred habitat 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 as many of the impacts will take a number of years to manifest, the assessment of the impacts should cover a long enough period of time. When applied to fluvial ecosystems, the analysis of the condition of the ecosystem before the change, and the forecast of future condition after the change raise formidable problems (Persat, 1991). Physically, the fluvial ecosystem stands out by its spatial and temporal components: multiple longitudinal gradients are expressed throughout the forked branched fluvial network, floods and low water levels alternate more or less regularly. These features greatly complicate the approach of the system. The study (Persat, 1991) focussed on the space and time scales difficulties required to understand the functioning of such an ecosystem and stresses the uncertain value of former case studies as comparative material for the expectation of future conditions, and thus raise the question of the reliability of forecasting.

### *3.2 Impacts, integrity and instream use*

After going over all the possible references, useful references that assess cumulative ecological impacts in the context of the terms of reference of this study are practically non-existent. The problem of ecological thresholds and indicators that could be used to assess the cumulative ecological impacts of water use, and their possible applications to the Great Lakes-St. Lawrence system, have never been addressed in the context of water uses and changes in levels and flows. However as some of them might have some interest for aspects of cumulative impact assessment, we have regrouped the 121 references in four broad categories to help in narrowing down the possible areas of interest. We realise that all classifications have strengths and weaknesses but we feel that the following categories that we have retained might be helpful: i) modelling, ii) climate change, iii) inventories, iv) ecological river integrity, v) instream uses.

*Modelling*

This category regroups sixteen articles of very diverse perspectives. The assessment frame work proposed by Madsen & Wright (1999) mentioned previously seems interesting: it essentially relies on i) the links between level/flow and the geomorphology of various habitats and ii) the knowledge of the relations between the species and their preferred habitat; however the major difficulty of application lies in a proper description of the nature of these various links. Rodier & Norton (1992) describe a framework for evaluation of scientific information on the adverse effects of physical stressors and Hart & Finelli (1999) propose a conceptual framework for investigating the multiple causal pathways by which flow influences benthic biota and focus particular attention on the local scales at which these organisms respond to flow.

Hudon (1997) proposes a conceptual model for vegetation responses to changing levels in the St. Lawrence river Marttunen (1992) proposes a system model for effects of lake regulation on European whitefish stocks Auble *et al.* (1994) present a direct gradient method to predict the vegetation change resulting from a proposed upstream dam or diversion Hill *et al.* (1998) propose a model based on richness of shoreline vegetation

Austin *et al.* (1979a, 1979b) present a mathematical simulation model describing vegetation successions Richards *et al.* (1997) used catchment's and river physical properties to predict the occurrence of specific aquatic insects. Finally Allan *et al. (*1997), Leclerc *et al.* (1994), Rousseau *et al.* (2000), Shippley *et al.* (1991), Toner & Keddy (1997) and Wiley *et al.* (1999*)* describe various types of regressions or numerical simulation models linking some hydrological characteristics of a stream with changes in habitats or ecological impacts.

It should be remembered that models that look at relationships with living organisms, and therefore at possible impacts or changes are just a very limited subset of the literature on modelling; this search did not include all types of various hydraulic or hydrologic models.

*Climate Change*

While climate change was not in itself the subject of this literature search, we have found some references that might be of interest, as climate change will affect rivers and flows thus impacting ecological integrity. Magnuson *et al.* (1997) examine the physical changes that might come from climate and affect all living organisms in streams Mortsch (1998) examines how climate change could alter the hydrology of the Great Lakes and affect wetland ecosystems. Wollmuth & Eheart (1999) and Meyer *et al.* (1999) explore several methods to control withdrawal from streams and effectiveness for maintaining critical stream flow. Bloczynski *et al.* (2000) propose a model to optimize the timing and type of protective structure under a range of management goals for wetlands that can either be optimal for fish or optimal for mammals and waterfowl, but not both.

*Inventories*

In this category we have regrouped articles dealing with descriptions of some observed and measured of physical and biological features of biota within the Great Lakes-St. Lawrence River system. Bedford (1992) present a summary of physical effects of the Great Lakes on tributaries and wetlands, Bush & Larry (1996) assessed habitat impairment of Lake Ontario Crowder *et al.* (1996) examine rate of natural and anthropogenic change of habitats in the Kingston basin (Lake Ontario).

Hudon (1997) shows a strong relationship between seasonal water levels and the percentage of emergent plant cover in Lake St. Pierre Hudon (2000) observed that discharge reduction in the St. Lawrence and the Ottawa River, induced an increase in phytoplankton taxa that generated noxious smells and odours. Hudon *et al.* (1996, 2000) looked at variation in phytoplankton biomass and maximum depth of macrophyte colonisation. Jean & Bouchard (1990, 1993, 1996) looked at the impact of small-scale variation in abiotic factors on the distribution of wetland vegetation and trees species colonising swamps in the St. Lawrence River Jean *et al.* (1993) analysed the impacts of water level fluctuations on wetlands in Lake St. Louis. Wilcox & Meeker (1991) investigated the effects of water level regulation on aquatic macrophyte communities and Morin & Leclerc (1998) looked at the evolution of the hydrology and plant biomass and wetlands in lake St. François. Bergeron *et al.* (1998) examined winter geomorphologic processes and their impacts on the migratory behaviour of the Atlantic tomcod Bellrose &

Low (1943) looked at the influence of floods and low water levels on the survival of muskrats.

*Ecological River Integrity*

A number of articles in this category describe physical characteristics and some ecological aspects of shore zone habitats and some other provide conceptual frameworks for describing impacts. They explore trends in alterations of fresh-water ecosystems, discuss the ecological consequences of biophysical alterations, the need for an ecosystem approach and identify some of the major scientific challenges and opportunities to effectively address the changes. While the articles are in some aspects theoretical and useful to explain the problem of ecological integrity they offer little practical guidance evaluating cumulative impacts. However they may be useful establishing an operational framework for impact analysis, monitoring protocols and agendas for scientific research for evaluation of cumulative impacts of changes in level or flows. In the following paragraph we present a brief summary of those article that in our opinion might be of interest, while in section 4.4 we present short abstracts of the some thirty-eight articles we have put in this category.

Karr (1991) looks at the need for operational definitions of terms like "biological integrity" and "unreasonable degradation" and for ecologically sound tools to measure divergence from societal goals that have increased interest in biological monitoring. Adamus & Stockwell (1983) present a state-of the-art review of wetland functions and Innis *et al.* (2000) summarise scientific knowledge concerning assessment methods addressing ecological integrity in wetlands and riparian zones with an emphasis on riparian areas. Naiman & Descamps (1997), Naiman et al. (2000) and Naiman & Turner (2000) explore trends in alteration of fresh water ecosystems and riparian zones and identify some of the major scientific challenges and opportunities to effectively address the changes. Rogers & Biggs (1999) propose the integration of value system end points and indicators of ecosystem integrity that could be used as a guide to establish monitoring protocols and Kleynhans (1996) proposes a qualitative procedure for the assessment of the habitat integrity status of a river in South Africa. 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.

Muhar *et al.* (2000) investigated the ecological status of Austrian rivers, placing an emphasis on evaluation criteria Bundi *et al.* (2000) present how stream assessment in Switzerland produce data for characterizing ecological conditions Cohen *et al.* (2000) explain the partitioning of a large basin in France into ecoregions to preserve the ecological integrity. Barbour *et al.* (2000) show the development of biological criteria within regulatory programs Habersack (2000) discusses the river scaling concept as a basis for ecological assessment Schmutz *et al.* (2000) propose a multilevel concept for fish based assessments of ecological integrity and Welcomme (1995) addresses the problem of integrity in rivers relative to fisheries for food. Extence *et al. (*1999) propose a method linking qualitative and semi-quantitative change in riverine benthic macroinvertebrate communities to prevailing flow regimes.

Walters (1997) examines why many case studies in adaptive management for riparian ecosystems have not produced good experimental management plans for resolving key uncertainties. Ward *et al.* (2000) propose a hierarchical approach for examining diversity patterns in floodplain rivers while Ward & Stanford (1995) examine the dynamic nature of alluvial flood plain rivers and Stanford *et al.* (1996) propose a general protocol for restoration of regulated rivers. Kondolf *et al.* (1987) describe methods for collecting relevant hydrologic data for predicting the impacts of flow reductions on riparian vegetation and Nilsson & Berggren (2000), after describing 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 of exotic species), look at future needs and directions.

Blanch *et al.* (1999) use selected water regime indices to describe the tolerances to flooding and exposure of littoral and floodplain plants of the River Murray in South Australia. Fjellhiem *et al.* (1993) describe benthic animal densities, biomass and production in a regulated west Norwegian river. Grossman *et al.* (1998) analysed the effects of environmental variation and interspecific interactions on the assemblage organization in stream fishes. Koehn (1993) examines changes to key habitat factors such as water and its condition the surrounding land which helps determine that condition conditions that the water creates within the stream and instream objects, that are responsible for the general decline in fish species. Spink *et al.* (1998) investigated a range of river floodplain sites in North America and Europe to determine what factors were determining nutrient richness and productivity.

Reid & Brooks (2000) recommend a range of physical, chemical and biological indicators for use for monitoring change in wetland health in response to environmental water allocations (EWAs) designed to redress some of the damage caused by regulation, via partial restoration of the natural hydrological regime that used to be experienced by associated floodplain wetlands. Johnson & Gage (1997) examine new perspectives in stream ecology and the refinement of tools used to quantify spatial and temporal heterogeneity. Karr & Chu (2000) examine the condition of the aquatic biota as the best means of understanding human impact. Nestler & Long (1997) present a hydrological analysis of historic stream data as the basis for cumulative impact analysis of riverine wetlands and 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. Raven *et al.* (2000) describe how the attributes of a method for determining the physical quality of rivers are well placed for use in environmental assessment and catchment planning in the U.K.

*Instream Uses*

The literature on instream use of water is relatively abundant, as we have over forty-six 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 potential available habitats and fishery resources. In this context, and therefore 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 the proponents consider to be thresholds for various stream resources, but touches very little on the problem of sensitivity in changes of thresholds.

Stalnaker *et al.* (1995) present a primer on the Instream Flow Incremental Methodology, while Stalnaker (1980) summarizes the effects of stream flow perturbations from a fisheries viewpoint and the pertinent recent literature identified which documents such effects. Rao *et al.* (1992) examine other methods to estimate instream flows as the instream flow incremental methodology (IFIM) that has been developed for estimating these flows requires data that are not commonly available and are expensive to acquire. Hardy (1998) examines emerging trends in applied instream flow assessments and Gippel & Stewardson (1998) examine the use of wetted perimeter in defining minimum environmental flows. Harpman *et al.* propose a method for quantifying the impacts of flow changes on fisheries. Bult *et al.* (1998) propose a multi-scale technique to study habitat selection by fish in riverine habitats. 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 (FIM) without consideration of the implications of so doing. Tarlock (1991) examines two new challenges to the instream flow to integrate flow protection.

Heggenes & Saltveit (1996) studied possible 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 and conclude that there is no such a thing as 'the' suitable minimum flow. Johnson & Covich (2000) report on the importance of night-time observations for determining habitat preferences of stream biota. 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 as the relative change in width and habitat with flow is greater for small rivers than for large. Lamouroux *et al.* (1998) present a new model to predict habitat suitability for lotic fish. Petts (1996) presents an approach to determining 'ecologically acceptable' flow regimes and volumes for regulated rivers that affect (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. Poff *et al.* (1997) examine the ecological responses to altered flow regimes. Pouilly & Souchon (1995) discuss the applicability of the Instream Flow Incremental Methodology and remark that the biological validity of the methodology remains its main uncertainty. Richter *et al.* (1997) propose a new method for setting stream flow based river ecosystem management targets.

Walker & Thoms (1993) analyse 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. Stromberg & Patten (1990) describe a methodology that allows determination of instream flow requirements for maintenance of riparian trees. Gehrke *et al.* (1999) analyse within catchments effects of flow alterations on fish assemblages, while Gippel *et al.* examine the impact of flow abstractions on the Thompson River, Australia. Humphries *et al.* (1996) examine how littoral habitats in large rivers are influenced to varying degrees by changes in discharge in two reaches of rivers in northern Tasmania, Australia.

Leonard & Orth (1988) examine the use of habitat guilds of fishes to determine instream flow requirements that were used in physical habitat simulations to determine relations between weighted usable area and discharge for three streams in the upper James River basin, Virginia. Auer (1994) examined how migratory lake sturgeon have responded to a change in facility operation, while Bain & Travnichek (1996) provided the basis of a general hypothesis of regulated stream flow effects on riverine fishes. Shelby *et al.* (1990) analyse 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. Rabeni (2000) evaluates the relation of physical habitat to benthic invertebrate communities in Missouri streams at both reference quality and habitat altered sites. Blinn *et al.* (1995) use five in situ experiments to test the influence of river discharge on the structure and benthos associated with cobble substrata in the Colorado River.

Johnson *et al.* (1995a, 1995b) use the Instream Flow Incremental methodology to assess the impacts of ground water abstractions upon habitat suitability for life stages of trout and salmon. Boulton *et al.* (1995) examine the functional significance of the hyporheic zone in stream and rivers Brunke & Gonser (1997) review the literature on the connectivity between rivers and groundwater systems. Bickerton *et al.* (1993) investigate the invertebrate communities and environmental characteristics of three English streams to determine the effects of ground water abstractions.

Milhous (1998) examine the links between sediment and habitats and the role instream flows play in removing undesirable accumulation of sediments. Cazaubon & Giudicellei (1984) analyse the impact of residual flows on the physical characteristics and benthic communities Englund & Malmqvist (1996) investigate the effects of flow regulation and habitat area on the macro invertebrates' fauna in north Swedish rivers. Foulger and Petts (1984) examine water quality implications of artificial flow fluctuations in regulated rivers.

Bunn & Davies (2000) evaluate the ultimate success of our biomonitoring approaches that depend on our understanding of the biophysical processes. Cardwell *et al.* (1995) examine ways to balance the human use of water with instream releases for environmental values.

### *3.3 Evaluation of the literature review*

As mentioned previously, useful references that assess cumulative ecological impacts in the context of the terms of reference of this study are practically non-existent. The problem of ecological indicators that could be used to assess the cumulative ecological impacts of water use and changes in levels and flows, and their possible applications to the Great Lakes-St. Lawrence system, have never been specifically addressed.

Large numbers of articles deal purely with description of impacts of regulation, withdrawals, dams construction and operation on biota (fish, mammals, benthos, birds, etc.) all over the world without specific information relating changes in flows or levels. Other articles make comparisons between regulated and non-regulated rivers and a few propose methods that could be retained. Effects of river management on biota, landscape ecology, environmental flows, geomorphologic processes and vegetation landscape on basin levels are often described without specific references to specific effects of levels and flows.

Some articles describe physical characteristics and some ecological aspects of shore zone habitats, while some others provide conceptual framework for describing impacts they offer little practical information evaluation of cumulative impacts of changes in level or flows. They explore trends in alterations of fresh-water ecosystems, discuss the ecological consequences of biophysical alterations, the need for an ecosystem approach and identify some of the major scientific challenges and opportunities to effectively address the changes. While some are theoretical and useful to explain the problem they offer little practical approaches to evaluate cumulative impacts but may sometimes be useful as a guide to establish monitoring protocols and agendas for scientific research.

While the search produced a number of possibly useful references it is very difficult for the author to pass a judgement on the relative value or merit of any specific articles as they lie in the most part behind the area of expertise. I will try however to make some very general comments on applicability of the results of this search.

What is striking at first is the diversity of key ecological end points used in the various publications: from shoreline and near-shore vegetation, to vegetation in inland or riverine/lacustrine wetlands, to macrophytes and submerged vegetation, to aquatic insects, plankton, benthos and finally 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 has not only a very strong social value representation and perspective but is also very often site specific and it is difficult to find an integrative concept that can be applied to management objectives (Rogers & Biggs, 1999).

Second, the words and concepts of measurements, indicators and thresholds are often used interchangeably, and sometimes even the concept of threshold becomes more of a descriptive value function 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 recognise that a distinction should be drawn 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, evaluation applies to the significance or importance of an impact and is often very value-laden.

To render operational the concept of sustainable ecosystem health, Rogers & Biggs, (1999) propose a methodology based on the integration of value systems endpoints and indicators of ecosystem health/integrity; it has been applied as the cornerstone of a consultative management process for the rivers of the Kruger National Park. It offers some interesting insights on how indicators, reference site and repeated assessments can integrate into comprehensive river management plans and not become an end in themselves and short on scientific rigor.

Some of the most promising methods or frameworks to assess ecological effects and impacts are based on habitat simulation methodologies (instream and others) and holistic methodologies (King *et al.*, 1999; Madsen & Wright, 1999) but as mentioned in some publications, knowledge just does not exist to move beyond the description of effects.

Hardy (1998) looking at tools and approaches that integrate the biological elements at the individual, population and community levels, notes that 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*". Meyer *et al.* (1999) remind 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*".

Linking specific changes in levels and flows to specific changes in biota will require much better data and models. Many current habitat simulation approaches are still in fairly early stages of development, and require further research, as well as rigorous testing tested for accuracy, cost and practicality and validation. In certain areas like for instance, methodologies addressing ground water in terms of links with surface flows in the river channel, as well as with conditions in the riparian zone, wetlands and floodplain are virtually absent.

An assumption common to the majority of habitat simulation methodologies is that modelling biological response to changes in physical microhabitat, as described by various hydraulic variables, with discharge, is an adequate level at which to make assessments about the environmental flow requirements of instream biota. Such an assumption is likely to be highly limited or even inappropriate.

The basic field data requirements are similar for the majority of present-day habitat simulation methodologies (Milhous *et al*., 1989). 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 kinds of in-channel conditions and microhabitats found within the study site, and thus relevant section of the river. Hydraulic variables include depth, velocity, substratum, cover, benthic shear stress and other near-bed indices. Similar point microhabitat data are required to describe the habitat requirements of the biota 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.

Expertise in hydroecological and hydraulic modelling is also essential, as well as specialist flow-related ecological knowledge on the biota under investigation. As habitat simulation methodologies are able to assess the impacts on physical habitat of incremental changes in flow, and typically have dynamic hydrological and habitat time series components, they could be used to examine a variety of alternative environmental flow scenarios for several species, life stages and or assemblages. Moreover, as they are computer-based, they are able to efficiently process large amounts of hydrological, hydraulic and biological data in a standardised yet flexible, interactive manner. Hydraulic and habitat modelling could also perform at a scale that is relevant to the environmental biota if pertinent data is available.

Particular efforts should made in defining the critical and significant time frame of the important, and very site specific, problems of relating changes in habitats to changes in levels and flows. Are they linked to changes in average or seasonal mean hydrologic values or in the frequencies and magnitudes of extremes (high and low flows)? Finally the most difficult issue and the one that will require the most scientific research, is linking changes in habitats 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 first problem arising is separation of the effects due to changes in levels and flows from effects possibly due to other stressing agents, if any. Then, the sensitivity of changes in hydrological or hydraulic variables upon the ecological end point has to be resolved as it is often the most critical link in the chain of cumulative effects. As shown in the literature that has been reviewed, a number of authors point to the non-linear nature of the relationships linking the various stressors to the ecological effects and the practical and theoretical difficulties in defining adequate ecological responses.

Overall, the review shows that despite the relatively recent emergence of habitat simulation methodologies a large amount of work remains to be done. Besides acquiring all pertinent data and knowledge specially on species-habitat linkages (for all ecological processes like reproduction, survival, and growth) and development of mathematical models it is recommended that useful methods be updated and cross-calibrated as soon as possible, that assessments be developed for some specific applications (with identified ecological end points) and that uncertainties be explicitly acknowledged.

## 4 - Descriptive inventory of literature

### *4-1 Modelling*

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 in land use/cover. 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. They the hydrologic record, as defined by a flow duration curve, to determine the inundation duration for each plot; this allows us to position cover types 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 (1) it is possible to cause substantial changes in riparian vegetation without changing mean annual flow, and (2) riparian vegetation is especially sensitive to changes in minimum and maximum flows. Principal advantages of this method are simplicity and reliance on relatively standard elements of plant community ecology and hydrologic engineering. Limitations include use of a single environmental gradient, restrictive assumption about changes in channel geometry, 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.

Hill *et al.* (1998) propose a model, based on the species richness of shoreline vegetation of 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 indicated 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.

Hart & Finelly (1999) propose a conceptual framework for investigating the multiple causal pathways by which flow influences benthic biota and focus particular attention on 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 produces 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.

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 average level during the growing season and the vertical range during the season.

Leclerc *et al.* (1994) developed 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 the Instream Flow Incremental Methodology and its Physical Habitat Simulation model that do not consider the displacement of habitat positions within the river that accompanies 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 analysing ecological impacts of water use in the Great Lakes St. Lawrence system. The 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. Lake levels and fluctuation cycles can be related 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 and could occur on the basis of whole lakes or the Great Lakes ecosystem. The ecological effects of forecasted physical changes can be added using knowledge of species-habitat relations. The analyses presented here begin 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 was placed 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.

Richards *et al.* (1997) used catchments and reach-scale physical properties to predict the occurrence of specific aquatic insects life history and behaviour traits across 58 catchments in a mixed land use 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) describes 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 as a foundation for future EPA proposals for risk assessment guidelines.

Rousseau *et al.* (2000) present an integrated modelling system prototype designed to assist decision makers in their assessment of various river basin management scenarios in terms of standard water physical and chemical parameters and standards for various uses of the water. The model provides a user-friendly framework to examine the impacts of agricultural, industrial, 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 a 6680 $km^2$ Chaudiere River basin in Quebec, Canada: (i) a timber harvest scenario and (ii) a municipal clean water program scenario. Simulation results of the timber harvest scenario showed how clear-cut activities could lead to earlier and larger spring runoff than in the investigated reference state. Results of the municipal clean water scenario revealed that substantial reduction 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 $m^2$) scale for the vegetation of 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 the 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) used 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 the mean daily temperature 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 of temperate and boreal zone wetlands.

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 variance 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 in many cases costly, solution is to develop and analyse data sets that are both spatially and temporally extensive.

### *4.2 Climate change*

Bloczynski *et al.* (2000) analyse 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 has developed a model to evaluate an investment decision made under uncertainty. The model considers the best available information on the role of wetlands as habitat, on the role of lake level variation in determining the extent of wetlands, and on 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

Magnuson *et al.* (1997) examine the physical changes that might come from climate change and would in turn affect the phytoplankton, zooplankton, benthos and fishes. Annual phytoplankton production may 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 the position in the hydrological flow system, in terrestrial vegetation and land use, in base climates and in the aquatic biota can all cause different responses. Climate change effects interact strongly with 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 is competing with other uses of water, and that competition is likely to be increased by climate change. They discuss potential ecological risks, benefits, and costs of climate change and identify information needs and model improvements that are required to improve our ability to predict and identify climate change impacts and to evaluate management options. The ability to predict impacts on water resources is still hindered both by the lack of good predictions of future climate at regional scales and by 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*".

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: (1) an increased frequency and duration of low water levels and (2) a 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 the new water level conditions by man-made structures or geomorphic conditions are at a particular risk.

Rhodes & Wiley (1993) report that contaminated sediments may be resuspended due to declining levels and represent a potentially long-term environmental remediation programme.

Wollmuth & Eheart (1999) explore several methods to control withdrawals from streams, examining each in detail and offering numerical examples that compare 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, especially, surface supplied irrigation spawned by such climate change. The results suggest that it is possible to implement regulations that at once (I) are consistent with the riparian doctrine; (2) control the hydrological and ecological impacts of offstream withdrawals effectively; and (3) preserve the primary economic functions of those withdrawals, including minimising economic risk.

### *4.3 Inventory*

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 based on velocity measurements, reviewing the possible physical effects can only be done by reviewing the current contributing physics known about the Great Lakes, and contrasting possible marine estuary transport mechanisms with what little is 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.

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

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

Bush & Larry (1996) assess habitat impairments impacting the aquatic resources of Lake Ontario. They estimate that during 1970-1990, Lake Ontario's ecosystem health was degraded by 58%. Impairments were caused almost equally by 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.

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 rapid change, 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 between the various components of the system.

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. Under low water levels, the lake becomes a large marshland that could support a high plant biomass whereas under 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 during the growing season and the vertical range during.

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% in the St. Lawrence River and 46% in the Ottawa River between summer 1994 and summer 1995 coincided, for stations in both water masses, with lower biomass and greater species richness and an increase in taxa that generate noxious smells and odours. 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. Hudon *et al.* (2000) examined the maximum depth of macrophyte colonization and depth distribution of macrophyte biomass were assessed, over 3 years, in late summer at six sites in the St. Lawrence River and two sites in the Ottawa River. The above ground and total biomass of macrophytes were related 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 that links St. Lawrence River and Ottawa River aquatic plants to environmental variables may eventually allow forecasting of wetland response to changes in water levels and water clarity resulting from climate variability and/or discharge regulation.

Jean & Bouchard (1991, 1993) Jean et al. (1993) tried to evaluate the relative importance of small-scale variation in abiotic factors and large-scale spatio-temporal variation on the distribution of wetland vegetation of a section of the Upper St. Lawrence River in Quebec. Time lag between a relative stabilization of species distribution and the reduction of natural disturbances (water level fluctuations and fires) could be a possible cause of the importance of spatio-temporal variables and 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. Using a dendrochronological analysis of three tree species colonizing a swamp along the St. Lawrence River, Jean & Bouchard (1996) report on (a) the extent to which water-level fluctuations have an impact on tree growth in comparison to climatic variations; (b) the responses of three species with hydrologic and climatic variations; and (c) the duration of the influence of water-level fluctuations on tree growth. Response function analyses were used to measure the influence of climate (temperature and precipitation) and water level on tree growth.

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

Wilcox & Meeker (1991) investigated 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 matforming species dominated transects where drawdown occurred in early winter and disturbance resulted from ice formation in the sediments.

### *4.4 Ecological river integrity*

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, area of 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.

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. Which type and scale of data are shown to have the strongest influence depends on the variable measured, and on study design as well. As aquatic scientists build on existing 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) within regulatory programs, to serve as thresholds by which to judge the attainment of designated aquatic life conditions of surface waters, is a major focus of states and Indian tribes within the USA. 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 USA.

Blanch *et al.* (1999) use selected water regime indices to describe the tolerances to flooding and exposure 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 summarised using minimum and maximum values and quartiles for the six indices, and a model based on minimum spanning tree techniques illustrates similarities between preferences.

Bundi *et al.* (2000) present how stream assessment, in Switzerland, should produce sound data suitable for characterizing the ecological condition of streams and for supporting their sustainable management. The methods should include a system approach as the basic unit and sound scientific principles of ecological integrity emphasising habitat connectivities. The methods should allow: (i) the condition of streams to be rationally described and judged, (ii) identification of different kind of impacts on a stream, (iii) verification of the effects of water protection measures, and (iv) identification of suitable future actions in the context of a whole stream system. In order to cover the various requirements they developed a modular concept for stream system oriented analysis.

Cohen *et al.* (1998) describe the partitioning of the Loire basin (105 000 $km^2$), (France) 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 as part of water management schemes. 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 types distribution is not different between regions; and (3) the factors governing distribution and longitudinal evolution of mesohabitats 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 cohesive rivers, 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, that incorporate 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, after 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 being most influential in predicting community structure in most chalk and limestone streams, whereas invertebrate communities colonizing rivers draining 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, investigation of habitat quality and LIFE score relationships in natural and degraded river reaches and evaluation of potential links with other biological modelling methods.

Fjellhiem *et al.* (1993) studied 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. Reduced densities of the chironomids caused a great part of the biomass reduction while an increase in the biomass was recorded for rheophilic insect larvae such as the stoneflies. The faunal change was due to the altered physical environment and the destruction of lentic habitats.

Grossman *et al.* (1998) analysed the effects of environmental variation and interspecific interactions on the assemblage organization in stream fishes inhabiting Coweeta Creek, North Carolina, USA. 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.

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 its 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.

Innis *et al.* (2000) summarise scientific knowledge concerning assessment methods addressing 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 is recommended 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,
- Assessment be developed for specific applications (with identified users),
- Uncertainty be explicitly acknowledged,
- Policy implications of specific assessments methods be openly discussed,
- Methods 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 that 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 to measure divergence from societal goals that have increased interest in biological monitoring. Assessment of 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 broadly based, multiparameter tool for the assessment of biotic integrity in running waters. IBI based on fish community attributes has 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 the aquatic biota as the best means of understanding and controlling humans' impact on the Earth's watercourses and on the whole water cycle. Biological monitoring, especially multimetric approaches such as the index of biological integrity, acknowledges the importance of rivers' 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 than narrow chemical criteria or conventional measures of urban development of sustaining living rivers.

Kleynhans (1996) assessed the riparian zone and instream habitat integrity of the Luvuvhu River (in the 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.

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 key habitat factors, which include: water and its condition; the surrounding land which helps determine that condition; conditions that the water creates within the stream; and instream objects.

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, USA. Because the extent and density of riparian vegetation depend largely on local geomorphic and hydrologic setting, sites-specific geomorphic and hydrologic information is needed. The methods described are: (a) preparing geomorphic maps from aerial photographs, (b) using well level records to evaluate the influence of streamflow on the riparian water table, (c) taking synoptic flow measurements to identify gaining and losing reaches, and (d) 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, Ushaped 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% were typical over reaches on alluvial fans. In a mountain valley, however, one stream gained up to 275% 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 and 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. Indicators proposed are retention of matter as an indicator for the functional characteristics and zonation of species as an indicator for the structural characteristics of the river ecosystem. Present river ecosystems are far from undisturbed. To allow efficient management of the river ecosystem, indicators and variables are required that reflects 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 programmes should reflect such an integrated spatial view. Finally, the study presents some recommendations for monitoring, in particular for the Rhine monitoring programme.

Muhar *et al.* (2000) investigate fifty-two of the largest Austrian rivers with catchment's areas greater than 500 $km^2$ (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 compared with original conditions. This assessment and evaluation of nearly 5000 river kilometres identifies the remaining river stretches with high habitat quality as well as those stretches that have been altered by systematic channelisation or hydropower development.

Naiman & Descamps (1997) discuss the unusually diverse array of species and environmental processes in riparian zones. The 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, and show how this viewpoint is changing as recognition of strong biological influences on physical structure are emerging. In combination, identifying natural stream characteristics that reflect variations in local geomorphology, climate, natural disturbance regimes and the dynamic features of the riparian forest and the interactions among individual components, as well as recognising the importance of biotic feedbacks on physical structure, 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 to effectively address the changes. Topics discussed include altered hydrological regimes, biogeochemical cycles, altered land use, riparian management, life history strategies, and relations 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 the incorporation of ecological principles into aquatic resource use and management decisions. 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 of sustainability.

Nestler & Long (1997) present an hydrological analysis of historic stream data collected on the Cache River at Patterson, Arkansas, USA, 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 baseflow 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 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 of 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 to evaluate the changes caused by already built projects and to 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 have been 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.

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

Reid & Brooks (2000) recommend a range of physical, chemical and biological indicators for use for monitoring change in wetland health in response to environmental water allocations (EWAs) designed to redress some of the damage caused by regulation, via partial restoration of the natural hydrological regime that used to be experienced by 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, wetland area and salinity. Aquatic macrophytes and macroinvertebrates are recommended as the primary biological indicators for monitoring change 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 with 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.

Rogers & Biggs (1999) propose the integration of value systems end points and indicators of ecosystem health/integrity as the cornerstone of a consultative management process for the rivers of the Kruger National Park. In trying to operationalize the notion of sustainable ecosystem health ecologists have focussed on identifying sets of indicators that can be used to assess river condition 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 programmes become ends in themselves rather than means to achieving specific management goals. The absence of a test of the results of monitoring, 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.

Spink *et al.* (1998) investigated a range of river floodplain sites in North America and Europe to determine what factors were determining nutrient richness and productivity. A principal component analysis revealed that phosphorus richness of the soil and plant growth were strongly associated with the size of the river and the position of the site, both in relation to the distance to the source of the river and to the river channel. Nitrogen mineralisation 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 fertiliser experiments showed that at several of the sites, production was not limited by nutrients. Climatic factors (temperature, latitude) also determine plant production. The hydrological regime that a floodplain is subjected to is a vital factor for determining both nutrient dynamics and plant production, but it is not straightforward to characterize due to the complex and variable nature of the flood pulse.

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 (example: a river plume, an estuarine hydrofront).

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 programmes such as required for the proposed Water Framework Directive of the EU. Out of five different biological organisation 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.

Shedlock *et al.* (1993) examines 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 both occur in the same wetland. Multidisciplinary studies incorporating hydrological, hydrochemical, geophysical, and sedimentologic data are necessary to identify such complexities in wetland hydrology.

Stanford *et al.* (1996) propose a general protocol for restoration of regulated rivers. They examine the four-dimensional nature of the river continuum and the propensity for riverine biodiversity and bioproduction to be largely controlled by habitat maintenance processes, such as cut and fill alluviation mediated by catchments 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, installation of artificial instream structures (river engineering) and predator control; and, practising adaptive ecosystem management

Vincent & Godson (1999) using examples from the St. Lawrence River, identify environmental pressures on large rivers that would greatly benefit from an integrated "whole ecosystem" approach towards their understanding and management: hydraulic control, channel modification, contaminant discharge, eutrophication, climate change and community shifts, including the invasion of 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.

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 ecosystems modelling efforts have been plagued by difficulties in representation of cross-scale effects (from rapid hydrologic change to long-term ecological response), lack of data on key processes that are difficult to study, and 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.

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.

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 integrity in river systems relative to fisheries for food as human uses of river and their flood plains 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 the channel flood-plain systems for fish and includes an evaluation of the impacts of the integrity of fish assemblages of other human uses of the shared ecosystem as those of fishing activities and management.

### *4.5 Instream uses*

Aadlland (1993) examines the selection of target species for instream flow studies of 114 fish species-life stage combinations in six Minnesota streams assigned membership in 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 located on the Sturgeon River, Michigan have responded to a change in facility operation negotiated during recent relicensing. Spawning characteristics of this stock of fish have been monitored for 6 years. The change in facility operation and therefore water discharge pattern, created changes in several characteristics of the spawning lake sturgeon population. There has been a reduction in time when adult lake sturgeon are observed on site, an increase in total number and size of adults, an increase in spawning-ready fish, and a change in location of capture. Constant and non fluctuating water flows produced by run-of-the-river operation appear to be triggers to reproductive readiness and allow more and larger fish to move onto spawning grounds.

Research during the 1980's (Bain & Travnichek, 1996) on fish communities and habitat in flow regulated rivers of the North-eastern United States provided the basis of 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 generalist 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 South-eastern USA river with extensive hydroelectric development.

Bickerton *et al.* (1993) investigated 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 between-site difference, and to a lesser extent changes in discharge, depth and substrate composition. All can be attributed at least in part to groundwater abstraction.

Blinn *et al.* (1995) have used five *in situ* experiments to test the influence of fluctuations in river discharge on the structure and function of the tailwaters benthos associated with cobble substrata in the Colorado River downstream from Glen Canyon Dam, Arizona, USA. Periods of daily desiccation and freezing during river fluctuation significantly limited community biomass and energy. The permanently submerged channel supported 4-fold higher macro invertebrate mass than the zone affected by level fluctuation.

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 and bed topography and 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.

Brunke & Gonser (1997) review the literature on the connectivity 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.

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.

Bunn & Davies (2000) evaluate the ultimate success of biomonitoring approaches that depend on our understanding of the biophysical processes that influence the structure and dynamics of stream and river systems and the way they function. Although biomonitoring approaches are being 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 been rarely tested with long-term data sets and there is evidence that this assumption is not true in some river systems.

Cardwell *et al.* (1995) examine ways to balance the human use of water 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 size and frequency of water supply shortages and the habitat available for fish species as the fish 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.

Cazaubon & Giudicelli (1999) analysed the impacts of the 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: the high daily and annual thermal amplitudes and the reduction of the diversity of available habitats.

Englund & Malmqvist (1996) examine the effects of flow regulation, habitat area and isolation on the macro invertebrate 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 changes of discharge was the most important factor. No effects on overall species richness of habitat size and isolation were found, 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 will 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.

Foulger & Petts (1984) analyse 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 for flow fluctuation as well as minimum and optimum flows. Due consideration must be given not only 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 the 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.

Gehrke *et al.* (1999) analyse 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 the upper Thomson River that 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 for severe or irreversible environmental impacts from application of the interim environmental flows in the upper river. Macroinvertebrate populations have recovered from disturbance during the construction phase, and the diversity of fish has not changed and still maintained a population of blackfish and grayling. However, there is concern that a lack of floods will result in 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. Unfavourably low flows have occurred since regulation, but wetland inundation floods still occur with the same frequency. Although current management practices do allow unfavourable flow conditions to occur occasionally, the regulated flow regime has not reduced the diversity of native fish present in the lower river.

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 over wetted perimeter as a variable to define habitat suitable for macro-invertebrates.

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 the instream flow incremental methodology, 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 re-regulate flows downstream of 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 placement of structures that improve hydraulic conditions to sustain maximum diversity of the benthic community.

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*".

Harpman et al. (1993) propose a methodology for quantifying and valuing the impacts of flow changes on a fishery. A quasi-population mode, termed the effective habitat model, is used to predict the effects of changing the timing and quantity of reservoir releases on downstream fish population of brown trout. An angler's 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 economic impact on the economic value of the fishery was limited.

Heggenes & Saltveit (1996) studied possible 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 will vary with stream structure, the hydro-physical variables in question and the fish species. More studies are needed to elucidate possible spatial and in particular temporal variations in fish habitat selection. Care must be taken in aggregating habitat suitability data into single-valued functions.

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 a raised water level, and a lowering of the ice cover during the winter causes rapid changes in the littoral benthos and vegetation. The scale of the harmful effects depends on both the range of regulated water level fluctuations and the 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 under hydropower production. This procedure is based on under water light climate and water level fluctuation data, which make it possible to calculate the proportion of the frozen littoral to the total littoral area. Another procedure calculates the biomass of the 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 it is economically and hydrologically possible. It offers a simple way to illustrate to the regulation-permit owners differences between various regulation practices.

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 the Instream Flow Incremental Methodology to assess the impact of groundwater abstraction upon habitat suitability for life-stages of trout and salmon of 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 analysed 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 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 at the 95-percentile exceedance level was depleted by 55% representing a decline in the Weighted Usable Area of 95%. The results provided by this analysis were used by the River Authority to negotiate a proposed 50 % 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.

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.

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 consideration of the implications of so doing. 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 the stream flow recommendations. Care should be taken to distinguish between real behavioural 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.

In modelling of 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.

Petts (1996) presents an approach to 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. This paper presents an approach to determining 'ecologically acceptable' flow regimes and volumes. 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 our capability for modelling the roles of different flows and patterns of flows in sustaining river ecosystems.

Poff *et al.*, (1997) define the natural flow regime, the role it plays in organisation and definition of the river ecosystem and its natural functions. They then examine the human alterations and the ecological responses to altered flow regimes and discuss some recent approaches to streamflow management and strategies for managing toward a natural flow regime.

Pouilly & Souchon (1995) discuss the applicability of the Instream Flow Incremental Methodology, presently the most used tool to evaluate 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 streams of reference quality in three ecoregions. Biological responses to habitat alterations were readily documented by taking into account both 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 relations of physical habitat to the biota need to be quantified so as to better establish reference conditions and to document those physical habitat alterations that actually impact the biota.

Rao *et al.* (1992) examine flows required for sustaining fish population in a stream. The instream flow incremental methodology (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, which are based only on flow rates, do not consider the characteristics of the fish population in the stream and hence are unrealistic. A modification of the 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 the IFIM but which gives results of the same order of magnitude as the IFIM is proposed. The method is illustrated by using data from streams in Indiana.

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 associated characteristics of timing, frequency, duration, and rates of change, in sustaining aquatic ecosystems. The method is intended for application on rivers wherein 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 using methods described in Richter *et al.* (1996). Richter *et al.* (1998) demonstrate the use of this approach for assessing hydrologic alteration at available 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.

Shelby *et al.* (1990) analyse 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 can be recognised and protected,

Stalnaker *et al.* (1995) present a primer on the Instream Flow Incremental Methodology (IFIM). Stalnaker (1980) summarizes the effects of stream flow perturbations from a fisheries viewpoint and the pertinent recent literature identified which documents such effects. Methods used for evaluating instream flow requirements for fisheries are reviewed and presented in three categories: 1) those suitable for early planning and general guidance, usually based upon hydrologic data; 2) those used in water allocation processes and flow regulation schemes, usually based upon stream channel by hydraulic measurements; and 3) those suitable for detailed ecological evaluations of impacts, usually based upon regression analyses of stream attributes vs. fish population attributes.

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 development of models that predict growth rates from hydrologic variables. Simple linear regression models were used to determine the relationship between annual growth of cottonwood and pine and 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 for development and use of 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.

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

Walker & Thoms (1993) analysed 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 variation, the Murray river-floodplain ecosystem evidently cannot accommodate these forms of disturbances.

### *4.6 International Joint Commission*

A Working Paper (Working Group 4, 2000) summarising the results of the Cumulative Impacts and Risk Assessment component of the recent IJC Reference on *Consumption, diversion and removal of Great Lakes Water* was reviewed as part of this assignment. 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*".

The following sections try to make a review of the main findings of that study that have not been covered in other parts of the present analysis.

All the IJC Study Board reports, that it was possible to review, approached cumulative impact assessment from a relatively narrow point of view. All the references to the IJC as well as the IJC directives to the Study Boards, asked to look 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. Numbers of criteria were imposed on the possible regulation plans in terms of maximum/minimum levels and flows that need to be preserved. The possible impacted sectors of activities that should be looked at by the plans 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 alternatives were derived by comparing a particular plan with a Basis of Comparison (BOC); one should not forget however that the 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.

#### *Erosion*

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

#### *Commercial fisheries*

The impact of various regulation plans on commercial fisheries was attempted in many studies. The International Great Lakes Levels Board (1973) study dealt mostly with the effects of lake levels regulation on fish stocks by looking at relations between water levels and commercial catch in pounds; this approach was recognised 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.

Manny (1984) looked at 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 (1984) examines the impacts of water withdrawals on fish, of water diversions and consumptive water withdrawals and the economic impact of water diversions on Great Lakes fish resources. He notes, 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 at 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, concludes that these studies revealed important clues about the status of knowledge and the need for information related to ecological consequences of water transfer. Understanding fundamental ecological processes of managed fish species is crucial to future water transfer studies.

### *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: i) to better understand the response of wetland communities to fluctuation in water levels and ii) to apply this knowledge generally and speculate on 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 in a river basin including regulation. 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. Such a working assumption should however be tested (Regier, 1999).

### *Water Quality*

Water quality characteristics were examined in detail in only two studies (International Lake Erie Regulation Study Board, 1981 and International Great Lakes Diversions and Consumptive Uses Study Board, 1981); they 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 deal mostly therefore with Lake Erie based on a one-foot lowering. Very little pertinent information is therefore available for the other lakes. However their 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%) and increase in *Cladophora* production (0.5% - 2.7%) all other impacts are negligible for the ranges of level variations resulting from implementation of the three regulation plans.

## 5. 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-years, multi-stakeholders and multi-million dollar studies. To finalize its report the WCD drew on the WCD Knowledge Base that consists 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 1000 topic-related submissions. All these reports are available on CD-ROM or can be downloaded from http://www.dams.org.

Amongst the seventeen thematic reviews, the 200 pages “TRII.1” (Berkamp *et al.*, 2000) deals with the subject of *Dams, Ecosystem Functions and Environmental Restoration*. Chapters 3 and 4 deal respectively with the ecosystem impacts of large dams and with responding to the ecosystem impacts of dams. While making for an interesting reading on this very complex and controversial subject the review offers very little specific contribution to the terms of reference of this literature survey as the whole report is written in a very general and descriptive way. Very little information is presented linking specific changes levels and flows to specific effects and impacts on ecosystem variables. Moreover, as pointed out in the 70 pages of comments received on a Circulation Draft of March 2000, from the sixteen reviewers, many of the existing and available literature on the subject was not reviewed.

In Annex 1 we present an *in extenso* copy of the Executive Summary, Conclusions and the Policy Recommendations of this Thematic Review to the WCD.

It should be reminded that this thematic 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 has been compiled based on contributions from a wide range of sources, and comments received from the review panel and WCD Forum. In Annex 2 we list the titles and authors of the sixteen contributing papers, which can be downloaded in PDF format from the WCD web site.

The following paragraphs will present a summary of some of the contributing papers, that seemed promising at that it was possible to examine in the time frame available.

King *et al.* (1999) present an extensive review of definition and implementation of instream flows. They look 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; they look at state-of-the-art methodologies, data requirements and expertise, strengths and weaknesses; they analyze in depth the following:

1. Hydrological type methodologies
2. Hydraulic rating methodologies
3. Habitat simulation methodologies
4. Methodologies for the maintenance of channel form, and fluvial geomorphological and sedimentological processes
5. Environmental flow methodologies for water quality purposes
6. Methodologies addressing the ecological flow requirements (EFR) of riparian vegetation
7. Methodologies addressing ecological flow requirements of wildlife
8. 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.
9. Methodologies addressing ground water 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, as well as with conditions in the riparian zone, wetlands and floodplain, are virtually absent.

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

King &Brown (1999) look at eight steps to informed-decision making such as situation assessment, specialist reviews and selection of representative components, developing predictive capacity of biophysical responses to dam-related flow changes, predicting social impacts of the 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, even after some considerable research effort, river scientists could probably only describe trends in river ecosystem response to management actions, and not predict the timing and severity of the response.

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 summarise the impacts on the biodiversity of molluscs, 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.

## 6. Conclusions and recommendations

Useful references that assess cumulative ecological impacts in the context of the terms of reference of this study are practically non-existent. The problem of ecological indicators that could be used to assess the cumulative ecological impacts of water use and changes in levels and flows, and their possible applications to the Great Lakes-St. Lawrence system, have never been specifically addressed.

While the search produced a number of possibly useful references it is very difficult for the author to pass a judgement on the relative value or merit of any specific articles as they lie in the most part behind the area of expertise. Some of the most promising methods or frameworks to assess ecological effects and impacts are based on habitat simulation methodologies (instream and others) and holistic methodologies (King *et al.*, 1999; Madsen & Wright, 1999). However as mentioned in some publications, knowledge just does not exist to move beyond the description of effects.

Linking specific changes in levels and flows to specific changes in biota will require much better data and models. Many current habitat simulation approaches are still in fairly early stages of development, and require further research, as well as rigorous testing tested for accuracy, cost and practicality and validation. In certain areas like for instance, methodologies addressing ground water in terms of links with surface flows in the river channel, as well as with conditions in the riparian zone, wetlands and floodplain are virtually absent.

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 kinds of in-channel conditions and microhabitats found within the study site, and thus relevant section of the river. Hydraulic variables include depth, velocity, substratum, cover, benthic shear stress and other near-bed indices. Similar point microhabitat data are required to describe the habitat requirements of the biota 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.

Expertise in hydroecological and hydraulic modelling is also essential, as well as specialist flow-related ecological knowledge on the biota under investigation. As habitat simulation methodologies are able to assess the impacts on physical habitat of incremental changes in flow, and typically have dynamic hydrological and habitat time series components, they could be used to examine a variety of alternative environmental flow scenarios for several species, life stages and or assemblages. Moreover, as they are computer-based, they are able to efficiently process large amounts of hydrological, hydraulic and biological data in a standardised yet flexible, interactive manner. Hydraulic and habitat modelling could also perform at a scale that is relevant to the environmental biota if pertinent data is available.

Particular efforts should made in defining the critical and significant time frame of the site specific problems relating changes in habitats to changes in levels and flows. Are they linked to changes in average or seasonal mean hydrologic values or in the frequencies and magnitudes of extremes (high and low flows)?

An assumption common to the majority of habitat simulation methodologies is that modelling biological response to changes in physical microhabitat, as described by various hydraulic variables, with discharge, is an adequate level at which to make assessments about the environmental flow requirements of instream biota. Such an assumption is likely to be highly limited or even inappropriate.

Overall, the review shows that despite the relatively recent emergence of habitat simulation methodologies a large amount of work remains to be done. The following is recommended as the next possible steps:

The first step should consist in a detailed analysis of the World Commission on Dams Thematic Report on *Definition & Implementation of Instream Flows* (King *et al.*, 1999); this analysis should be carried out by experts in the field of habitat assessment with an objective of possible implementation of some of the methodologies in the Great Lakes S. Lawrence River Basin. As mentioned previously it was not possible to carry out this detailed review within the context of the present literature survey. Such an analysis should only not cover only the main report with all its references but also examine the Internet references mentioned in Annexes 1 and 2 of King *et al.* (1999); attention should also be paid to the numerous comments of the external reviewers.

The next steps should consist in acquiring all pertinent data and knowledge especially on species-habitat linkages and development of mathematical models. This approach could follow the framework described by Madsen & Wright (1999) and consist essentially in the following items:

- Ensure that we have a complete description of shoreline habitat types in the Great Lakes St. Lawrence River Basin. Apparently these shoreline types have already been encoded for the Great Lakes and one would have to ensure that similar information is also 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 these shorelines;

- Evaluate the effects of changes of habitats as they may affect the various biotic communities (plants, invertebrates, fishes and other vertebrates) in the Great Lakes St. Lawrence River Basin and pay special attention to the ecological processes essential for life i.e. reproduction, survival, growth and habitat;

- Develop appropriate habitats simulation models for all reaches of interest;

- It is further recommended that useful methods be updated and cross calibrated as soon as possible, that assessments be developed for some specific applications (with identified ecological end points) and that uncertainties be explicitly acknowledged.

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## Annex 1

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. It does so by first reviewing the importance of natural river basin ecosystems and examining the impact of dams on these ecosystems. It then examines the current status of approaches being taken to addressing these impacts through the continuum of "avoidance-mitigation-compensation-restoration". Based upon this analysis the report concludes with an assessment of the areas of convergence and divergence on these issues within the dams debate and provides a set of recommendations to the Commission.

**River Basin Ecosystems and Biodiversity**. Each river basin contains many natural ecosystems including 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 US$ 33 trillion per year of which roughly 25% 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 result in a significant impact of dams on freshwater biodiversity, which is already under special threat. Global estimates of endangered freshwater fish reach 30% of the known species. And 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 habitats 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 even by a single dam, and multiple dams worsen this situation dramatically. In the Northern hemisphere 77% of the largest rivers are affected by dams and on many rivers fully natural reaches are restricted to headwaters. The global impacts of dams on the global water cycle are increasingly recognised.

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 dependent not only on the dam structure and its 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 and these 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 fulfil functions and yield a range of services that are of substantial economic and cultural value to society, the ecosystem changes that result from the creation of dams 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 externalisation 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 this loss of welfare and implement financial and institutional mechanisms to assimilate these costs into the accounting structure.

The review stresses however that, even when these steps are taken, the valuation of ecosystems and the consideration of development options is not a straightforward accounting exercise. It needs to be recognised 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 multi-criteria decision-making and raises awareness of costs that are currently hidden and negated in the accounting exercise.

**Responding to the Ecosystem Impacts of Dams**. 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; iv) de-commissioning of the dam and restoration of the riverine ecosystem.

Within this framework of avoidance, mitigation, compensation and restoration, there are a wide range of specific measures that can be taken appropriate to specific circumstances of each dam.

The Thematic Review evaluates experience in 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 themselves. Whether these impacts are significant varies from case to case.

While there is experience of good mitigation, 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 co-operative process with the design team and stakeholders;
- monitoring of feedback and evaluation of mitigation effectiveness, and
- adequate financial and institutional resources;

If any one of these conditions is absent, then 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 is therefore at present not a credible option in all cases and all circumstances. In addition the weaknesses of the EIA process for many projects (cf Thematic Review V.2) reduce the possibilities for positive outcomes. This would tend to encourage a strategy of avoidance and minimisation rather than one of mitigation if the aim is to maintain biodiversity and ecosystem functions and services for the foreseeable future. Alternative tools for maintaining ecosystem health therefore need to be pursued.

The review argues that improved scientific predictive capacity and improved 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: i) Indicators for Hydro-project selection; ii) Indicators of Ecological Integrity; iii) 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 today 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 and especially the value to be attached to the intrinsic value of nature. This highlights the importance of ensuring that project approval be based on multi-criteria decision-making, not just economic cost-benefits analyses or on a purely eco-centric 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 necessitate the establishment of appropriate institutions to promote equitable water use, especially between upstream and downstream ecosystems and livelihoods.

The Review argues that most success in bridging the differences outlined is likely to be made by strengthening options assessment and the evaluation of 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 environmental impacts of dams should concentrate on developing legitimate and accepted processes for dam planning, design and management within the river basin context. Secondly, 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.

## 6. Conclusions and Policy Recommendations for WCD

### 6.1 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 impacted most 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, the direct and indirect economic value of these services is highly significant to local, national and regional economies. In most cases one or more sector of society depends upon these values (e.g. fisheries, grazing) while in some the total value of the benefit 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 the consequences of dams has resulted in the benefits of many dams being overstated. The importance of these natural ecosystems is today widely recognised 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 underlined that dams have a wide range of major impacts upon natural ecosystems, that most of these are negative, that many are irreversible, and that they are manifest in economic and social costs. Perhaps surprisingly, the review has noted that there is today widespread, but not complete, agreement as to the reality and importance of these impacts and their costs. The review has also recognised 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. A review of these approaches highlights, however, that while there is good evidence through practical experience 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 utilised, 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 co-operative process with the design team and stakeholders;

- monitoring of feedback and evaluation of 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, under present political, economic and institutional conditions, rarely be successfully implemented. Alternative approaches to maintaining ecosystem health therefore need to be pursued.

## 6.2 Recommendations

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

**1. Recognise the important role of natural ecosystems in contributing to sustainable development.** If river basin development is to be truly sustainable it needs to recognise the wide range of goods and services that are provided to human society by natural ecosystems. All major development investment, including dam construction, should seek to conserve and enhance these ecosystems and their value to society. Actions that diminish these values should be minimised.

**2. Recognise the importance of biodiversity and promote its conservation.** Biodiversity is recognised 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 minimise threats to biodiversity. In the past dams have contributed significantly to endangerment and extinction of species. In future no dam should proceed if it is shown to have a high probability of having a significant detrimental effect on species diversity.

**3. Dams must be considered within a framework of river basin management plans and nternational/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 life.

**4. Recognise and manage for uncertainty.** There is enormous variation between river basins, rivers, ecosystems, dams and associated projects. This diversity, together with the seriously limited quantity and quality of information on the functioning 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, capacity to manage the dam in a flexible manner and so adapt to improved understanding of ecosystem requirements, should be incorporated into dam design. This precautionary approach should be recognised as a central feature of planning, design and management of dams, especially as many are probably irreversible.

**5. Ensure effective multi-sector participation in planning, design and management of dams.** In order to help recognise 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. Maximise adaptive capacity.** When the participatory design processes recommended above leads 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 programme 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 recommendation on dam operation from monitoring bodies.

**7. Promote incorporation of environmental management features into dam design**. In addition to features that provide for adaptive management as a permanent element of the dam cycle, 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 with regard to ecosystems and biodiversity, need to be enshrined in national legislation governing dams and river basin development. This should be promoted together with measures to strengthen enforcement, such as the use of environmental bonds, direct compensation revenue sharing (hydropower), or environmental trust funds as a guarantee of compliance.

**9. Promote application of tools to foster ecosystem health.**

**(I)** **Environmental Flow Releases.** EFRs are being used in 25 countries and today 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% 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 developing further the knowledge-base required to improve this tool adapting it to local needs, 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 the development of indicators of ecosystem health. These can be used for setting 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 minimise ecosystem impacts: reservoir surface area; water retention time in the reservoir; biomass flooded; length of river impounded; number of inflows to mainstream from undammed down-river tributaries; and access roads through sensitive areas. 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 modern technologies and/or altering dam operation so that where feasible, dams are improved to comply with up-to-date standards of environmental care.

## Annex 2

List of contributing papers to the thematic Reviews 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)