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Environmental Impact Assessment Review
23 (2003) 723–745

Environmental Impact Assessment Review

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Cumulative effect assessment in Canada: a regional framework for aquatic ecosystems

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Received 1 December 2002; received in revised form 1 May 2003; accepted 1 May 2003

Abstract

Sustainable development of the aquatic environment depends upon routine and defensible cumulative effects assessment (CEA). CEA is the process of predicting the consequences of development relative to an assessment of existing environmental quality. Theoretically, it provides an on-going mechanism to evaluate if levels of development exceed the environment's assimilative capacity; i.e., its ability to sustain itself. In practice, the link between CEA and sustainable development has not been realized because CEA concepts and methods have developed along two dichotomous tracks. One track views CEA as an extension of the environmental assessment (EA) process for project developments. Under this track, stressor-based (S-B) methods have been developed where the emphasis is on local, project-related stressors, their link with aquatic indicators, and the potential for environmental effects through stressor-indicator interactions. S-B methods focus on the proposed development and prediction of project-related effects. They lack a mechanism to quantify existing aquatic quality especially at scales broader than an isolated development. This limitation results in the prediction of potential effects relative to a poorly defined baseline state. The other track views CEA as a broader, regional assessment tool where effects-based (E-B) methods specialize in quantification of existing aquatic effects over broad spatial scales. However, the predictive capabilities of E-B methods are limited because they are retrospective, i.e., the stressor causing the effect is identified after the effect has been measured. When used in isolation, S-B and E-B methods do not address CEA in the context necessary for sustainable development. However, if the strengths of these approaches were integrated into a holistic framework for CEA, an operational mechanism would exist to better monitor and assess sustainable development of our

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0195-9255/03/$ – see front matter.
doi:10.1016/S0195-9255(03)00113-6

aquatic resources. This paper reviews the existing conceptual basis of CEA in Canada including existing methodologies, limitations and strengths. A conceptual framework for integrating project-based and regional-based CEA is presented.

Keywords: Cumulative effects assessment; Environmental impact assessment; Environmental planning; Environmental monitoring; Sustainable development

1. Introduction

In Canada, some rivers and landscapes have been degraded (e.g., St. Lawrence and Fraser Rivers; Great Lakes) and in most cases, it would be difficult to identify one guilty party (Drouin and LeBlanc, 1994; Culp et al., 2000a). The accumulation of multiple stressors (e.g., urban development, pulp and paper mills, oil sands developments, chemical industries, hydroelectric dams, agriculture, and mining) has created cumulative effects (O'Riordan, 1986; Bonnell and Storey, 2000; Munkittrick et al., 2000; Spaling et al., 2000; Environment Canada, 2001a). A cumulative effect (CE) is defined as an effect on the environment that results from the incremental, accumulating and interacting impacts of an action when added to other past, present, and reasonably foreseeable future actions (Hegmann et al., 1999). Socio-economic and cultural consequences resulting from these biophysical environmental effects are also included in this definition (Canadian Environmental Assessment Agency (CEAAgency), 1999a). CEs may result from the addition or extraction of materials from the environment as well as from the interaction between man-made and natural stressors. Effects can also result from individually minor yet collectively significant actions taking place over a period of time and/or space (Cocklin et al., 1992a).

Cumulative effects assessment (CEA) is the process of systematically analyzing cumulative environmental change (Sears and Yu, 1994; Spaling, 1994; Smit and Spaling, 1995). Two dominant CEA approaches have emerged for aquatic systems. One approach views CEA as an extension of the environmental assessment (EA) process for project developments (Spaling and Smit, 1993; Duinker, 1994; Griffiths et al., 1998). The focus of this approach is the stressors associated with a development proposal and prediction of how those stressors may interact with the aquatic environment. The proponent is responsible for conducting this project-based CEA. The other approach views CEA as a broader, regional assessment tool to provide scientific information for decision-making related to sustainable development (Clark, 1994; Lawrence, 1997; Bonnell and Storey, 2000; Piper, 2002). The focus is on quantifying existing environmental effects first and working retrospectively to identify potential stressors. Griffiths et al. (1998) suggest that regional CEA is the responsibility of government.

Both project-based and regional-based approaches are necessary for effective CEA and sustainable development of the environment (Cocklin et al., 1992a;

Sears and Yu, 1994; Slocombe, 1994; Dubé and Munkittrick, 2001). However, an operational framework that integrates these approaches is not available (Sonntag et al., 1987) because a "responsible owner" has not been identified to develop, implement and manage it (Griffiths et al., 1998). In addition, there is an incorrect perception that the science of CEA is not at a stage to support it (Foran and Ferenc, 1999; Munkittrick et al., 2000).

A need exists to develop a holistic CEA framework where the strengths of project-based and regional-based approaches are recognized and integrated (Dubé and Munkittrick, 2001). This paper reviews existing CEA concepts and methods and presents a holistic, integrated framework for aquatic systems.

2. Existing conceptual basis for CEA

2.1. CEA under EA (project-based CEA)

In North America, CEA was first formally recognized in the EA process where the environmental consequences of project development are considered prior to project approval (Duinker, 1994). In 1992, the Canadian government included a requirement to address CEs when a project is subject to a federal environmental assessment under the *Canadian Environmental Assessment Act (CEAA)* (Hegmann et al., 1999). Several Canadian provinces also enshrined CEA in their legislation (e.g., British Columbia, Alberta, Quebec) or EA guidelines (e.g., Saskatchewan, Manitoba, Ontario) (Griffiths et al., 1998). Therefore, it is not surprising that many implement CEA as an extension of an EA (Fig. 1A) (Spaling and Smit, 1993; Duinker, 1994; Slocombe, 1994). Legislation that incorporated CEA as a component of an EA preempted the emergence of a regional approach (Spaling and Smit, 1993) and led to development of project-based methods (Cocklin et al., 1992a).

It has been recognized that the goals for CEA, as defined under the *CEAA*, may not be attainable using a project-based approach because the scale of CEA is

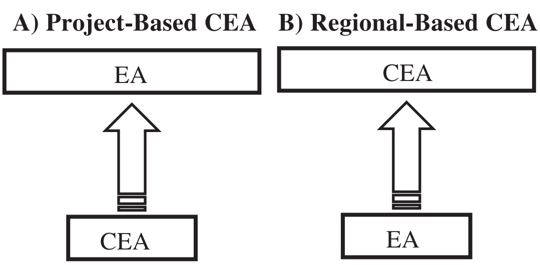

Fig. 1. Conceptual basis for cumulative effects assessment (CEA) relative to the environmental assessment (EA) process where (A) CEA exists as an extension of the EA process or (B) the EA process contributes to a broader CEA.

beyond the scope of a single project or proponent (Contant and Wiggins, 1991; Drouin and LeBlanc, 1994; Bonnell and Storey, 2000). CEA requires broader temporal and spatial boundaries than those used in project-based assessments as effects may occur at locations far removed from the project in space and time. Drouin and LeBlanc (1994) and Ross (1994) suggest that it is not the responsibility of individual proponents to address environmental impacts at this scale especially when it involves developments of business competitors and multiple jurisdictions. Project proponents often have insufficient information regarding other projects and their effects, and have little or no control over these activities (Therivel et al., 1992). Despite this, project-based CEA is an important means to incorporate environmental considerations into decisions regarding individual development proposals and it is reasonable to expect proponents to assess these (Spaling and Smit, 1993; Clark, 1994).

2.2. EA under CEA (regional-based CEA)

Regional-based CEA is a broader, regional environmental management operation that could incorporate CEAs conducted under the EA process but the latter is not the main driver (Fig. 1B) (Cocklin et al., 1992a). Regional CEA approaches have largely developed outside of the EA process and emphasize characterization of the environmental response to multiple stressors. Environmental management is based on the environmental response to cumulative stress. Some of the best known Canadian examples of regional-based aquatic CEA include the Northern River Basin Study (NRBS) (Culp et al., 2000a) and the Moose River Basin (MRB) study (Munkittrick et al., 2000).

Regional approaches are effective for CEA because they are conducted at broader spatial and temporal scales and are not constrained by the EA process, e.g., application and review schedules (Harwell and Gentile, 2000). These approaches also offer a realistic mechanism to assess sustainable development of the environment (Slocombe, 1993; Bonnell and Storey, 2000). As Rees (1988) points out, "planning for sustainable development requires systematic identification and monitoring of cumulative impact trends in significant environmental variables". Although the term sustainable development has not typically been linked with CEA, an association between these concepts has been identified. Regional CEA presents a framework for analysis consistent with the concept of sustainable development (Cocklin et al., 1992a; Piper, 2002).

Despite its importance, regional-based CEA has not become the cornerstone of CEA practice because there is not a mechanism in place to sustain it. Regional CEA studies have been conducted through multi-stakeholder research initiatives for specific basins or watersheds of interest (Culp et al., 2000a; Munkittrick et al., 2000). The studies are extensive in scope but are not ongoing; typically covering 3- to 5-year periods. These studies also occur outside of the EA process thus lacking a legislative trigger for continuance.

3. Existing methods for CEA

CEA methods and the quality of their application vary considerably (Spaling and Smit, 1994; Griffiths et al., 1998; CEAAgency, 2001). Methods have developed to support either project-based or regional-based conceptual views. Project-based CEAs emphasize S-B methods for prediction of effects (Cocklin et al., 1992a; Smit and Spaling, 1995; Ross, 1998; Hegmann et al., 1999; Bonnell and Storey, 2000; Spaling et al., 2000) whereas, E-B methods were developed for regional-based CEA to measure existing environmental quality (Fig. 2) (Culp et al., 2000a; Munkittrick et al., 2000; Gentile and Harwell, 2001).

3.1. Stressor-based methods

Hegmann et al. (1999) describe five stages for completing a S-B CEA under the *CEAA* including; (1) Scoping, (2) Analysis of Effects, (3) Identification of Mitigation, (4) Evaluation of Significance, and (5) Follow-up. S-B approaches follow a causal-based predictive framework (Spaling and Smit, 1993). They focus on predicting the CEs associated with a specific agent of change (e.g., mine development) (Cocklin et al., 1992a). Most often a *description* of local, baseline conditions is provided and this data populates predictive models to assess if project-related stressors will cause significant and adverse environmental effects (Fig. 3A) (Lyon, 1987).

S-B methods have been reviewed previously (Cocklin et al., 1992b; Spaling and Smit, 1993; Griffiths et al., 1998) and include spatial analysis (Johnston et al., 1988; Cocklin et al., 1992b), network analysis (Cocklin et al., 1992b), biogeographic analysis (Johnston et al., 1990), interactive matrices, ecological modeling, and expert opinion (Spaling and Smit, 1994). In Canada, S-B approaches have been used for developments such as the Alberta Pacific Forest Industries Pulp Mill and the Cardinal River Coals, Cheviot Coal Mine in Alberta (Spaling, 1994; Griffiths et al., 1998).

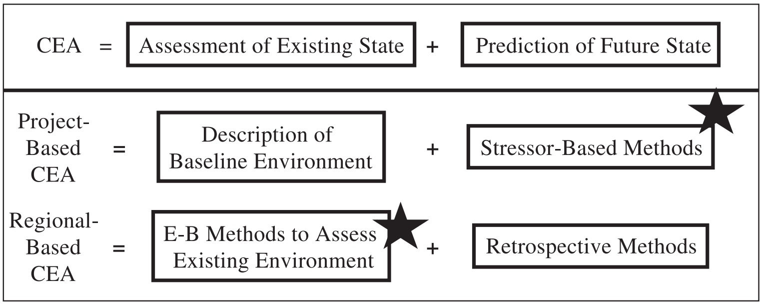

Fig. 2. Components required for cumulative effect assessment (CEA) and point of emphasis (star) for existing project-based and regional-based methods.

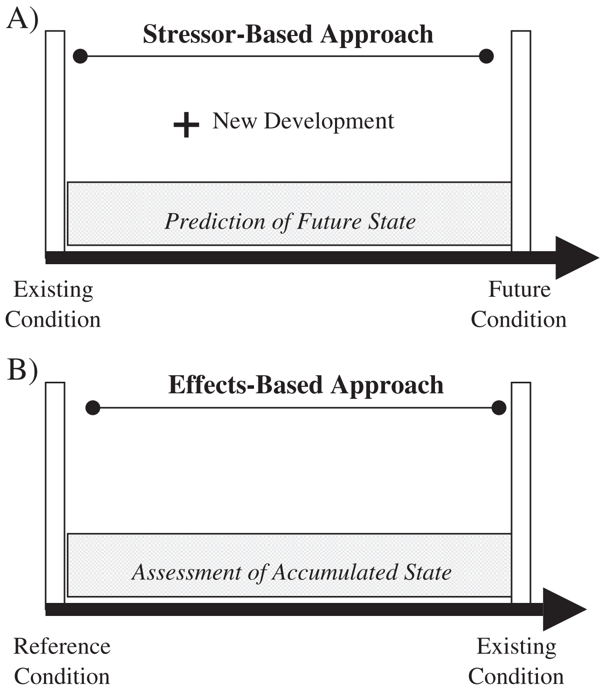

Fig. 3. Comparisons conducted under (A) stressor-based and (B) effects-based approaches. Stressor-based approaches predict the effects of development relative to the existing environmental state. Effects-based approaches assess the existing environmental condition relative to a reference condition (modified from Dubé and Munkittrick, 2001).

There are three main deficiencies associated with the use of S-B methods for CEA. One of the greatest deficiencies is a lack of sufficient, sustainable information on baseline environmental conditions (Dickert and Tuttle, 1985; O'Riordan, 1986; Sears and Yu, 1994; Griffiths et al., 1998; CEAAgency, 1999b; Hegmann et al., 1999). *Assessment* of baseline information to quantify if environmental effects exist *before development* is also a deficiency (Munkittrick et al., 2000). Environmental "bottom-lines" or thresholds for key environmental indicators (physical, chemical and biological) must be specified and assessed on an on-going basis to answer the following questions (Rees, 1995; Hegmann et al., 1999). Has a particular indicator in the environment exceeded a threshold? If not, then how close is it to exceedance? Will the proposed development result in threshold exceedances beyond those currently measured? Without an assessment capacity for the baseline data, data is simply accumulated and not evaluated (Rees, 1995). A third deficiency of S-B methods is they lack a mechanism for incorporating environmental data collected during follow-up programs (CEA-Agency, 2001).

The deficiencies associated with S-B methods have potential consequences. The potential for a development to cause environmental effects can be underestimated if predictive models are applied to poorly defined baseline data. The complexity of CEA precludes understanding of all project stressors and all stressor/environment interactions (Drouin and LeBlanc, 1994; Ross, 1994; Hegmann et al., 1999; Munkittrick et al., 2000; Gentile and Harwell, 2001). S-B methods assume identification of all project stressors. If the environmental quality is not accurately assessed before development, predictions may underestimate environmental effects due to unknown stressors, a lack of understanding of the assimilative capacity of the environment, or unknown stressor interactions (Contant and Wiggins, 1991). Prediction of environmental effects could also be underestimated in the absence of a solid environmental baseline, because it was not identified that aquatic biota were at threshold levels prior to development.

Lack of follow-up monitoring precludes our ability to assess the accuracy of impact predictions and improve the quality of S-B predictive tools (Hegmann et al., 1999). Furthermore, if the environmental response to stress is not measured before and after development there is the potential for the impacts associated with a project to be overestimated. The variability within an aquatic environment can be high due to natural perturbations. If this natural variability is not quantified before and after development, project proponents are unable to separate changes due to development from those due to natural causes.

3.2. Effects-based methods

In this paper, regional approaches refer to those developed external to the EA process where E-B quantification of existing environmental quality is emphasized over stressor identification. Other approaches developed within the Canadian EA process have been categorized as "regional" including sector-wide S-B approaches (e.g., oil sands development in Alberta; Spaling et al., 2000) and planning approaches (e.g., hydroelectric development in Newfoundland; Bonnell and Storey, 2000). However, the main drivers for these are development and the project approval process. Thus, these "regional" approaches are fundamentally S-B, albeit at an expanded scope.

E-B approaches measure the environmental response to stress and give "literal" feedback from the system being protected (Cairns, 1986; Foran and Ferenc, 1999). As such, they identify effects that may occur due to unidentified stressors or multiple stressor interactions (Munkittrick et al., 2000). E-B approaches measure changes in environmental quality by comparing indicators at a site of interest to those at "reference" sites (Fig. 3B) (Munkittrick et al., 2000). The magnitude of the difference between the indicators determines the level of change. Steps in the approach include definition of the geographical boundaries of the study area, selection of indicators, assessment of effects, and determination of effect significance (Environment Canada, 1998, 2001b; Munkittrick et al., 2000). If changes in environmental quality are measured, the stressors causing those effects are then identified.

In 1999, a report prepared for the CEAAgency stated "... there are few guidelines, standards, or procedures for the design of baseline environmental studies or environmental effects monitoring programs" (CEAAgency, 1999c). However, E-B studies in Canadian waters have provided a solid practice for environmental effects monitoring design, environmental indicator selection, and for setting threshold levels to evaluate the significance of a change. For example, the Canadian Environmental Effects Monitoring (EEM) Program has evolved since the late 1980s to detect the effects of pulp mill and metal mining effluents on surface waters as required under the federal *Fisheries Act* (Environment Canada, 1998, 2001b; Dumaresq et al., 2002; Walker et al., 2002). Individual mills or mines conduct localized E-B assessments on a recurring basis.

EEM programs were designed to provide a site-specific, yet nationally consistent, approach to monitoring changes in aquatic environments receiving industrial discharges. Differences between reference and exposure sites are measured for fish (as an indicator of fish population health) and benthic invertebrate communities (as an indicator of fish habitat condition) (Environment Canada, 1998, 2001b). Differences in chemical body burdens in edible fish tissue are also measured as an indicator of changes affecting the use of fisheries resources. Biological indicators were selected as opposed to chemical and physical measures (e.g., water and sediment quality) because biota integrate a cumulative response to environmental stress (Cairns, 1986; Environment Canada, 1998, 2001b; Munkittrick et al., 2000). Within each indicator, core "effect" endpoints have been selected. Sentinel fish species are monitored for changes in survival (i.e., age), energy use (i.e., size-at-age, gonad size), and energy storage (i.e., condition, liver size). Benthic invertebrate communities are monitored for changes in total abundance, taxa richness, Simpson's diversity or evenness, and the Bray–Curtis Index of dissimilarity. Physical and chemical measurements are "supporting" endpoints that are used to assist with interpretation of the biological data.

The "effect" endpoints are not stressor-dependent (e.g., specific to the pulp and paper industry) but are indicators of fundamental biological properties that would respond to multiple stressor types (Lowell et al., 2003). As such, they are relevant for any environmental monitoring program including baseline environmental studies conducted under the EA process. Further, the EEM program is state-of-the science and has shown that core effect endpoints can be used in site-specific monitoring studies to establish broad-scale, biotic response patterns to stressor exposure (Lowell et al., 2003).

In addition to identifying biological indicators of aquatic quality, the EEM program has established benchmarks to determine when a change in quality is significant (Environment Canada, 1998, 2001b). An "effect" is defined as a statistically significant response in at least one of the effect endpoints in comparisons between samples taken in an exposure area (or could be an area proposed for development, or a developed area) to those taken in a reference area. Variability in an endpoint measured at a reference site is the benchmark for assessing the significance of a change. A statistically significant change occurs if the variability measured in an endpoint *among* reference and exposed sites is greater than the variability measured *within* sites. Using this approach, it is possible to separate out changes due to development from those caused by natural perturbations (Munkittrick et al., 2000). If a single site is measured over time, (e.g., pre- and post-development) and it is not compared to a reference site, then there is no basis to determine if any measured changes were due to a specific development or natural causes. However, if indicators at a site are compared to a reference site, both before and after development, then it is possible to separate out effects due to development (Fig. 4).

It has been argued that statistical significance may not be an appropriate benchmark because statistical differences may not be ecologically, socially, or economically important (Munkittrick et al., 2002). Although a change at a site may be outside of the natural variability measured at a reference site, it is difficult to determine if it will result in ecologically important consequences (e.g., loss of species). Often changes are measured in aquatic systems but they continue to be viable and function (Munkittrick et al., 2000). Science-based thresholds that indicate an ecologically significant change have not yet been developed. In the interim, a statistically significant difference can be set *as the starting point* for evaluating if an effect occurs. If an effect occurs, then the magnitude and direction of that effect relative to the reference condition can be examined. If this information is provided to stakeholders before and after project development to illustrate if indicators have changed and by how much, this would facilitate discussions on the ecological, social, and economic acceptability of those changes (Fig. 5).

It has also been argued that E-B methods are local and not suitable for regional-based CEA. However, local monitoring studies can be regionalized by simple addition of stations over a larger spatial area (Munkittrick et al., 2000). E-B methods can also result in broader scale assessments if the same core endpoints are sampled and changes are evaluated using consistent benchmarks (e.g., reference site variability). If local E-B assessments were conducted by EA

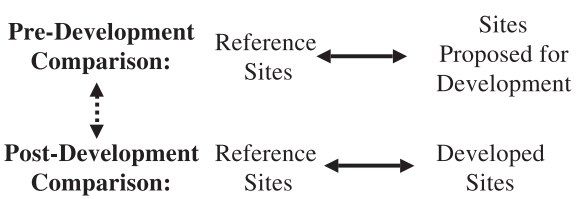

Fig. 4. Effects-based comparisons before and after project development. Spatial comparisons within each time period determine if changes occur that are outside natural variability. Temporal comparisons determine project-related effects.

Site X: Site Effect Summary					
Trophic Level	**Response**	**Endpoint**	**Effect?**	**Direction**	**Magnitude**
Fish	Survival	Age	✓	Dev>Ref	15%
	Energy Use	Size-at-age	X	X	X
		Gonad size	✓	Dev<Ref	25%
	Energy Storage	Condition	X	X	X
		Liver size	✓	Dev>Ref	20%
Benthos	Total Abundance		✓	Dev>Ref	50%
	Taxa Richness		X	X	X
	Simpsons Diversity		X	X	X
	Bray-Curtis		✓	Dev<Ref	15%

Fig. 5. Example of the information collected by the Environmental Effects Monitoring programs in Canada (Environment Canada, 2001b). Core effect endpoints are measured for key biological components to determine if effects exists, the direction of the effect (i.e., is the response measured at a developed site less than or greater than that measured at a reference site), and the magnitude of the effect relative to the reference site.

practitioners before and after development and consistent indicators and benchmarks used, regional E-B assessments could compound from local studies.

Lack of suitable reference areas is often cited as a limitation of E-B approaches as few landscapes have been untouched by human activity (Clark, 1994). However, reference sites need not be "pristine" for an E-B assessment. Consider the scenario where a new development is proposed 8 km downstream of an existing point source discharge (Fig. 6). Reference sites could be sampled upstream of the proposed development (Reference Site A) and upstream of the existing discharge (Reference Site B). Potentially impacted sites could be sampled downstream of the proposed development and compared to both reference sites to measure the presence, direction and magnitude of any existing effects. These comparisons conducted before and after development would illustrate any effects of the new project in combination with effects from the

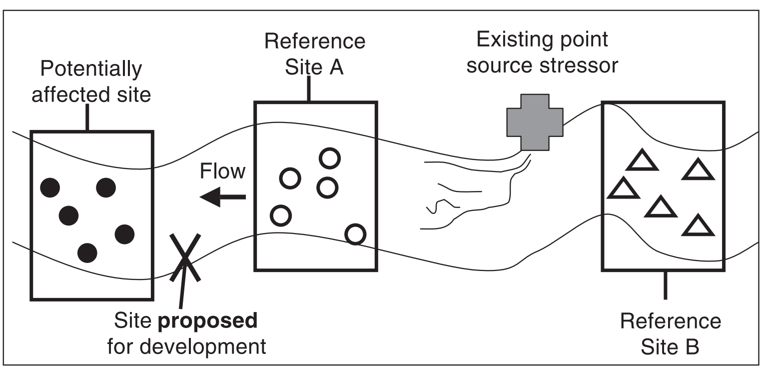

Fig. 6. Possibilities for reference site selection in a riverine scenario influenced by multiple stressors.

point source, i.e., the cumulative effect. In multiple stressor scenarios such as this, these comparisons will not show the effect of the new development in isolation. This type of information can be obtained through investigation of cause, weight of evidence, and mesocosm techniques (Culp et al., 2000b; Lowell et al., 2000; Dubé et al., 2002; Hewitt et al., in press). However, from a CE standpoint, what is important is measurement of the contribution to the combined effect.

E-B methods can be used to effectively and consistently measure the environmental response to stress. However, identification of the stressors causing the effects occurs after effects have been measured (Munkittrick et al., 2000). This limits the predictive capabilities of E-B approaches for CEA. CEA requires that effects of proposed developments be predicted prospectively, not retrospectively.

4. A framework for CEA of Canada's inland waters

Conceptually, CEA is a feasible mechanism through which sustainable development can be achieved yet it remains a methodological challenge because E-B and S-B methods fail to address the needs for CEA when used in isolation (Sonntag et al., 1987; Cocklin et al., 1992b; Clark, 1994; Drouin and LeBlanc, 1994; CEAAgency, 2001). A strategy is proposed to integrate the advantages of existing approaches into a more holistic framework.

4.1. Justification for beginning with water

The methodological complexity of CEA is overwhelming. Consideration of multiple impacts from multiple sources over broad temporal and spatial scales is a scientific challenge for single media (e.g., water) let alone for combined environmental receivers (e.g., water and air and land). This complexity increases with the additional considerations of socio-economic impacts related to environmental degradation and the intricacies of multi-jurisdictional management. Moving forward to better CEA requires progressive implementation of new methodologies where the possibilities for effective demonstration are realistic. Freshwater systems offer this possibility because of the existing state-of-the science. Data sets and benchmarks exist as does a demonstrated approach to separate out natural variability from effects due to development (Cairns, 1986).

4.2. Proposed strategy for project-based aquatic CEA

Project-based CEA would be conducted by EA proponents and consist of three progressive stages: (1) Pre-development E-B assessment to determine existing aquatic quality; (2) Pre-development S-B assessment to predict project effects relative to (1); and (3) Follow-up monitoring to measure project effects after development (Fig. 7; Column 1).

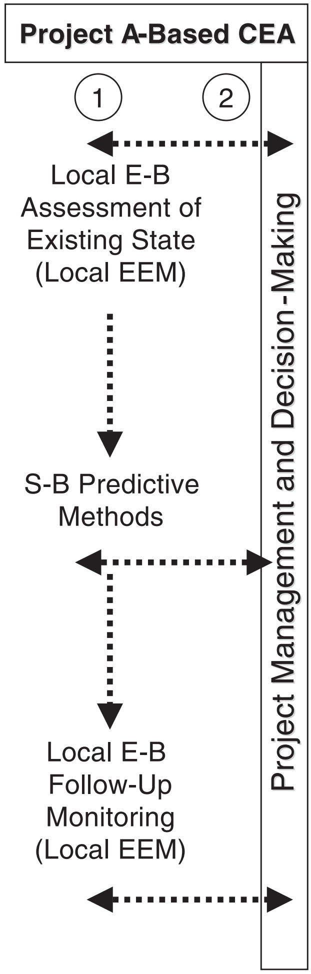

Fig. 7. Framework for project-based cumulative effects assessment (CEA) consisting of three progressive stages (column 1) including effects-based (E-B) assessment of existing aquatic state, stressor-based (S-B) assessment to predict development effects relative to the existing state, and E-B follow-up monitoring. E-B assessment would be implemented using local environmental effects monitoring (EEM) studies. Project-based CEA involves stakeholder input (column 2) at key decision stages.

Quantification of the existing environmental state is the first step for CEA because it is difficult to predict the impact of future development when the existing status and sensitivity of the system are unknown (Slocombe, 1993). E-B methods offer the greatest advantages for assessment of existing state because their effectiveness has been demonstrated and they are operational (Lowell et al., 2003). If the E-B standard is used, consistency in data collection, assessment, and interpretation will establish a common base for the state-of-the environment

(Roots, 1986; Sears and Yu, 1994). Development of a core monitoring standard is essential for local-scale monitoring to contribute to regional E-B assessments (Dubé and Munkittrick, 2001).

It is recommended that EA proponents that would normally be required to obtain relevant field data conduct local, E-B assessments using the guidance established for the Canadian EEM program for study design, selection of boundaries, sample stations, species, indicators and benchmarks (Environment Canada, 1998, 2001b). It is also recommended that the effect endpoints used in the EEM program be adopted and reference site variability be used as the initial benchmark for determination of effects. Additional, site-specific endpoints can be incorporated into the E-B assessment as "effect" endpoints or supporting endpoints depending upon stakeholder input (Fig. 7; Column 2). If a statistically significant difference is measured between effect endpoints sampled at reference sites and the site proposed for development, then a change has occurred. The direction and magnitude of that change relative to the mean reference response for that indicator should then be determined. If these recommendations are adopted, EA proponents will be required to conduct fieldwork in addition to summarizing historical information on baseline aquatic data (Clark, 1994). Proponents currently conduct some form of environmental monitoring to fill gaps in historical data. The design of these programs requires review to ensure they are consistent with the EEM model and the regional CEA framework.

Information collected during the E-B assessment is used to focus S-B predictive methods (Munkittrick et al., 2000; Dubé and Munkittrick, 2001). Existing S-B practices for EA would be acceptable to implement at this stage of the framework (Fig. 7; Column 1). Spatial analysis, network analysis, interactive matrices and ecological modeling would all benefit from the information gathered during the E-B stage (Cocklin et al., 1992a). The CEA can be moved forward by determining if project-related stressors have the potential to move aquatic indicators closer to, or beyond, benchmark levels of change.

Due to the complexity of CEA, checks and balances are required. Follow-up monitoring is essential for scientific verification and environmental safeguarding (Spaling and Smit, 1993; Bonnell and Storey, 2000; O'Riordan, 1986; CEA-Agency, 1999c, 2001). Thus, the final stage of the project-based CEA is follow-up monitoring (Fig. 7; Column 1). An E-B assessment is conducted using the same methodology as the pre-development E-B assessment (i.e., same sites, species, endpoints, and benchmarks). Comparisons are conducted as illustrated in Fig. 4 and the accuracy of impact predictions is evaluated. Follow-up monitoring is the primary mechanism for adaptive management at both project and regional levels (Slocombe, 1993). If effects are measured that were not anticipated, a mechanism exists for adjusting management strategies and mitigation options. Follow-up monitoring can also improve S-B predictive methods by verifying our understanding of stressor–receptor interactions (CEAAgency, 2001).

CEA is a multi-stakeholder process and requires a framework with identified loci for stakeholder input into decision-making (CEAAgency, 2001). At the project level, decisions are required prior to the E-B assessment, after the S-B prediction, and after follow-up monitoring (Fig. 7; Column 2). These decisions are necessary to design an E-B program consistent with project and regional goals, to determine a priori when an effect exists and when that effect is important, and to determine the conditions under which project development will be approved. Decisions are also required to determine when impact predictions will be deemed inaccurate and how adaptive management will be implemented.

Stakeholder consultation is not suggested after the E-B assessment but after completion of both the E-B and S-B stages because the process of predicting effects for a proposed development should not be delayed if existing effects are measured. The project proponent must assess their CEs in the context of the existing effects, but they should not be responsible for evaluating and managing existing effects unrelated to their specific application. Regional-level stakeholder input is required to consider the importance (ecological, social, economic) of existing effects.

A CEA framework should identify key points where decisions are required and the information needed for those decisions to be made. For example, science can play a critical role for informed participation in decision-making by recommending indicators, benchmarks, and assessing E-B data consistent with regional CEA (Slocombe, 1993; Spaling and Smit, 1993). If environmental effects are measured, that could be the first step for determining significance as defined under the *CEAA* (Drouin and LeBlanc, 1994; Bonnell and Storey, 2000). The role of science would be to quantify a level of change relative to a benchmark and not to determine if that change is unacceptable (Munkittrick et al., 2000). If changes are measured, this information could be used by stakeholders to determine the acceptability of those effects in broader ecological, social and economic terms (Munkittrick et al., 2000). As Fox (1986) states, there are two major technical aspects of CEA; one aspect is concerned with measuring the cumulative physical and biological effects, and the other is concerned with translating those effects into social consequences. Science can provide an important contribution to the analysis and evaluation of cumulative environmental change at key points in a decision-making framework.

4.3. Strategy for regional-based aquatic CEA

CEA is conducted for a region as an independent, integrated, environmental monitoring and assessment operation. The vision is to develop an on-going "weather station" for aquatic quality. In this way, regional CEA exists as its own entity but incorporates information from project-based CEAs (Fig. 8; Columns 1 and 2). Project-based CEA is thus viewed as a means of incorporating environmental considerations into a larger assessment and planning process (Bonnell and Storey, 2000).

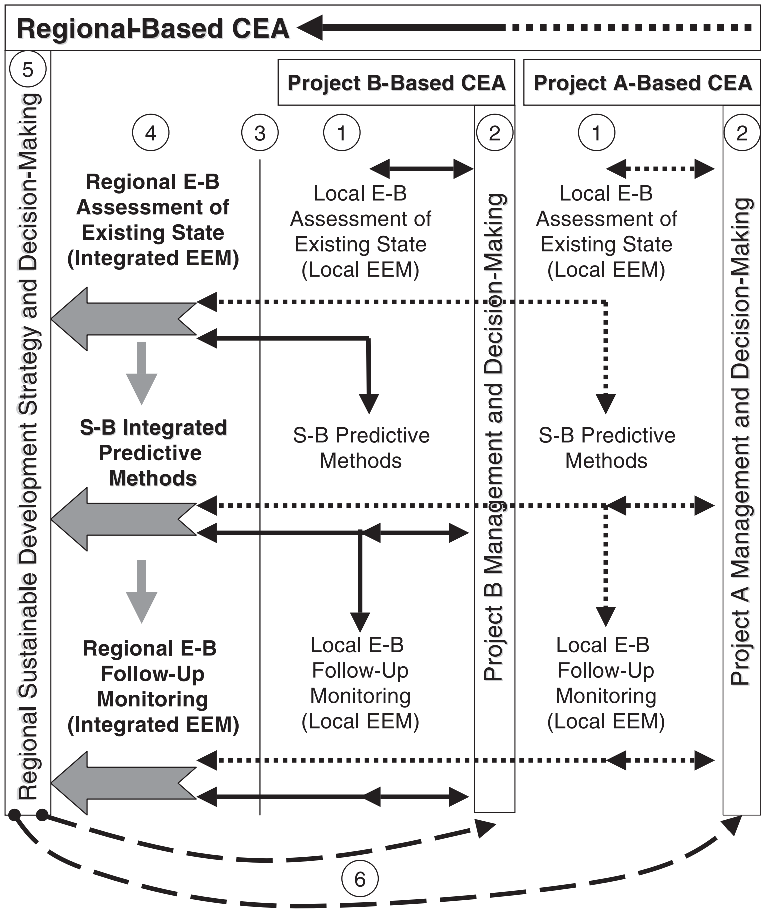

Fig. 8. Framework for regional-based cumulative effects assessment (CEA) that integrates information from multiple project-based CEAs (Project A; dashed lines and Project B; solid lines). Each project-based CEA consists of a local effects-based (E-B) assessment, a stressor-based (S-B) assessment, follow-up monitoring (column 1), and loci for stakeholder input (column 2). Project-based information contributes to stages of regional-based CEA (column 3). Regional CEA consists of integrated E-B, S-B and follow-up stages (column 4) and provides information to a regional sustainable development strategy (column 5). Regional decision-making provides adaptive management (circle 6) for project-based CEA.

Regional CEA consists of E-B, S-B, and follow-up components as integrated and broadened stages (Fig. 8; Column 4). Information from these stages feeds into a regional sustainable development strategy for decision-making and adaptive management (Fig. 8; Column 5). E-B assessment is required on an on-going basis to monitor effects due to development, the consequences of incorrect impact predictions, effects due to unknown impacts or unknown cumulative impact interactions, and ultimately to determine if aquatic systems are being pushed beyond their assimilative capacity. It is required at a regional scale to limit fragmentation and be consistent with the scale necessary to assess sustainable development.

The aquatic "weather station" would be a central data repository containing E-B information on key indicators of aquatic ecosystem health (e.g., water quality and quantity, biological quality) and levels of development (Clark, 1994; Drouin and LeBlanc, 1994; Lawrence, 1997). Environmental quality information could come from provincial and federal monitoring programs as well as from the EA process. This data could be integrated into a spatially explicit, geographic information system (GIS) where it could be displayed, graphed, summarized, and be accessible to different users including aquatic resource managers, scientists, EA stakeholders and the public (Roots, 1986). Examples exist of these types of science-based communication and data assessment tools (Dickert and Tuttle, 1985; Lyon, 1987; Johnston et al., 1988; Childers and Gosselink, 1990; Thomas et al., 1991; Cocklin et al., 1992a,b; Slocombe, 1993).

The regional CEA operation would also have a capacity to assess the data against established benchmarks. Collection of data that is not assessed against a benchmark provides no opportunity to evaluate changes over time or space (Lyon, 1987). In Canada, many benchmarks exist for aquatic components but they are applied to data sets residing in different programs and jurisdictions. For example, the EEM programs have established biological indicators and benchmarks for aquatic systems (Environment Canada, 1998, 2001b; Munkittrick et al., 2002; Lowell et al., 2003). National (CCME, 1999) and provincial (e.g., Alberta Environment, 1999) water quality guidelines also exist. If the different data sets and their respective benchmarks can be integrated it would provide an "accumulating" effect assessment for aquatic systems. It has been stated that benchmarks need to be developed specifically for CEA (i.e., a CEA index) (Griffiths et al., 1998; CEAAgency, 1999c). However, development of CEA-specific indicators is not possible until existing benchmarks for aquatic components are evaluated.

Conducting ongoing, data to benchmark comparisons for multi-jurisdictional data sets is a significant task and beyond manual computation and assimilation. The assessed information for each comparison, and for each aquatic component, would require integration to provide a visual, spatially explicit state of the aquatic environment. At the same time, the basis for the assessment must be transparent so users can explore why aquatic quality was calculated to be poor to excellent in particular areas. To ensure consistency, quality assurance and quality control, the regional CEA operation would require automation (Johnston et al., 1988).

The regional E-B assessment would be available to multiple end users including the public but would be maintained by a scientific authority to ensure science-based consistency in the process. The framework proposes that EA proponents could draw information from the regional E-B assessment as well as contribute baseline and follow-up information to it. The importance of information flow from the project-level to the regional level (Fig. 8; Column

3) is critical especially if a project proponent has measured effects in their local environment before their specific development has started. It may be outside of a proponent's responsibility to manage effects caused by the presence of existing stressors, but it is within the interest of regional stakeholders to address the acceptability of existing effects and adaptively manage them if required (Fig. 8; Column 5; Circle 6).

Incorporating project-level E-B information into a regional E-B strategy offers significant advantages for stakeholders with an interest in follow-up monitoring (Fig. 8; Column 4). If the initial assessment of existing state is entered into a regional E-B assessment, then this information can be tracked, repeated after development, and development-related differences interpreted. This is important from a project management point-of-view to provide an avenue to adaptively manage the project if impact predictions were inaccurate. This is also critical from a regional perspective to track multiple project developments to determine if development is proceeding according to targets established under the regional sustainable development strategy.

Regional E-B information can be used to facilitate development of improved S-B predictive tools for forecasting development scenarios for single projects. For example, in the EA for the Alberta Pacific Forest Industries Pulp Mill in Alberta, Canada, proponents were given access to a large provincial water quality monitoring data set on dissolved oxygen levels in the Athabasca River (Spaling, 1994; Griffiths et al., 1998). Access to this E-B information was critical to apply a S-B model to predict the potential consequence of discharging an effluent high in organics and biochemical oxygen demand to the river. Regional E-B information can also be used to develop S-B tools for forecasting environmental impacts of development scenarios involving multiple projects. This application would be a useful planning tool to support decisions under a regional sustainable development strategy. Regional S-B methods have a good starting point in Canada based on oil sands applications in AB (Spaling et al., 2000) and hydropower applications in Newfoundland (Bonnell and Storey, 2000). However, further work is required to broaden regional, S-B methodologies beyond sector-specific applications.

One of the critical components of the regional CEA framework is the regional sustainable development strategy (Fig. 8; Column 5). These are not new in Canada as land-use planning is commonly used to establish an order of preference among a set of resource allocation choices. This planning is *a priori* and sets the stage for the type and magnitude of development relative to the goals and objectives set out for the region through multi-stakeholder consultation (Spaling and Smit, 1994). Bonnell and Storey (2000) applied this planning approach to assess multiple small hydro developments in Newfoundland, Canada. Spaling (1994) also describe how this approach was used to evaluate development of the Bow River Valley corridor in Banff National Park, AB. In the northern river basins, a Regional Sustainable Development Strategy currently exists for the Athabasca Oil Sands Area. Information generated during regional

CEA can be incorporated into a regional planning process and used to adaptively manage development at more local scales (Fig. 8; Circle 6). Certainly, establishing regional planning objectives and comparing existing and proposed development to those objectives are essential elements for sustainable development of the environment.

4.4. Implementation of the regional CEA framework

Methods for implementing a regional E-B assessment are being developed for the Prairie and Northern Region of Canada (Dubé et al., unpublished; National Water Research Institute, Environment Canada, Saskatoon, SK). EcoAtlas-CE (Cumulative Effects) is a GIS-based multi-module software tool designed to integrate and assess multi-jurisdictional databases for aquatic CEA. Databases included in the software to date are the Canadian HYDEX/HYDAT hydrometric database, the national Aquatic Chemistry and Biological Information System (ACBIS), Alberta provincial water quality monitoring data, Alberta provincial point source effluent quality data (pulp and municipal sewage effluents), the national Municipal Water Use Database (MUD), and biological data from the national EEM Program. These databases have been collected independently by federal, provincial, and municipal sources and have a long-term, on-going record of monitoring. The data at each location of collection can be described temporally and spatially using user-defined graphing menus.

The assessment component of EcoAtlas-CE consists of automated comparisons of data to benchmarks to illustrate ‘‘degrees’’ of aquatic quality on map layers (Dubé et al., unpublished; National Water Research Institute, Environment Canada, Saskatoon, SK). Assessments are conducted for all water and biological quality data sets. The software contains an EcoAtlas Water Quality Index (EWQI) Calculator where water quality data at a site or series of sites are compared to water quality guidelines and the Canadian Water Quality Index (CCME, 2001a,b) is calculated. The index can be calculated for a particular time interval, for all variables at a site or sites (i.e., general index), or for groups of variables (i.e., nutrient index, pesticide index, etc). The objectives are set by the user. The results from the EWQI calculator are displayed in EcoAtlas-CE to show sites where water quality is rated from excellent to poor for the period of calculation.

EcoAtlas-CE also contains a module called the EEM Statistical Assessment Tool that automatically assesses biological data collected using the EEM study design (Dubé et al., unpublished; National Water Research Institute, Environment Canada, Saskatoon, SK). It currently uses data from the national EEM database to determine if core ‘‘effect’’ endpoints significantly differ between reference and exposure areas for particular sites. The assessment for each site is displayed in EcoAtlas-CE as either a green (no effect) or a red (effect) square on a regional map. Information on the effects is available for each point as summarized graphs and statistical results. When assessments for each site are consistently analyzed and displayed, regional effects can be illustrated. The EEM Statistical Assessment module was designed to assess data in the national EEM database and to provide a mechanism for EA proponents to integrate their E-B monitoring data. If proponents conduct E-B monitoring using the EEM model and analyze the data using the module, site-specific applications could be integrated into the regional E-B system (integrated EEM) (Fig. 8; Column 3).

EcoAtlas-CE was developed as a demonstration application under the Northern Rivers Ecosystem Initiative to illustrate if and how the proposed CEA framework could be implemented. The vision is to continue to develop the system for CEA and multi-stakeholder use because it can provide an institutional "memory" for monitoring, assessing and predicting CEs (Johnston et al., 1988; Moffatt, 1990; Cocklin et al., 1992b). It also has obvious contributions for state-of-the environment reporting (Johnston et al., 1988; Cocklin et al., 1992a).

5. Concluding remarks

Significant progress in environmental management is likely to be realized if the conceptual and methodological links between sustainable development, state-of-the environment reporting, and CEA can be consolidated and given practical expression (Slocombe, 1994; Cocklin et al., 1992b; Piper, 2002). To date, the link between CEA and sustainable development has not been realized because CEA concepts and methods have developed along two dichotomous tracks. One track views CEA as an extension of the EA process for project developments and has resulted in development of S-B CEA methods. The other track views CEA as a broader, regional assessment tool where E-B methods specialize in quantification of existing aquatic effects. When used in isolation, S-B and E-B methods do not address CEA in the context necessary for sustainable development. This paper describes a framework for aquatic systems that could improve CEA and its ability to better monitor and assess sustainable development of our aquatic resources.

In order for the framework vision to be realized the following points need consideration:

- A mechanism is needed for the framework to be sustained. Regional CEA requires a consistent, science-based process over large scales and involving multiple stakeholders. Development, implementation, and maintenance of a regional CEA framework require that a science-based champion or "responsible owner" be identified and supported.
- There is an incorrect perception that the science of CEA is not at a stage to support a regional CEA framework for aquatic systems. Linkages between CEA research, environmental monitoring programs (e.g., Canadian EEM program), and front-line EA practice need to be strengthened to ensure state-of-the science developments are communicated to address gaps in CEA practice.

- The role of science in aquatic CEA requires review so that clear loci for contribution to project-based and regional-based CEA are identified. Obvious contributions include development and implementation of regional E-B assessments.
- It must be recognized that CEA is a science and science must be supported by data that is collected, managed, and assessed in a format consistent with the needs for CEA. In Canada, aquatic data is collected, managed, and assessed by different jurisdictions and by different programs within each jurisdiction. This has resulted in fragmentation, a lack of consistency, and limited data access. This has also significantly restricted how existing data can be used for CEA. These limitations could be overcome if a regional approach was adopted by stakeholders and the science of CEA was used to direct the collection and management of information from the top down.

Acknowledgements

Drs. J. M. Culp and K.R. Munkittrick provided insightful comments on this manuscript. J. Inkster for editorial efforts and H. Popoff for library services.

References

Alberta Environment. Surface water quality guidelines for use in Alberta. Edmonton, AB, Canada: Environmental Sciences Division, Alberta Environmental Protection; 1999.

Bonnell S, Storey K. Addressing cumulative effects through strategic environmental assessment: a case study of small hydro development in Newfoundland, Canada. J Environ Assess Policy Manag 2000;2:477–99.

Cairns Jr J. Scientific perspective: freshwater. In: Beanlands GE, Erckmann WJ, Orians GH, O'Riordan J, Policansky D, Sadar MH, Sadler B, editors. Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective. Canadian Environmental Assessment Research Council and U.S. National Research Council, Ministry of Supply and Services, Cat. No. En 106-2/1985, Ottawa, ON, Canada; 1986. p. 39–43.

Canadian Council of Ministers of the Environment (CCME). Canadian environmental quality guidelines. Winnipeg, MB, Canada: Canadian Council of Ministers of the Environment; 1999.

Canadian Council of Ministers of the Environment (CCME). Canadian water quality guidelines for the protection of aquatic life: Canadian water quality index 1.0, user's manual. Canadian environmental quality guidelines, 1999. Winnipeg, MB, Canada: Canadian Council of Ministers of the Environment; 2001a. 5 pp.

Canadian Council of Ministers of the Environment (CCME). Canadian water quality guidelines for the protection of aquatic life: Canadian water quality index 1.0, technical report. Canadian environmental quality guidelines, 1999. Winnipeg, MB, Canada: Canadian Council of Ministers of the Environment; 2001b. 13 pp.

Canadian Environmental Assessment Agency (CEAAgency). Operational policy statement: addressing cumulative environmental effects under the Canadian environmental assessment act. Cat No. OPS_EOP/3-1999, Hull, QC, Canada; 1999a.

Canadian Environmental Assessment Agency (CEAAgency). Review of the Canadian environmental assessment act: a discussion paper for public consultation. http://www.ceaa.gc.ca/0007/0002/0001/index_e.htm, Hull, QC, Canada; 1999b.

Canadian Environmental Assessment Agency (CEAAgency). Options and tools for improving follow-up: a discussion paper. http://www.ceaa.gc.ca/0007/0002/0002/bkstd04_e.htm, Hull, QC, Canada; 1999c.

Canadian Environmental Assessment Agency (CEAAgency). Report of the minister of the environment to the parliament of Canada on the review of the Canadian environmental assessment act: strengthening environmental assessment for Canadians. http://www.ceaa.gc.ca/0007/index_e.htm), Hull, QC, Canada; 2001.

Childers DL, Gosselink JG. Assessment of cumulative impacts to water quality in a forested wetland landscape. J Environ Qual 1990;19:455–64.

Clark R. Cumulative effects assessment: a tool for sustainable development. Impact Assess 1994;12: 319–31.

Cocklin C, Parker S, Hay J. Notes on cumulative environmental change: I. Concepts and issues. J Environ Manag 1992a;35:31–49.

Cocklin C, Parker S, Hay J. Notes on cumulative environmental change: II. A contribution to methodology. J Environ Manag 1992b;35:51–67.

Contant CK, Wiggins LL. Defining and analyzing cumulative environmental impacts. Environ Impact Asses Rev 1991;11:297–309.

Culp JM, Cash KJ, Wrona FJ. Integrated assessment of ecosystem integrity of large northern rivers: the Northern River Basins study example. J Aquat Ecosyst Stress Recovery 2000a;8:1–5.

Culp JM, Lowell RB, Cash KJ. Integrating mesocosm experiments with field and laboratory studies to generate weight-of-evidence risk assessments for large rivers. Environ Toxicol Chem 2000b;19: 1167–73.

Dickert TG, Tuttle AE. Cumulative impact assessment in environmental planning: a coastal wetland watershed example. Environ Impact Asses Rev 1985;5:37–64.

Drouin C, LeBlanc P. The Canadian environmental assessment act and cumulative environmental effects. In: Kennedy AJ, editor. Cumulative effects assessment in Canada: from concept to practice. Fifteenth Symposium of Alberta Society of Professional Biologists, 13–14 April 1994, Calgary, AB, Canada. Edmonton, AB, Canada: Alberta Association of Professional Biologists; 1994. p. 25–36.

Dubé MG, Munkittrick KR. Integration of effects-based and stressor-based approaches into a holistic framework for cumulative effects assessment in aquatic ecosystems. Hum Ecol Risk Assess 2001;7:247–58.

Dubé MG, Culp JM, Cash KJ, Glozier NE, MacLatchy DL, Podemski CL, et al. Artificial streams for environmental effects monitoring (EEM): development and application in Canada over the past decade. Water Qual Res J Can 2002;37:155–80.

Duinker PN. Cumulative effects assessment: what's the big deal? In: Kennedy AJ, editor. Cumulative effects assessment in Canada: from concept to practice. Fifteenth Symposium of Alberta Society of Professional Biologists, 13–14 April 1994, Calgary, AB, Canada. Edmonton, AB, Canada: Alberta Association of Professional Biologists; 1994. p. 11–24.

Dumaresq C, Hedley K, Michelutti R. Overview of the metal mining environmental effects monitoring program. Water Qual Res J Can 2002;37:213–8.

Environment Canada. Pulp and paper technical guidance for aquatic environmental effects monitoring. EEM/1998/1, National EEM Office, Science Policy and Environmental Quality Branch, Ottawa, ON, Canada; 1998.

Environment Canada. Threats to sources of drinking water and aquatic ecosystem health in Canada. NWRI Scientific Assessment Report Series No. 1, National Water Research Institute, Burlington, ON, Canada; 2001a.

Environment Canada. Metal mining guidance document for aquatic environmental effects monitoring. http://www.ec.gc.ca/eem, National EEM Office, Science Policy and Environmental Quality Branch, Ottawa, ON, Canada; 2001b.

Foran JA, Ferenc SA. Multiple stressors in ecological risk and impact assessment. SETAC Pellston Workshop on Multiple Stressors in Ecological Risk and Impact Assessment: 13–18 September

1997, Pellston, Michigan, USA. Pensacola, FL, USA: Society of Environmental Toxicology and Chemistry; 1999. p. 1–50.

Fox IK. Management perspective: commentary I. In: Beanlands GE, Erckmann WJ, Orians GH, O'Riordan J, Policansky D, Sadar MH, Sadler B, editors. Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective. Canadian Environmental Assessment Research Council and U.S. National Research Council, Ministry of Supply and Services, Cat. No. En 106-2/1985, Ottawa, ON, Canada; 1986. p. 67–9.

Gentile JH, Harwell MA. Strategies for assessing cumulative ecological risks. Hum Ecol Risk Assess 2001;7:239–46.

Griffiths, A, McCoy, E, Green, J, Hegmann, G. Cumulative effects assessment. Prepared for Alberta Environmental Protection by Macleod Institute for Environmental Analysis, Calgary, AB, Canada; 1998.

Harwell MA, Gentile JH. Environmental decision-making for multiple stressors: framework, tools, case studies, and prospects. In: Ferenc SA, Foran JA, editors. Multiple stressors in ecological risk and impact assessment: approaches to risk estimation. Pensacola, FL, USA: Society of Environmental Toxicology and Chemistry (SETAC); 2000. p. 169–235.

Hegmann G, Cocklin C, Creasey R, Dupuis S, Kennedy A, Kingsley L, et al. Cumulative effects assessment practitioners guide. Prepared by AXYS Environmental Consulting and CEA Working Group for the Canadian Environmental Assessment Agency, Hull, QC, Canada; 1999.

Hewitt LM, Dubé MG, Culp JM, MacLatchy DL, Munkittrick KR. A proposed framework for investigation of cause in environmental effects monitoring. Hum Ecol Risk Assess; 2003;9:195–211.

Johnston CA, Detenbeck NE, Bonde JP, Niemi GJ. Geographic information systems for cumulative impact assessment. Photogramm Eng Remote Sensing 1988;54:1609–15.

Johnston CA, Detenbeck NE, Niemi GJ. The cumulative effect of wetlands on stream water quality and quantity: a landscape approach. Biogeochemistry 1990;10:105–41.

Lawrence DP. Integrating sustainability and environmental impact assessment. Environ Manag 1997; 21:23–42.

Lowell RB, Culp JM, Dubé MG. A weight-of-evidence approach for northern river risk assessment: integrating the effects of multiple stressors. Environ Toxicol Chem 2000;19:1182–90.

Lowell RB, Ribey S, Ellis IK, Porter E, Culp JM, Grapentine LC, et al. National assessment of the pulp and paper environmental effects monitoring data. Ottawa, ON, Canada: National EEM Office, National Water Research Institute, Environment Canada; 2003.

Lyon WA. Environmental impact analysis as related to river basin management. Water Pollut Control Assoc PA 1987:17–21.

Moffatt I. The potentialities and problems associated with applying information technology to information management. J Environ Manag 1990;0:209–20.

Munkittrick KR, McMaster ME, Van Der Kraak G, Portt C, Gibbons WN, Farwell A, et al. Development of methods for effects-driven cumulative effects assessment using fish populations: Moose River Project. Florida, USA: Society of Environmental Toxicology and Chemistry; 2000.

Munkittrick KR, McGeachy SA, McMaster ME, Courtenay SC. Overview of freshwater fish studies from the pulp and paper environmental effects monitoring program. Water Qual Res J Can 2002;37:49–77.

O'Riordan J. Management perspective: cumulative assessment and the freshwater environment. In: Beanlands GE, Erckmann WJ, Orians GH, O'Riordan J, Policansky D, Sadar MH, Sadler B, editors. Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective. Canadian Environmental Assessment Research Council and U.S. National Research Council, Ministry of Supply and Services, Cat. No. En 106-2/1985, Ottawa, ON, Canada; 1986. p. 55–66.

Piper JM. CEA and sustainable development: Evidence from UK case studies. Environ Impact Asses Rev 2002;22:17–36.

Rees WE. A role for environmental impact assessment in achieving sustainable development. Environ Impact Asses Rev 1988;8:273–91.

Rees WE. Cumulative environmental assessment and global change. Environ Impact Asses Rev 1995;15:295–309.

Roots EF. Closing remarks: a current assessment of cumulative assessment. In: Beanlands GE, Erckmann WJ, Orians GH, O'Riordan J, Policansky D, Sadar MH, Sadler B, editors. Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective. Canadian Environmental Assessment Research Council and U.S. National Research Council, Ministry of Supply and Services, Cat. No. En 106-2/1985, Ottawa, ON, Canada; 1986. p. 149–60.

Ross WA. Assessing cumulative effects: both impossible and essential. In: Kennedy AJ, editor. Cumulative effects assessment in Canada: from concept to practice. Fifteenth Symposium of Alberta Society of Professional Biologists, 13–14 April 1994, Calgary, AB. Edmonton, AB, Canada: Alberta Association of Professional Biologists; 1994. p. 3–9.

Ross WA. Cumulative effects assessment: learning from Canadian case studies. Impact Assess Proj Apprais 1998;16:267–76.

Sears SK, Yu MS. Prototype guidelines for assessing the cumulative environmental effects of Ontario Hydro hydroelectric modification projects. In: Kennedy AJ, editor. Cumulative effects assessment in Canada: from concept to practice. Fifteenth Symposium of Alberta Society of Professional Biologists, 13–14 April 1994, Calgary, AB. Edmonton, AB, Canada: Alberta Association of Professional Biologists; 1994. p. 179–88.

Slocombe DS. Implementing ecosystem-based management. Bioscience 1993;43:612–22.

Slocombe DS. Ecosystem integrity as a basis for cumulative effects assessment. In: Kennedy AJ, editor. Cumulative effects assessment in Canada: from concept to practice. Fifteenth Symposium of Alberta Society of Professional Biologists, 13–14 April 1994, Calgary, AB. Edmonton, AB, Canada: Alberta Association of Professional Biologists; 1994. p. 93–102.

Smit B, Spaling H. Methods for cumulative effects assessment. Environ Impact Asses Rev 1995;15: 81–106.

Sonntag NC, Everitt RR, Rattie LP, Colnett DL, Wolf CP, Truett JC, et al. Cumulative effects assessment: a context for further research and development. Cat. No. En106-7/1987E, Canadian Environmental Assessment Research Council, Minister of Supply and Services, Canada; 1987.

Spaling H. Cumulative effects assessment: concepts and principles. Impact Assess 1994;12:231–52.

Spaling H, Smit B. Cumulative environmental change: conceptual frameworks, evaluation approaches, and institutional perspectives. Environ Manag 1993;17:587–600.

Spaling H, Smit B. Classification and evaluation methods for cumulative effects assessment. In: Kennedy AJ, editor. Cumulative effects assessment in Canada: from concept to practice. Fifteenth Symposium of Alberta Society of Professional Biologists, 13–14 April 1994, Calgary, AB. Edmonton, AB, Canada: Alberta Association of Professional Biologists; 1994. p. 47–65.

Spaling H, Zweir J, Ross W, Creasey R. Managing regional cumulative effects of oil sands development in Alberta, Canada. J Environ Assess Policy Manag 2000;2:501–28.

Therivel R, Wilson E, Thompson S, Heaney D, Pritchard D. Strategic Environmental Assessment. London, UK: Earthscan Publications; 1992.

Thomas, GL, Backus, EH, Christensen, HH, Weigand, J. Prince William Sound: Copper River: North Gulf of Alaska Ecosystem. Prince William Sound Science Centre and Copper River Delta Institute, Cordova, AK, and Conservation International, Washington, DC, USA; 1991.

Walker SL, Hedley K, Porter E. Pulp and paper environmental effects monitoring in Canada: an overview. Water Qual Res J Canada 2002;37:7–19.

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