ELSEVIER

METHODS FOR CUMULATIVE EFFECTS ASSESSMENT

Barry Smit and Harry Spaling

University of Guelph, Ontario, Canada

A variety of methodological tools are available to analyze and assess cumulative effects. This article develops a classification of methods for cumulative effects assessment, and evaluates them using criteria derived from recently proposed conceptual frameworks of cumulative environmental change. The classification differentiates two broad approaches. Analytical approaches include spatial analysis, network analysis, biogeographic analysis, interactive matrices, ecological modeling, and expert opinion. Planning approaches are classified into multi-criteria evaluation, programming models, land suitability evaluation, and process guidelines. Selected methods of CEA are evaluated for their ability to consider multiple perturbations, additive and interactive pathways of accumulation, and different types of cumulative effects. Geographic information systems, landscape analysis, and simulation modeling are shown to be useful methods of CEA. Loop analysis and cause–effect diagramming serve mainly as heuristic devices. A challenge for future methodological development is the design and testing of methods that incorporate processes of cumulative environmental change.

Interest in cumulative environmental change, or cumulative effects, has grown over the last two decades. This increased attention is related to both the institutional and the scientific bases of environmental impact assessment (EIA). Current policy and regulatory requirements, in countries such as Canada and the United States, demand that EIA generate information to identify, analyze, and evaluate cumulative effects. This demand has stimulated the science of EIA to

---

Address requests for reprints to: Harry Spaling, Department of Geography, University of Guelph, Guelph, Ontario, Canada N1G 2W1.

ENVIRON IMPACT ASSESS REV 1995;15:81–106

655 Avenue of the Americas, New York, NY 10010

0195-9255/95/$9.50
SSDI 0195-9255(94)00027-X

advance the theoretical understanding of cumulative environmental change, and to develop methods for cumulative effects assessment (CEA).

Concepts and definitions of cumulative effects are beginning to be developed (e.g., Cocklin et al. 1992a; Contant and Wiggins 1991; Irwin and Rodes 1992; Spaling and Smit 1993). Frameworks generally follow a causal model consisting of three main components:

1. sources of cumulative environmental change, suggesting that cumulative effects may emanate from single or multiple activities, similar or different in kind;
2. pathways or processes of accumulation, inferring that environmental changes accumulate over time and across space in an additive or interactive manner; and
3. a typology of cumulative effects, implying that cumulative environmental changes can be differentiated, generally according to temporal and spatial attributes.

Concurrent with the theoretical work, methodological tools for cumulative effects assessment are also being developed, tested, and applied. Of particular interest are methods that have been developed or applied specifically to incorporate one or more of the main components of the conceptual model. For example, some methods emphasize multiple sources of environmental change (e.g., Bain et al. 1986; Ziemer et al. 1991), others stress pathways of accumulation (e.g., Cada and Hunsaker 1990; Peterson et al. 1987), and still others focus on one or more types of cumulative effects (e.g., Cocklin et al. 1992b; Gosselink and Lee 1989; Johnston et al. 1990).

This article classifies methodological approaches to CEA, and evaluates the utility of selected methods to analyze and assess cumulative effects. The intent is not to develop new methods or procedures, but rather to review and appraise existing ones. Such a critique should assist in the development of methods and in the selection of tools for specific cumulative effects problems. The applicability of conventional methods of EIA to the analysis of cumulative effects has been addressed elsewhere (e.g., Cocklin et al. 1992b; Lane et al. 1988; Nichols and Hyman 1982; Whitney and MacLaren 1985). The focus here is on methods specifically applied to CEA, or developed for it. The range of methods considered is broader than that typically acknowledged in the EIA process. This broader perspective demonstrates the potential contribution of other methodologies (e.g., regional planning, threshold indicator analysis, linear programming), generally outside of conventional EIA practice, to the analysis and assessment of cumulative effects. These methods are not scrutinized exhaustively, but are classified into broad categories with representative examples considered from each. The evaluation is based on criteria derived from the conceptual framework described previously and its key attributes, particularly the notions of temporal and spatial accumulation.

The article begins by briefly distinguishing two distinct approaches to CEA: an analytical approach and a planning approach. Previous evaluations of CEA methods are reviewed to highlight classifications and criteria common to these appraisals. The next section proposes a general scheme to classify methods of CEA. This is followed by a description of evaluation criteria, which are then used to evaluate selected methods of cumulative effects assessment.

Approaches to Cumulative Effects Assessment

Cumulative effects assessment is the process of systematically analyzing and evaluating cumulative environmental change. There are two distinct, but related, approaches to CEA (Spaling and Smit 1993). The prevalent approach views CEA primarily as an information-generating activity using principles of research design and scientific analysis (e.g., Baskerville 1986; Bedford and Preston 1988; Bronson et al. 1991; CEARC and USNRC 1986; Clark 1986; Gosselink and Lee 1989; Horak et al. 1983; Hunsaker 1989). A premise of this approach is that information resulting from scientific investigation is communicated to decision-makers, leading to more rational decisions. CEA is considered to be an analytical exercise, distinct from planning and decision-making, but linked to it through information flow.

A second, less common approach to CEA utilizes planning principles and procedures to determine an order of preference among a set of resource allocation choices. Preference is based on explicit social norms that act as decision rules to compare and rank alternative choices, and to trade off environmental, economic, and social objectives. This approach regards cumulative effects assessment as a correlate to regional or comprehensive planning (Bardecki 1990; Davies 1991; Hubbard 1990; Jacobs and Sadler 1990; Mentor 1985; Stakhiv 1988, 1991; Vlachos 1982; Williamson 1990). It extends beyond the analytical function of information collection, analysis, and interpretation to also include value setting, multi-goal orientation and participatory decision-making.

These two approaches represent different interpretations of the scope of CEA. The analytical approach adopts a narrower focus emphasizing an analytical function, whereas the planning approach adopts a broader definition to also include normative evaluation and management.

Previous Classifications

Two previous classifications of CEA methods reveal the distinction between the analytical and planning approaches to CEA described earlier. Sonntag et al. (1987) classified CEA methods into three categories:

1. Matrix methods use matrice multiplication techniques to determine the interactive effect of multiple projects on various environmental components (e.g., Bain et al. 1986; Clark 1986), or to identify higher order effects (e.g., Shopley et al. 1990).

2. Causal analyses use flow diagrams to identify key cause-and-effect relationships in complex systems involving human and environmental components and interactions. Specific techniques include loop analysis (Lane et al. 1988) and cause–effect diagramming (Williamson et al. 1987).
3. Meta-modeling builds on the simulation modeling and multidisciplinary workshops of adaptive environmental assessment and management (Holling 1978). A meta-model framework integrates various submodels to analyze a range of spatial (local to global), temporal (fast to slow), and system (ecological, social, and economic) dimensions. Meta-modeling is particularly focused on accumulation of environmental changes that can trigger "surprise" events at specific temporal and spatial scales.

This classification of CEA methods reflects an analytical perspective. It presumes a scientific or technical approach, and places normative evaluation outside of this domain.

Stakhiv's (1988, 1991) classification distinguishes methods from the perspective of planning:

1. Valuation methods are static evaluation procedures that assign numerical weightings to reflect the relative value of a prescribed set of attributes. An example is multi-attribute tradeoff analysis (MTA) (e.g., Jourdonnais et al. 1990).
2. Linked deterministic and simulation models use mass balance equations or input–output techniques to link physical or ecological models with econometric models to evaluate policy options and management alternatives (e.g., Braat and Van Lierop 1987).
3. Unified, holistic, theoretical approaches utilize a key concept such as energetics that provides a single metric or common frame of reference for analysis and evaluation. A study by Gilliland and Risser (1977) of energy flow in a New Mexico missile range exemplifies this category.
4. Land use designation approaches incorporate public values and environmental goals to delineate spatially differentiated zones that segregate various types and levels of human activity. For example, Dickert and Tuttle (1985) define a land disturbance target based on erosion susceptibility to evaluate the cumulative impact of future land development projects.
5. Comprehensive planning and evaluation refer to an all-encompassing process of problem identification, objective setting, formulating and evaluating alternatives, and plan selection. Davies (1991) has integrated these elements with concepts of ecosystem health and cumulative environmental effects into an ecosystem-based planning framework for the Toronto waterfront.

Normative evaluation is an underlying attribute of all the classes in Stakhiv's scheme. Methods for evaluating planning options or for promoting environmental management are likely to be quite different from those intended to identify and document the nature and extent of cumulative effects. Of course, the latter may serve the former in a variety of ways, but the purposes and tools are different. This distinction is fundamental to the classification that follows.

Proposed Classification of CEA Methods

A proposed scheme for classifying CEA methods is presented in Figure 1. The scheme distinguishes methods according to both their analytical verses planning orientation, and their principal tool or structure of analysis. Normative evaluation refers to a process or procedure designed to rank or choose "what ought to be" according to prescribed social goals or evaluative criteria. Analytical methods place normative evaluation and prescription outside their methodology. Planning methods incorporate normative evaluation into their methodological procedures.

There are methodological links among the categories identified in Figure 1. For instance, spatial analysis captures methods that model and document the locational patterns and dynamics of cumulative effects, but spatial structure and the results of spatial analyses are also important elements in planning approaches such as programming models and land suitability evaluation. For example, Sebastiani et al. (1989) analyzed aerial photographs to describe and explain cumulative land use changes in Laguna La Reina, Venezuela, for the period 1949–1986, and then used this information, along with other input, to formulate policy guidelines for land use planning. Similarly, matrices are utilized to specify the interactive effects of multiple projects on environmental components (e.g., Cada and McLean 1985; Emery 1986; Witmer et al. 1988). Matrices are also used in multi-criteria evaluation exercises (e.g., Stakhiv 1991), often using results from interaction analyses.

The classification scheme is refined further in Tables 1 and 2. Each category is characterized by its main feature, its distinguishing mode of analysis, and representative methods. For example, interactive matrices (Table 1) are analytical methods that typically utilize matrix multiplication and aggregation techniques to estimate total cumulative effects. A specific representative method is the Argonne multiple matrix (Bain et al. 1986). Interactive matrices have evolved from the basic two-dimensional matrix (project activities × environmental components) first used by Leopold (1971) to evaluate environmental impacts of human actions. Land suitability evaluation (Table 2) is designated as a planning approach because it uses normatively defined ecological thresholds, and acceptable levels of ecosystem stress, to evaluate cumulative effects of past, present, and proposed land uses. These normative criteria are used to differentiate areas according to their suitability for future development. Dickert and Tuttle (1985) use this technique to assess cumulative effects of proposed land developments in an urbanizing coastal watershed in California. Land suitability evaluation is an extension of land capability analysis that classifies lands on the basis of soil,

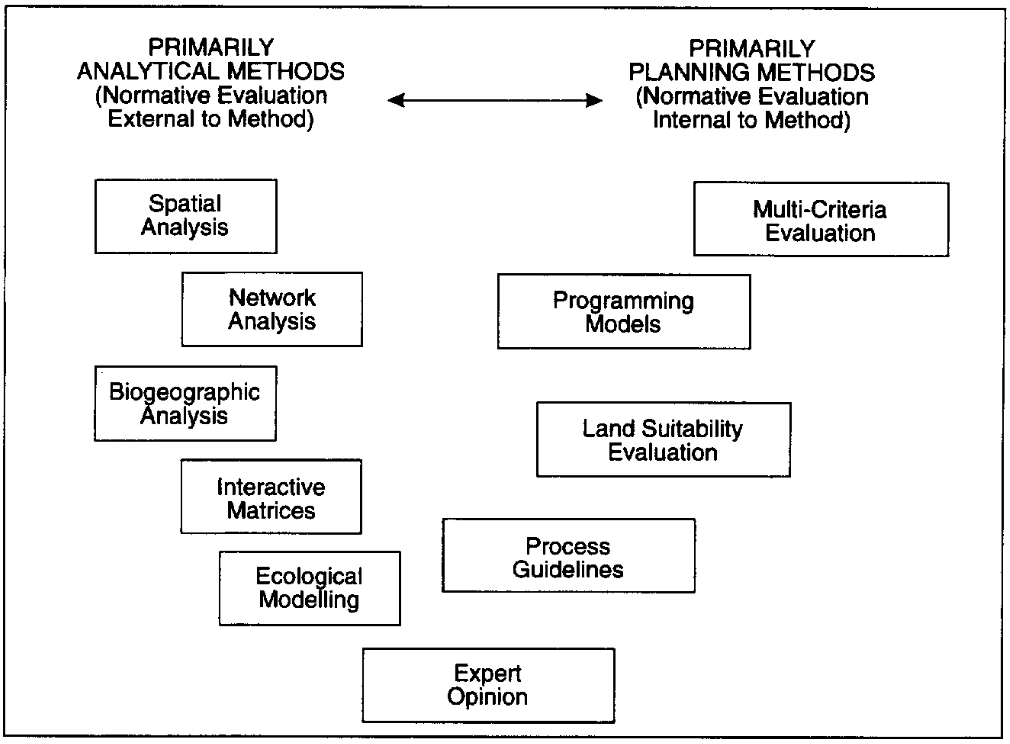

FIGURE 1. Schematic classification of methods for cumulative effects assessment.

moisture, vegetation, and other biophysical attributes, and assesses their capability for specified land uses (Smit et al. 1987). With "suitability," this information is evaluated and rated to determine a ranked order of preferred land uses (McHarg 1969).

Evaluation of CEA Methods

The remainder of the article evaluates selected methods of CEA, one from each category of the classification.

The few previous studies that have evaluated methods of cumulative effects assessment vary by the comprehensiveness and type of criteria utilized in the evaluation. Some report generally on strengths and weaknesses, but do not clearly specify the criteria upon which the evaluation is based (e.g., Bronson et al. 1991; Lane et al. 1988). Others use an explicit set of evaluation criteria, but focus on a specific cumulative effects problem, and thus have limited generic utility (e.g., Stull et al. 1987). Work by Horak et al. (1983) and Stull et al. (1988) is noteworthy because their evaluation criteria are based on theoretical principles and concepts. The evaluation below builds on this early work by incorporating recent theoretical and methodological developments. Finally, unlike evaluations of EIA methods, almost all evaluations of CEA methods are reported in unpublished sources, and generally have not been disseminated in the scholarly literature.

TABLE 1. Analytical Methods for Cumulative Effects Assessment

Category	Main Feature	Mode of Analysis	Representative Method(s)	Reference
Spatial analysis	map spatial changes over time	sequential geographical analysis	Geographic information systems (GIS)	Johnston et al. (1988) Cocklin et al. (1992b)
Network analysis	identify core structure and interactions of a system	flow diagrams; network analysis	Loop analysis Sorenson's network	Lane et al. (1988) Sorenson (1971)
Biogeographic analysis	analyze structure and function of landscape unit	regional pattern analysis	Landscape analysis	Gosselink and Lee (1989) Johnston et al. (1990)
Interactive matrices	sum additive and interactive effects; identify higher order effects	matrix multiplication and aggregation techniques	Argonne multiple matrix; synoptic matrix; extended CIM; modified CIAP	Bain et al. (1986) Clark (1986) Shopley et al. (1990) Emery (1986)
Ecological modeling	model behavior of an environmental system or system component	mathematical simulation modeling	Hypothetical modeling of forest harvesting	Ziemer et al. (1991)
Expert opinion	problem-solving using professional expertise	group process techniques (e.g., Delphi, nominal group technique)	Cause-and-effect diagramming	Williamson et al. (1987) Armour and Williamson (1988)

The criteria used in this evaluation are based on the three components of the conceptual framework described previously: multiple sources of cumulative environmental change, additive or interactive processes of accumulation, and various types of cumulative effects. These notions form the bases of six evaluation criteria:

1. Temporal accumulation occurs when the interval between one perturbation and succeeding perturbations is too small for an environmental system, or system component or process, to assimilate or recover from the perturbation. Temporal accumulation requires that a method consider time scale and frequency of a perturbation. A method should incorporate an extended time horizon to detect long-term, incremental environmental change, and also account for time lags.
2. Spatial accumulation occurs where the spatial proximity between perturbations is smaller than the distance required to remove or disperse the perturbations. A method should recognize the geographic scale of

TABLE 2. Planning Methods for Cumulative Effects Assessment

Category	Main Feature	Mode of Analysis	Representative Method(s)	Reference
Multi-criteria evaluation	use of a priori criteria to evaluate alternatives	weighing of parameters and computational ranking of scenarios	Multi-attribute tradeoff analysis	Jourdonnais et al. (1990)
Programming models	optimize alternative objective functions subject to specified constraints	mass-balance equations	Linear programming	Stakhiv (1988, 1991)
Land suitability evaluation	use ecological criteria to specify location and intensity of potential land uses	define acceptable levels of ecosystem health and target thresholds utilizing ecological indicators	Land disturbance target Ecosystem-based planning	Dickert and Tuttle (1985) OMMAH (1982) Davies (1991)
Process guidelines	logic framework to conduct CEA	systematic sequence of procedural steps	Snohomish guidelines CEA decision tree	Stull et al. (1987) Lane et al. (1988)

perturbations and set spatial boundaries accordingly. It should also account for cross-boundary movements at the same scale (e.g., intraregional) and movements between different scales (e.g., local to regional to global). A method should acknowledge variation in spatial density because perturbations and effects are differentiated over space. Configuration is a significant characteristic because some methods may be oriented toward a certain pattern (point, linear, areal) more than others. The ability to consider an areal pattern is particularly important because cumulative effects assessment is often conducted in a regional context.

3. Perturbation type refers to a method's ability to account for perturbations that are single or multiple in kind. For a method to fulfill this criterion, it should recognize perturbations that originate from multiple sources, or the same source repeated over time or across space. A method should also consider whether an action stimulates or propagates additional developments that trigger further sources of perturbation.
4. Processes of accumulation emphasize pathways or relationships that link cause and effect. A method should have the ability to trace and account for specific processes of environmental change. It should differentiate between additive and interactive processes, and incorporate a technique that aggregates the effect of each.

5. Functional effects refer to alterations to processes (e.g., energy flows, nutrient cycling, succession), or modifications to controlling properties (e.g., assimilation capacity, carrying capacity, thresholds). A method should be able to identify, analyze, and assess functional change in an environmental system, or a system component or process, after perturbation. The criterion of functional effects generally implies time-oriented changes and includes time-crowding, time lags, and triggers and thresholds.
6. Structural effects include population shifts, habitat modification, and alterations to geophysical resources (e.g., air, water, soil). Analogous to functional effects, a method should be able to identify, analyze, and assess structural change in an environmental system, or a system component or process, after perturbation. Structural change is viewed as essentially spatial and includes space-crowding, cross-boundary flows, and fragmentation effects.

Other, more pragmatic criteria (e.g., data and technology requirements, time demands, cost) are also relevant to evaluating the utility of CEA methods, but these are not considered here in detail. The focus in this evaluation is on the theoretical basis of methods, particularly on their capacity to address the main components of the conceptual framework.

Of the two broad approaches to CEA identified in the classification (Figure 1), planning methods are distinguished by their inherent inclusion of normative evaluation, invariably in addition to an analytical component (McAllister 1980). The theoretical model that provides the evaluative criteria for this article focuses on the analytical function of CEA, that is, the analysis of cumulative effects rather than the appraisal of planning or management options. Thus, it is the analytical dimensions of CEA methods that are appraised.

Ten methods of cumulative effects assessment are evaluated. These methods are selected on the basis of their representativeness of the 10 categories identified in the classification (Tables 1 and 2), and their application potential, as supported by cases documented in the literature. For each category, a brief description of the method is given, followed by an evaluation utilizing the criteria outlined previously.

Spatial Analysis

Geographic information systems (GIS) are computerized data systems that store, retrieve, manipulate, and display spatial information. Changes in the spatial distribution of environmental attributes are usually captured by documenting the distributions at specific time intervals. These are often correlated with changes in land use or development patterns documented over the same time periods. Several studies have applied GIS technology to examine cumulative effects through time-series analysis (Cocklin et al. 1992b; Johnston et al. 1988; Walker et al. 1986).

TABLE 3. Summary Evaluation of Selected CEA Methods

	Evaluation Criteria						
Method	Temporal Accumulation	Spatial Accumulation	Type of Perturbation	Process of Accumulation	Functional Change	Structural Change	Reference
Geographic information system	S	S	S	X	P	S	Johnston et al. (1988) Cocklin et al. (1992b)
Loop analysis	X	X	S	S	X	X	Lane et al. (1988)
Landscape analysis	S	S	S	S	P	S	Gosselink & Lee (1989)
Argonne multiple matrix	X	P	S	S	X	X	Bain et al. (1986)
Simulation modeling	S	S	S	S	S	S	Ziemer et al. (1991)
Cause–effect diagramming	X	X	S	S	X	X	Williamson et al. (1987)
Multi-attribute tradeoff analysis	X	P	S	X	X	X	Jourdonnais et al. (1990)
Linear programming	P	S	S	P	P	S	Stakhiv (1988, 1991)
Land disturbance target	S	S	P	P	S	S	Dickert and Tuttle (1985)
CEA Reference Guide	S	S	S	P	S	S	Lane et al (1988)

Abbreviations: S, satisfactorily meets criterion; P, partially meets criterion; X, does not meet criterion.

An obvious contribution of GIS to cumulative effects assessment is its explicit consideration of the spatial dimension (Table 3). The geographic scale of analysis is very flexible, ranging from regional to local to site-specific applications, depending on the resolution of available data. Accumulation of environmental change from one scale to the next is also readily achieved. For example, Walker et al. (1986) and Cocklin et al. (1992b), using GIS to study cumulative environmental change in areas ecologically sensitive to development, demonstrated increasing refinement of geographic scale from regional to local levels, and accumulation of environmental change at each scale. Variation in spatial density, proximity, and relative location are also considered. For example, Johnston et al. (1988) found that the cumulative effect of wetlands on regional water quality depends on the location of wetlands in a watershed and their proximity to each other.

GIS can also be used to analyze temporal change. Data layers, representing different time intervals, provide the basis for determining incremental environmental change. Time lags can also be detected provided that the study period is of sufficient duration and the time intervals are of sufficient length. Although GIS is capable of considering long time horizons, this aspect of the temporal dimension is usually limited by the length of historical record for which spatial information (e.g., aerial photographs) is available.

GIS is capable of considering perturbations that originate from single or multiple sources, and the effect of these perturbations on single or multiple environmental components (e.g., Cocklin et al. 1992b), so long as the perturbations have a spatial manifestation.

Structural change is addressed in GIS via the display of spatial crowding and fragmentation effects. Spatial movement within a bounded area can be depicted, as well as accumulation across scale boundaries. Functional effects are only partially considered. GIS can only detect time lags and time-crowding with respect to changes in spatial structure at discrete points in time, provided the historical record is of sufficient duration and detail. It does not explicitly consider triggers and thresholds.

The most significant weakness of GIS is its inability to incorporate processes of accumulation (Table 3). Cause-and-effect relationships are not identified or analyzed, but assumed or inferred from spatial association. Additive and interactive processes are not differentiated and, where spatial change is measured over time, it is presumed to be additive. A related assumption is that a series of spatial changes in an environmental variable is the result of the same process acting on that variable over time. Cocklin et al. (1992b) suggest that such processes, and other related complex interactions (e.g., synergism, compounding), should be represented by "side-models" that can be incorporated into GIS.

Overall, GIS is a powerful and useful tool for carrying out spatial analysis of cumulative environmental change, although data requirements and variation in availability of data among different locales are likely to restrict the adoption of GIS as a widespread tool for CEA. Its utility for CEA is generally applicable to mapping sources of cumulative environmental change and cumulative effects, with limited application for the analysis of pathways of cumulative environmental change.

Network Analysis

Loop analysis is a " . . . a qualitative, network technique that is based on feedback relationships" (Lane et al. 1988:8–17). The concept of feedback distinguishes loop analysis from other forms of network analysis such as Sorensen's (1971) network that assumes unidirectional causality.

Procedurally, a core or composite network is constructed depicting linkages and feedback relationships consistently evident in a series of individual loop diagrams, each describing a system at specific time intervals. The core network is used to determine the effects of a perturbation on system variables and interactions, identify components and pathways most sensitive to environmental change, and select linkages for more detailed quantitative modeling. Loop analysis has been used in marine ecology to model plankton communities (e.g., Lane 1986), and recommended for analysis of cumulative effects (Lane et al. 1988), but its application in CEA remains largely untested.

The main characteristic of loop analysis is its focus on linkages and feedback relationships. These interactions provide a basis for the analysis of processes that link cause and effect. Thus, loop analysis meets the criterion of processes of accumulation (Table 3). Although the method does not explicitly differentiate additive and interactive processes, these are potentially discernible from the composite network diagram. Similarly, with sufficient data and the aid of simulation modeling, various pathways of cumulative environmental change might also be determined. The method also fulfills the criterion of perturbation type (Table 3). Loop diagrams can incorporate perturbations that originate from single or multiple sources.

Loop analysis is essentially aspatial, and does not explicitly consider geographic scale, spatial density, or configuration. Similarly, the method does not account for long time horizons or differentiate continuous and discrete events. Whereas individual loop diagrams are each based on a sampling point in time, the analytical intent is to construct a representative composite diagram of a system, rather than conduct a time-series analysis.

Weak temporal and spatial resolution hamper the analysis of functional and structural change (Table 3). Loop analysis can indicate changes in direction (positive, negative, zero) and the relative strength of a set of functional relationships, and changes in organization of a system structure, but these do not incorporate explicit temporal and spatial dimensions.

Loop analysis is a useful tool for conceptualizing and illustrating interrelationships and pathways in CEA. Its application to CEA is most suitable as a heuristic device.

Biogeographic Analysis

Landscape analysis is based on principles of biogeography and landscape ecology. These principles emphasize the spatial pattern of ecological components and processes within a defined land unit, usually a watershed or other naturally bounded region.

Specific indicators that relate to structural and functional attributes at the landscape level are used to measure cumulative environmental change. For example, in a study of cumulative effects in bottomland hardwood forests, Gosselink and Lee (1989) used three indices to represent structural aspects of the landscape (forest loss, forest contiguity, and forest pattern), and five indices to characterize functional aspects (change in stream discharge, change in water residence time, trends in stream nutrient concentrations, nutrient loading rates, and native biotic diversity). Changes in these indices represent cumulative effects on landscape integrity.

Landscape analysis satisfies both spatial and temporal evaluation criteria (Table 3). Spatial considerations include the regional scale of analysis, and the incorporation of size, shape, pattern, configuration, and contiguity. Relative location of environmental components is also considered. Although spatial movement within a land unit is inherent in landscape analysis, movement of environmental components and processes from one land unit to another are generally not considered because boundaries are firmly established and adhered to in the analysis. From a temporal perspective, the method is amenable to time-series analysis to detect incremental changes in landscape components and processes. It is capable of considering an extended time horizon but, similar to GIS, the duration is restricted to the length of the historical record for which landscape data are available.

Both single and multiple sources of perturbation can be considered. Although landscape analysis does not directly account for secondary development, it does provide a regional context for considering its effects. Functional effects characterized by time-crowding and time lags are discernible in this method, depending on the availability of long-term historical records, but triggers and thresholds are not analyzed explicitly. In contrast, cumulative environmental changes distinguished by spatial crowding and fragmentation effects are distinctly accounted for, thereby satisfying the criterion of structural change (Table 3).

Like GIS, landscape analysis represents a promising methodology for cumulative effects assessment, especially where the focus is on spatially variable land surface phenomenon. Also like GIS, a potential constraint to widespread application of landscape analysis is its requirement for a comprehensive regional inventory comprised of detailed data on ecological components and processes at the landscape scale.

Interactive Matrices

The Argonne multiple matrix (AMM) was developed to analyze the additive and interactive effects of various configurations of multiple projects (Bain et al. 1986). The total cumulative effect for any configuration is assumed to be the sum of project-specific effects adjusted for interactions among projects and their effects. Expert opinion is used to establish three types of data: scores that define the level of effect of each project on selected environmental components, weighting coefficients that reflect the relative value of each component, and interaction coefficients that measure the effect of each pair of projects on each component. These data sets are entered into matrices that are manipulated to calculate a total score indicating the cumulative effect for each project configuration. Applications of AMM have focused primarily on the cumulative effects of multiple hydroelectric projects on fish and wildlife (e.g., Irving and Bain 1989; Witmer and O'Neil 1988).

AMM differentiates additive and interactive processes of cumulative environmental change. This distinction certainly addresses processes of accumulation and represents a notable methodological contribution (Table 3). The matrix is also able to account for multiple projects of the same type (e.g., hydroelectric dams), and presumably it is equally applicable to multiple projects of different kinds (e.g., hydroelectric dam, transmission corridor, road network).

Temporal and spatial dimensions are considered by experts in determining coefficient values, but they are not specifically addressed in the matrix structure. The matrix interactions pertain to one time period and there is no mechanism to distinguish time lags. The Argonne matrix is also characterized by weak spatial resolution, but there are improvements over conventional matrices. The spatial dimension is apparent in alternate configurations of multiple projects, but accumulation among geographic scales and movement across project boundaries are not considered explicitly. Spatial and temporal dimensions are highly bounded because of the project focus of this method. Other problems with the Argonne matrix include an exclusive biological emphasis, extensive reliance on expert judgment, and use of a dimensionless scale (i.e., cumulative effects score) that does not distinguish the nature of effects (i.e., structure or function).

AMM's utility for CEA is its consideration of multiple sources of cumulative environmental change, their interactions, and an assessment of total cumulative effect. However, cumulative effects are not differentiated by type, and parameter values rely extensively on expert judgment.

Ecological Modeling

Simulation models provide a simplified representation of dynamic, complex systems. These models are designed to emulate the behavior of an environmental system or system component. Accuracy of the simulation is highly dependent on the validity of the model relationships and the quality of data reflected in constraints and parameters.

Ziemer et al. (1991) used a simulation model to analyze the cumulative effects of hypothetical timber harvesting strategies on stream bed conditions in a watershed over a 200-year period. Harvest strategies are distinguished on the basis of the cutting pattern and timing relative to the stream headwaters and mouth. This study shows that simulation modeling is highly flexible in defining temporal and spatial variation of the perturbation. It also demonstrates the benefit of hypothetical modeling in considering timeframes and complexity generally beyond the analytical capability of field and experimental studies.

Simulation modeling meets most of the requirements of the evaluation criteria (Table 3). Spatially and temporally variable processes can be simulated with appropriate disaggregation in the model. Variations in the frequency of perturbations and long timeframes can be considered, particularly in hypothetical simulations. The geographic scale of analysis is usually local or regional, the scales with highest resolution of available data, although global simulations of cumulative sources, pathways, and effects are implicit in studies of planetary climatic change (e.g., Gabriel et al. 1991) and world resources (e.g., Meadows et al. 1974). Accumulation of environmental change between scales is potentially accounted for by linking model output at each scale (i.e., "cascading" models). The method adequately addresses spatial density and configuration. Simulation modeling considers single or multiple perturbations, and the effects of these perturbations on abiotic and biotic components.

Simulation models focus on cause-and-effect linkages, and can generally differentiate additive and interactive processes. They offer one of the best prospects for analyzing specific pathways of cumulative environmental change. Because simulation models focus on functional change or structural change, or both, they can identify cumulative environmental changes such as time lags, thresholds, spatial crowding, and fragmentation effects.

Although the utility of simulation modeling is seemingly broad according to the criteria utilized here, several cautions pertaining to its application merit attention. First, application is dependent on reliable data and model validation, and available resources (money, time), technology, and expertise. Second, to date, applications of models in CEA may consider single or multiple perturbations, but usually analyze the effect of these perturbations on only one environmental component (e.g., Keane et al. 1990; USDA-FS 1990). Third, simulation models are only applicable to environmental systems for which system organization and behavior are reasonably well understood. These pragmatic cautions balance the positive theoretical evaluation noted earlier.

Expert Opinion

Whereas analyst opinion has some role in nearly every method, some techniques are based almost exclusively on expert opinion. Cause-and-effect diagramming, based on the collaborative efforts of experts in workshop settings (Armour and

Williamson 1988), specify cause–effect linkages in flow diagrams. This method is distinguished by both its product and means of construction. The knowledge of experts is transformed into the diagrams, usually problem-oriented, using workshop procedures such as nominal group technique. Cause-and-effect diagramming has been used in cumulative effects assessment to investigate problems of water quality in Chesapeake Bay (Williamson et al. 1987).

A strength of this method is its focus on relationships that link cause and effect (Table 3). It does not explicitly distinguish additive and interactive relationships, but these could be differentiated qualitatively in the diagram. The causal diagram can incorporate either single or multiple perturbations.

This technique is closely related to methods of network analysis and, thus, is generally atemporal and aspatial. Thus the method generally is not strong in addressing temporal and spatial accumulation, or functional and structural change.

Certainly, cause-and-effect diagramming considers sources, pathways, and effects. Its utility for CEA is primarily heuristic, providing an organizing framework for more empirical analyses.

Multi-criteria Evaluation

Multi-attribute tradeoff analysis (MTA) is a decision-making procedure that uses utility theory to compare and rank alternative courses of action. These alternatives can vary in their type of environmental effect and in the intensity of the same effect. MTA provides a systematic process for trading off environmental effects of various alternatives to aid decision-making (Stull et al. 1987).

Application of MTA to CEA is limited. Jourdonnais et al. (1990) utilized MTA to evaluate cumulative effects of various scenarios for stream regulation in the Flathead River Basin of Montana. In this study, impact indices are calculated by multiplying geographic and importance weights of an environmental component by the impact of each regulation scenario on each component. Expert opinion is used to determine weight and impact values. Individual indices are summed to reflect cumulative effects for each stream regulation scenario.

The range of alternatives considered by MTA can readily incorporate single and multiple configurations of projects and secondary developments, thus the criterion of perturbation type is addressed (Table 3). Because of MTA's planning orientation, it is more a user of cumulative effects information than a generator. Thus, MTA does not perform well on most other evaluation criteria.

The study by Jourdonnais et al. (1990) demonstrates that the spatial criterion is partially met by incorporating geographical distribution of environmental components as a weighted factor, but other spatial aspects are not explicitly considered. Nor does MTA analyze processes of accumulation, or differentiate functional or structural effects. The method essentially assumes that these are known, and provides a framework for evaluating them. MTA does not necessarily exclude consideration of these criteria. Cumulative effects of developments on environmental attributes could be estimated for long time periods and across broad spatial scales, recognizing various processes of accumulation and their implications for functional and structural effects. Similarly, techniques such as simulation modeling could be used to inform the expert opinion. But in the end, MTA uses the results of such considerations to summarize effects and then introduces value judgments to weight and aggregate scores. Thus, it is a useful evaluation and decision tool that can aid in the application of cumulative effects analyses for environmental policy and management.

Programming Models

Linear programming (LP) is a tool that identifies resource allocations (solutions) which are feasible given specified environmental and other conditions (constraints), and then selects some "optimal" allocation based on a specified decision rule (objective function). LP is often used as an explanatory model to gain insights into processes, to estimate the influences of changes in conditions, and to predict consequences of given scenarios. In this explanatory model, the objective function is specified to reflect some broad underlying force or process (e.g., profit maximization in economic models). For planning purposes, LP functions and sometimes LP constraints are specified to reflect some social goal or value. In this model, LP evaluations serve a similar role to multi-criteria evaluations. In fact, one type of LP, multiple goal programming, is essentially an algebraic equivalent of a multi-criteria tradeoff matrix.

Stakhiv (1988, 1991) used linear programming in a hypothetical case to investigate cumulative effects of various development scenarios in a coastal wetland on environmental attributes (e.g., dissolved oxygen, production of detritus). One of the LP products is a tradeoff curve for net annual income, representing varying levels of development and dissolved oxygen deficit in the wetland. In this study, LP is demonstrated as a planning tool for CEA, because the cumulative effect of development scenarios are evaluated on the basis of specified decision rules (e.g., maximize income, minimize dissolved oxygen deficit).

Various types and numbers of perturbations can be specified in LP constraints, including development options (Table 3). Multiple environmental components also can be represented, either in constraints or as part of the objective function. Secondary actions can be accounted for through scenarios based on incremental development. Spatial accumulation can be considered in LP with attributes such as density and location disaggregated in constraints and in solution variables. Accumulation across scales is not addressed directly. LP analyses are usually comparative static, and temporal accumulation is rarely considered explicitly (Table 3).

Processes of accumulation are essential in LP to specify linkages between possible activities and environmental components (i.e., constraints) and the solution or choice variables (objective function). However, LP does not identify these or estimate their values; it requires them for the LP analysis. These linkages are assigned coefficients to reflect the interaction of each component for each activity. The criterion of structural effects is satisfactorily met (Table 3). Changes such as space-crowding and fragmentation effects attributable to each alternative can be identified and evaluated. The weak temporal resolution of linear programming impedes detailed consideration of functional change. Defined thresholds and time lags can be displayed if alternative scenarios indicate a time series.

Linear programming offers a potential planning approach to investigate and manage cumulative environmental problems. Application in CEA would be a novel departure from typical socioeconomic applications.

Land Suitability Evaluation

Land disturbance target—the essence of this method is to select an indicator of environmental quality and to establish an allowable target or threshold for this indicator, which is then used as a decision criterion to evaluate the cumulative effects of existing and future development within an area. Dickert and Tuttle (1985) applied the land disturbance target to a coastal watershed in California. Their application differentiates sub-units in the watershed according to erosion susceptibility, and defines acceptable levels (targets) of erodibility for each sub-unit. These are used to identify areas where existing land uses exceed the land disturbance target so that future developments can be evaluated (i.e., not approved in areas falling below target levels and permitted in areas exceeding target levels).

Another application of this approach is the Ontario lakeshore capacity simulation model (OMMAH 1982). Analogous to the land disturbance target of Dickert and Tuttle (1985), the model uses lakeshore carrying capacity to evaluate existing and proposed developments, notably cottages, around inland lakes. Various development scenarios are simulated to predict environmental response in key environmental indicators: land use, water quality, fisheries, and wildlife habitat. Each response is assessed against predefined targets of acceptable disturbance. The model does not explicitly acknowledge cumulative effects, but its purpose and application are consistent with a land disturbance approach to CEA. Bardecki (1992) advocates the model as a key mechanism for the management of cumulative effects on Ontario lakes.

Spatial analysis is a basic component in determining the land disturbance target and in differentiating areas for which future development is to be allowed or prohibited (Table 3). The geographic scale of analysis is flexible ranging from sub-units of a watershed to an entire basin. Consideration of spatial density is evident in the varying measurements of land disturbance. The disturbance target is essentially used to establish tolerable levels of spatial crowding.

Dickert and Tuttle (1985) consider multiple types of perturbations, as reflected in various land uses, but incorporate only one measure of environmental change (i.e., erodibility). They also assume causality between erosion and different types and intensities of land use. The Ontario lakeshore capacity model generally considers only one perturbation (e.g., cottage development), but incorporates changes in multiple environmental components. The lakeshore model can analyze cause–effect relationships to indicate response in each indicator. Neither application differentiates additive or interactive processes of accumulation.

The method does consider functional and structural change. The land disturbance target is based on a threshold concept that incorporates time-dependent processes (e.g., erosion, land use change). Time-crowding and space-crowding can be important principles in specifying target levels.

Criticisms of this method include a dependency on a single activity (e.g., cottage development) or sole indicator of environmental change (e.g., erodibility), data requirements dependent on a time-limited historical record, and an assumption that past land use trends and environmental responses are continued into the future.

This approach focuses on sources and, depending on the indicator selected, pathways of cumulative environmental change, and spatially oriented cumulative effects. Applications are particularly suitable for development planning at the local and regional levels. It provides significant potential as a planning tool to evaluate and manage cumulative effects at these scales.

Process Guidelines

Process guidelines are not a distinct method, but a set of sequential steps to follow in organizing and conducting a CEA. Examples include adaptive environmental assessment and management (Holling 1978), Snohomish guidelines (Stull et al. 1987), methodology for the analysis of cumulative impacts of corps permit activities (Dames and Moore 1981), cumulative impact assessment procedure (Horak et al. 1983), and *Reference Guide to CEA* (Lane et al. 1988). Many of these examples incorporate workshops, expert opinion, and an assortment of analytical and evaluation techniques.

The *Reference Guide to CEA* developed by Lane et al. (1988) and based on previous work by Dames and Moore (1981) is evaluated here. This approach consists of three main steps:

1. Step one involves a decision tree diagram beginning with a series of directional questions to establish whether a CEA is needed for a particular problem. Major considerations include the type, size and number of projects, and spatial and temporal scales of anticipated effects.
2. Step two requires a decision between two possible approaches to the analysis of cumulative effects, depending on the type identified in step one. Ex ante analysis is applied to identify and analyze cumulative environ-

mental change in the future. Post analysis is implemented when cumulative effects are currently observable, but causality and origin are not known.

3. Step three involves evaluation of development scenarios, assessment of the acceptability of future states of the environment, and appraisal of management options. Interdisciplinary expertise, "affected publics," and workshops are an inherent part of this step.

Temporal and spatial aspects are considered explicitly in the guide (Table 3). It can analyze short-term or long-term cumulative effects from past, present, or future perspectives. The geographical scale of analysis is regional, and spatial density and configuration are addressed. A spatial limitation is its exclusion of environmental change at the local level. For example, the decision tree instructs the user not to implement a CEA if spatial boundaries do not extend beyond the local ecosystem level. The guide regards the spatial scale of cumulative effects to be inherently regional. This limitation effectively inhibits consideration of accumulation of environmental change emanating from local scales.

The guide acknowledges single and multiple types of perturbations (Table 3). Despite the emphasis on causality, including feedback loops, the criterion of processes of accumulation is only partially met. This is because additive and interactive processes are not differentiated. The criteria of functional and spatial changes are adequately addressed. The guide focuses on the identification of cumulative environmental change characterized by time-crowding, or space-crowding, or both. Time lags and fragmentation effects are also considered explicitly.

The guide satisfactorily meets most of the evaluation criteria because of the flexibility in selecting specific analytical and planning techniques. Any combination of methods evaluated previously are potentially suitable. However, the flexibility of the guide also means a lack of specificity. For example, step two requires determination of causality, but only general concepts are provided. Similarly, step three necessitates evaluation of development scenarios and management options, but specific procedural guidance is lacking.

The guide is most suited as an organizing framework within which to carry out a comprehensive cumulative effects assessment, including the selection and application of more rigorous methods and techniques.

Conclusion

There is no standard method of cumulative effects assessment among the variety of analytically and planning-oriented tools to analyze and evaluate cumulative effects. The methods vary in their consideration of the main components of the conceptual framework. Some are project or activity-oriented (e.g., Argonne multiple matrix) emphasizing the source of cumulative environmental change. Others (e.g., loop analysis, cause–effect diagramming) focus on pathways or processes of accumulation. Still others (e.g., land disturbance target) stress a specific type of cumulative effect (e.g., thresholds). Further, simulation modeling is capable of considering sources, pathways, and effects, but requires information on processes and response invariably determined from other methods. This diversity in methodological tools provides for a variety of applications.

In general, methods of CEA are able to consider the spatial dimension more frequently than temporal aspects (Table 3). This is somewhat related to time-limited data bases (e.g., historical record) but, more importantly, reveals an inherent difficulty in accounting for time-dependent processes. The variability and stochastic nature of these processes makes it difficult to incorporate them into many methods. This suggests that future methodological development be directed toward CEA methods that analyze and evaluate pathways of cumulative environmental change.

CEA methods can be classified in various ways. One approach is to build on the traditional classification of EIA methods (e.g., checklists, networks, matrices, overlays, modeling), recognizing that the methodological structure of these techniques is basic to many methods of cumulative effects assessment. Another way is to distinguish methods on the basis of timing of the analysis relative to the occurrence of causes, pathways, and effects. Thus, ex ante methods estimate future cumulative effects given proposed source(s) of cumulative environmental change. Monitoring methods measure change in human activities and environmental components and processes over real time. Posterior or hindsight methods describe and explain cumulative effects after the fact, tracing their origin to specific pathways and human actions. According to this temporal classification, analytical approaches are generally able to analyze past, present, or future cumulative effects, but planning approaches, by definition, involve only ex ante methods.

The classification of CEA methods developed in this article is based first on the purpose, namely inclusion or exclusion of normative evaluation in the study objectives. Once this question is resolved, the performance of various methods can be used to guide the selection of appropriate tools. For example, an analytical consideration of cumulative effects problems characterized by spatial accumulation might lead to the use of GIS or landscape analysis; whereas a planning approach may extend these analyses to also use an acceptable disturbance target for land suitability evaluation.

The wide range of available methods, and their evolving nature, provides a rationale for methodological pluralism. The suitable combination of methods will depend on the nature of the problem, purpose of the analysis, access to and quality of data, and available resources. For comprehensive CEA, a mix of methods is appropriate, perhaps even necessary, in order to analyze and evaluate sources, pathways, and effects. Thus, a cumulative effects assessment may begin with a method useful for conceptual understanding (e.g., cause–effect diagramming). This may be followed by more comprehensive approaches and empirical analyses, such as landscape analysis or simulation modeling. Results from the analytical investigation may be incorporated into a normative evaluation (e.g., multi-criteria evaluation, land suitability evaluation) that contributes to environmental policy and decision-making. Application of a variety of tools is needed to analyze, evaluate, and manage cumulative effects.

This article has made a fundamental distinction between analytical and planning approaches to CEA. Perhaps this distinction should be reflected in the terminology. "Cumulative effects assessment" has emerged as accepted nomenclature to refer to a systematic procedure for the analysis and evaluation of cumulative environmental change. We propose that "cumulative effects analysis" denotes analytical investigation, including identifying and documenting effects, processes, and sources; providing explanation of temporal and spatial accumulations; and estimating or predicting cumulative effects of actual or proposed human actions. Then, we propose that "cumulative effects evaluation" be used for the normative evaluation and decision-making applications of CEA. These terms build on the distinct, but related, approaches to CEA, and reflect emerging methodological development and practice.

Support for this research has been provided by the Social Sciences and Humanities Research Council of Canada and the Ontario Ministry of Agriculture and Food.

References

Armour, C., and Williamson, S. 1988. *Guidance for Modeling Causes and Effects in Environmental Problem Solving*. Biological Report 89(4). Washington, DC: Fish and Wildlife Service, U.S. Department of the Interior.

Bain, M.B., Irving, J.S., Olsen, R.D., Stull, E.A., and Witmer, G.W. 1986. *Cumulative Impact Assessment: Evaluating the Environmental Effects of Multiple Human Developments*. ANL/EES-TM-309 Energy and Environmental Systems Division. Argonne, IL: Argonne National Laboratory.

Bardecki, M.J. 1990. Coping with cumulative impacts: An assessment of legislative and administrative mechanisms. *Impact Assessment Bulletin* 8(1,2):319–344.

Bardecki, M.J. 1992. *Policies and Procedures for Cumulative Impact Management*. Paper presented to the Canadian Association of Geographers, May 19–22, Vancouver, B.C.

Baskerville, G. 1986. Some scientific issues in cumulative environmental impact assessment. In *Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Bedford, B.L., and Preston, E.M. 1988. Developing the scientific basis for assessing cumulative effects of wetland loss and degradation on landscape functions: Status, perspectives, and prospects. *Environmental Management* 12:751–771.

Braat, L., and Van Lierop, W. 1987. *Economic-Ecological Modeling*. Amsterdam: North-Holland.

Bronson, E., Sears S.K., and Paterson, W.M. 1991. *A Perspective on Cumulative Effects Assessment.* Report No. 91016. Toronto: Environmental Studies and Assessments Department, Ontario Hydro.

Cada, G.F., and Hunsaker, C.T. 1990. Cumulative impacts of hydropower development: Reaching a watershed in impact assessment. *Environmental Professional* 12:2–9.

Cada, G., and McLean, R. 1985. An approach for assessing the impacts on fisheries of basin-wide hydropower development. In *Proceedings of the Symposium on Small Hydropower and Fisheries*, F. Olson, R. White, and R. Hamre (eds). Bethesda, MD: American Fisheries Society.

CEARC (Canadian Environmental Assessment Research Council) and USNRC (United States National Research Council). 1986. *Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Clark, W.C. 1986. The cumulative impacts of human activities on the atmosphere. In *Proceedings of the Workshop on Cumulative Environmental Effects: A Binational Perspective*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Cocklin, C., Parker, S., and Hay, J. 1992a. Notes on cumulative environmental change I: Concepts and issues. *Journal of Environmental Management* 35:31–49.

Cocklin, C., Parker, S., and Hay, J. 1992b. Notes on cumulative environmental change II: A contribution to methodology. *Journal of Environmental Management* 35:51–67.

Contant, C.K., and Wiggins, L.L. 1991. Defining and analyzing cumulative environmental impacts. *Environmental Impact Assessment Review* 11:297–309.

Dames and Moore. 1981. *Methodology for the Analysis of Cumulative Impacts of Corps Permit Activities Regulated by the U.S. Army Corps of Engineers.* Final Draft Handbook. Fort Belvoir, VA: Institute for Water Resources, U.S. Army Corps of Engineers.

Davies, K. 1991. *Towards Ecosystem-Based Planning: A Perspective on Cumulative Environmental Effects.* Report prepared for The Royal Commission on the Future of the Toronto Waterfront and Environment Canada. Ottawa: Minister of Supply and Services.

Dickert, T.G., and Tuttle, A.E. 1985. Cumulative impact assessment in environmental planning: A coastal wetland watershed example. *Environmental Impact Assessment Review* 5:27–64.

Emery, R. 1986. Impact interaction potential: A basin-wide algorithm for assessing cumulative impacts from hydropower projects. *Journal of Environmental Management* 23:341–360.

Gabriel, A., Ollerhead, J., Spaling, H., and Smit, B. 1991. Spatial perspectives on human implications of global climatic change. *Operational Geographer* 9(3):17–24.

Gilliland, M., and Risser, P. 1977. The use of systems diagrams for environmental impact assessment: Procedures and an application. *Ecological Modeling* 3:183–209.

Gosselink, J., and Lee, L. 1989. Cumulative impact assessment in bottomland hardwood forests. *Wetlands* 9:93–174.

Holling, C.S. (ed.) 1978. *Adaptive Environmental Assessment and Management*. New York: John Wiley.

Horak, G.C., Vlachos, E.V., and Cline, E.W. 1983. *Methodological Guidance for Assessing Cumulative Impacts on Fish and Wildlife*. Washington, DC: Office of Biological Services, U.S. Fish and Wildlife Service.

Hubbard, P. 1990. *Cumulative Effects Assessment and Regional Planning in Southern Ontario*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Hunsaker, C. 1989. Ecosystem assessment methods for cumulative effects at the regional scale. In *The Scientific Challenges of NEPA: Future Directions Based on 20 Years of Experience*, S. Hildebrand and J. Cannon (eds). Chelsea, MI: Lewis Publishers.

Irving, J., and Bain, M. 1989. Assessing cumulative impact on fish and wildlife in the Salmon River, Idaho. In *The Scientific Challenges of NEPA: Future Directions Based on 20 Years of Experience*, S. Hildebrand and J. Cannon (eds). Chelsea, MI: Lewis Publishers.

Irwin, F., and Rodes, B. 1992. *Making Decisions on Cumulative Environmental Impacts: A Conceptual Framework*. Baltimore, MD: World Wildlife Fund.

Jacobs, P., and Sadler, B. 1990. *Sustainable Development and Environmental Assessment: Perspectives on Planning for a Common Future*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Johnston, C.A., Detenbeck, N.E., Bonde, J.P., and Niemi, G.J. 1988. Geographic information systems for cumulative impact assessment. *Photogrammetric Engineering and Remote Sensing* 54:1609–1615.

Johnston, C.A., Detenbeck, N.E., and Niemi, G.J. 1990. The cumulative effects of wetlands on stream water quality and quantity: A landscape approach. *Biogeochemistry* 10:105–141.

Jourdonnais, J., Stanford, J., Hauer, F., and Hall, C. 1990. Assessing options for stream regulation using hydrologic simulations and cumulative impact analysis: Flathead River basin, U.S.A. *Regulated Rivers: Research and Management* 5:279–293.

Keane, R. E., Arno, S., and Brown, J. 1990. Simulating cumulative fire effects in Ponderosa Pine/Douglas-Fir forests. *Ecology* 71:189–203.

Lane, P.A. 1986. Symmetry, change, perturbation, and observing mode in natural communities. *Ecology* 67:223–239.

Lane, P.A., Wallace, R.R., Johnson, R.J., and Bernard, D. 1988. *A Reference Guide to Cumulative Effects Assessment in Canada*. Volume 1, Hull, Quebec: Canadian Environmental Assessment Research Council.

Leopold, L. 1971. *A Procedure for Evaluating Environmental Impacts*. Circular 645, U.S. Geological Survey. Washington, DC: Government Printing Office.

McAllister, D.M. 1980. *Evaluation in Environmental Planning: Assessing Environmental, Social, Economic and Political Trade-offs*. Cambridge, MA: MIT Press.

McHarg, I. 1969. *Design with Nature*. Garden City, NY: Doubleday.

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W. 1974. *The Limits to Growth*, 2nd edition. New York: Signet.

Mentor, J. 1985. Cumulative impacts and comprehensive planning: A problem of synergism and a policy dilemma. In *Proceedings of the Symposium on Small Hydropower and Fisheries*, F. Olson, R. White, and R. Hamre (eds). Bethesda, MD: American Fisheries Society.

Nichols, R., and Hyman, E. 1982. Evaluation of environmental assessment methods. *Journal of Water Resources Planning and Management Division (ASCE)* 108:87–105.

OMMAH (Ontario Ministry of Municipal Affairs and Housing). 1982. *The Ontario Lakeshore Capacity Simulation Model: An Introduction.* Toronto, Ontario: Ontario Ministry of Municipal Affairs and Housing.

Peterson, E.B., Chan, Y.-H., Peterson, N.M., Constable, G.A., Caton, R.B., Davis, C.S., Wallace, R.R., and Yarranton, G.A. 1987. *Cumulative Effects Assessment in Canada: An Agenda for Action and Research*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Sebastiani, M., Sambrano, A., Villamizar, A., and Villalba, C. 1989. Cumulative impact and sequential geographical analysis as tools for land use planning. A case study: Laguna La Reina, Miranda State, Venezuela. *Journal of Environmental Management* 29:237–248.

Shopley, J.B., Sowman, M., and Fuggle, R. 1990. Extending the capability of the component interaction matrix as a technique for addressing secondary impacts in environmental assessment. *Journal of Environmental Management* 31:197–213.

Smit, B., Ludlow, L., Johnston, T., and Flaherty, M. 1987. Identifying important agricultural lands: A critique. *Canadian Geographer* 31:356–365.

Sonntag, N.C., Everitt, R.R., Rattie, L.P., Colnett, D.L., Wolf, C.P., Truett, J.C., Dorcey, A.H.J., and Holling, C.S. 1987. *Cumulative Effects Assessment: A Context for Further Research and Development*, Hull, Quebec: Canadian Environmental Assessment Research Council.

Sorensen, J.C. 1971. *A Framework for Identification and Control of Resource Degradation and Conflict in the Multiple Use of the Coastal Zone.* Berkeley, CA: Department of Landscape Architecture, University of California.

Spaling, H., and Smit, B. 1993. Cumulative environmental change: Conceptual frameworks, evaluation approaches, and institutional perspectives. *Environmental Management* 17:587–600.

Stakhiv, E.Z. 1988. An evaluation paradigm for cumulative impact analysis. *Environmental Management* 12:725–748.

Stakhiv, E.Z. 1991. *A Cumulative Impact Analysis Framework for the U.S.Army Corps of Engineers Regulatory Program.* Draft report (February 1991). Fort Belvoir, VA: Institute for Water Resources, U.S. Army Corps of Engineers.

Stull, E.A., LaGory, K.E., and Vinikour,W.S. 1987. *Methodologies for Assessing Cumulative Environmental Effects of Hydroelectric Development on Fish and Wildlife in the Columbia River Basin.* Volumes 1 and 2. Portland, OR: Bonneville Power Administration, U.S. Department of Energy.

Stull, E.A., Bain, M.B., Irving, J.S., LaGory, K.E., Olsen, R.D., and Witmer, G.W. 1988. Cumulative impact assessment: Issues to consider in selecting a cumulative assessment method. In *Waterpower '87: Proceedings of the International Conference on Hydropower*, B.W. Clowes (ed). Volume 1. New York: American Society of Civil Engineers.

USDA-FS (United States Department of Agriculture - Forestry Service). 1990. *CEM—A Model for Assessing Effects on Grizzly Bears.* Missoula, MT: USDA-FS Region 1.

Vlachos, E. 1982. Cumulative impact analysis. *Impact Assessment Bulletin* 1:60–70.

Walker, D., Webber, P., Walker, M., Lederer, N. Meehan, R., and Nordstrand, E. 1986. Use of geobotanical maps and automated mapping techniques to examine cumulative impacts in the Prudhoe Bay Oilfield, Alaska. *Environmental Conservation* 13:149–160.

Whitney, J.B.R., and MacLaren, V.W. 1985. A framework for the assessment of EIA methodologies. In *Environmental Impact Assessment: the Canadian Experience*, J.B.R. Whitney and V.W. MacLaren (eds). Toronto: Institute for Environmental Studies, University of Toronto.

Williamson, S.C. 1990. *Cumulative Impacts Assessment and Management Planning: Lessons Learned to Date.* Unpublished manuscript. Fort Collins, CO: National Ecology Research Center, U.S. Fish and Wildlife Service.

Williamson, S., Armour, C., Kinser, G., Funderburk, S., and Hall, T. 1987. Cumulative impacts assessment: An application to Chesapeake Bay. *Transactions of the North American Wildlife and Natural Resources Conference* 52:377–388.

Witmer, G.W., and O'Neil, T.A. 1988. *Assessing Cumulative Impacts to Wintering Bald Eagles and Their Habitats in Western Washington.* Argonne, IL: Argonne National Laboratory.

Ziemer, R., Lewis, J., Rice, R., and Lisle, T. 1991. Modeling the cumulative watershed effects of forest management strategies. *Journal of Environmental Quality* 20:36–42.