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Cumulative Effects Assessments: An Evaluation of DFO Science Research Options

G.S. Jamieson and L. Chew

Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, B.C. V9R 5K6

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Abstract

Resource managers are increasingly becoming concerned about the cumulative effects arising from different environmental impacts, and how such effects should be considered in a regulatory manner. Here, we present a literature review of the subject in general, discuss the complexities of adequately assessing cumulative effects issues, and review how cumulative effect review processes relating to the aquatic and marine environments have been addressed. A still generic problem is that, although guidelines imposed by agencies often now specify that an assessor must consider the cumulative effects of potential impacts, there are no widely accepted methodologies outlined on how to do so quantitatively with respect to aquatic and marine environments. In fact, the difficulties in conducting assessments over the spatial and temporal scales involved suggest that developing such methodologies will be years away.

Over a decade ago, it was recognised that social and economic factors are the driving force behind management activities that can cause cumulative effects. In the long term, changing social values and perspectives with regard to the environment will likely be the most effective way to increase public awareness of cumulative effects issues and to minimise their consequences. Therefore, given both that quantitative evaluations of cumulative effects will not readily be achievable in the near future and the limited resources that are available with DFO for cumulative effects studies, we suggest that the most cost-effective short term approach is to model discrete systems in a manner that will show managers and the interested public some of the consequences of accepted minor impacts that are cumulatively expressed. The simple act of constructing such models should also advance our understanding of what research priorities might be for the longer-term development of credible, quantitative cumulative effects evaluation methodologies for aquatic and marine systems. We conclude by providing suggestions and recommendations on how such models can best be developed at this time.

Résumé

Les gestionnaires des ressources s’inquiètent de plus en plus des effets cumulatifs de divers impacts environnementaux et se demandent comment ces effets cumulatifs devraient être envisagés sur le plan de la réglementation. Nous présentons un examen des documents sur le sujet en général, discutons de la complexité de la démarche pour faire une évaluation adéquate des questions concernant les effets cumulatifs et examinons comment les processus d’examen des effets cumulatifs concernant les milieux aquatiques et marins ont été envisagés. Il reste un problème générique, soit le fait que, même si les lignes directrices imposées par des organismes précisent souvent que l’évaluateur doit tenir compte des effets cumulatifs des impacts possibles, il n’existe pas de méthodologie généralement reconnue pour en faire une évaluation quantitative en ce qui concerne les milieux aquatiques et marins. En fait, les difficultés inhérentes au processus d’évaluation à l’échelle spatiale et temporelle portent à croire que de telles méthodologies ne seront établies que dans plusieurs années.

Il y a plus de dix ans, il a été reconnu que les facteurs sociaux et économiques étaient la force motrice des activités de gestion qui peuvent donner lieu à des effets cumulatifs. À long terme, les valeurs sociales et les perspectives changeantes concernant l’environnement constitueront probablement la façon la plus efficace de sensibiliser le public aux questions des effets cumulatifs et de réduire leurs répercussions. Ainsi, puisque les évaluations quantitatives des effets cumulatifs ne pourront être effectuées dans un avenir rapproché et que les ressources disponibles au MPO pour ces évaluations sont limitées, nous suggérons que l’approche la plus rentable à court terme constitue l’élaboration de modèles de systèmes distincts de manière à montrer aux gestionnaires et aux intéressés certaines répercussions cumulatives d’impacts mineurs reconnus. Le simple fait d’élaborer de tels modèles devrait également nous permettre de mieux déterminer les priorités de recherche en ce qui concerne l’établissement à long terme de méthodologies quantitatives et crédibles d’évaluation des effets cumulatifs pour les écosystèmes aquatiques et marins. En conclusion, nous présentons des suggestions et des recommandations sur la meilleure façon d’élaborer de tels modèles pour l’instant.

Introduction

Cumulative effects means different things to people with different backgrounds. For stock assessment biologists, it often means the accumulated factors, such as mortality, that occur in the different life stages of a species, and which ultimately determine the size of a recruiting population. To habitat managers conducting reviews under the *Canadian Environmental Assessment Act*, it means identifying Valued Ecosystem Components (VECs) that may be affected by the specific action being assessed; identifying other actions that have occurred, exist, or may yet occur which may also affect those same VECs identified; considering the incremental *additive* effects of the proposed action on the VECs assessed; and then considering the total effects of all the potential actions on the VECs.

Here , we define cumulative effects as:

> "…the impact on the environment which results from the incremental impact of the action when added to other past, present and reasonably foreseeable future actions … (and) can result from individually minor but collectively significant actions taking place over a period of time." (Council on Environmental Quality, 1971)

There are four generally recognised pathways of accumulation in cumulative effects that can be classified as either additive or interactive (Peterson et al., 1987).

1) Additive accumulation occurs linearly from the summation of repeated action of a single process in the absence of interactive processes.
2) The interaction of impacts from persistent additions of a single process can result in a non-linear response, such as biomagnification.
3) Compounding effects can occur due to the additive effects of two or more processes.
4) Finally, synergistic impacts occur when two or more processes interact creating an effect greater (or less than) the simple summation of those processes (Peterson et al., 1987).

Ecosystem responses are more likely to accumulate along one of the latter pathways, with the potential for additional impacts from indirect and secondary effects (Cocklin et al., 1992a).

Until about 15 years ago, environmental impact assessments were conducted only on a project-specific basis. However, in the 1980s there was increasing emphasis placed on taking more of a regional perspective to consider multiple project developments within a broader geographic context (Peterson et al., 1987). In 1985, the Canadian Environmental Assessment Research Council (CEARC) and the U.S. National Research Council (NRC) held a workshop to explore this trend and the implications for future management considerations of cumulative effects (CEARC and U.S. NRC, 1986). Subsequent CEARC reports identified habitat alienation, habitat fragmentation, and the occupation of land by man-made features on a list of the most significant cumulative effects issues facing Canadians (Peterson et al., 1987). Furthermore, CEARC made recommendations for additional research towards the understanding of causative factors in cumulative effects and mapping the pathways of causation, in addition to the methodological development of computer simulation models for use as a cumulative effects evaluation tool (Sonntag et al., 1987).

In the mid-1990s, the newly proclaimed federal *Canadian Environmental Assessment Act* included a regulatory requirement for consideration of cumulative effects in environmental assessment. On the provincial level, both the British Columbia *Environmental Assessment Act* and the Alberta *Environmental Protection and Enhancement Act* also mention cumulative effects factors to be included in environmental impact assessment reports. Federally, cumulative environmental effects are specified in the *Act* in paragraph 16(1)(a) of the, which states:

> "Every screening or comprehensive study of a project and every mediation or assessment by a review panel shall include a consideration of the environmental effects of the project, including … any cumulative environmental effects that are likely to result from the project in combination with other projects or activities that have been or will be carried out."

Although the emphasis on cumulative environmental effects is often placed on biophysical effects, assessments under the *Act* can extend beyond to include the effects of such changes on health and socio-economic conditions, physical and cultural heritage and other environmental effects as defined in Paragraph 2 of the *Act* (CEAA, 1999). To assist responsible authorities in ensuring that cumulative effects requirements are carried out, the Canadian Environmental Assessment Agency has published two documents: *A Reference Guide for the Canadian Environmental Assessment Act: Addressing Cumulative Environmental Effects* (CEAA, 1994) and *Cumulative Effects Assessment Practitioners Guide* (Hegmann et al., 1998). The agency also offers a 2-day course on cumulative effects assessment techniques. In the practitioners guide (Hegmann et al., 1998), the Canadian Environmental Assessment Agency (CEAA) does recognise that cumulative effects assessment is an evolving practice, and that assessments can only be conducted based on the best scientific data and analysis currently available. However, there are still limitations that need to be addressed, particularly with regard to understanding and characterising the complex interactions of biological organisms. Suggested areas for improvement include better understanding of specific interactions among various actions and resulting synergistic effects, finer resolution in establishing regional thresholds, more proven analytical approaches producing quantitative results, and the need to gain an understanding of the influence of cumulative socio-economic changes on regional environments (Hegmann et al., 1998).

Research programs such as QUEST at the University of British Columbia and PRISM at the University of Washington are working towards modelling the complex interactions between human land use and resulting ecosystem impacts through the use of technological developments in remote sensing and Geographic Information Systems (GIS). Millions of dollars have been committed in each of these programs, which are on-going, with deliverables produced at specified time intervals.

Cumulative effects in aquatic environments have been identified by the Habitat and Enhancement Branch (HEB) of Fisheries and Oceans Canada (DFO) as a high priority for managers in consideration of the potential impact of proposed developments. This need sparked a proposal in 1999 (G. Jamieson, unpublished) for the development of a tool for the prediction of cumulative impacts on fisheries resources. However, this proposal was not funded and there remains no scientifically tested methodology developed to predict cumulative environmental effects on fishery resources in a quantitative manner. In this report, we summarise the history of cumulative effects research and assessments, and suggest direction in which DFO might move to scientifically address cumulative affects issues directly relevant to its mandate to conserve and sustain aquatic and marine resources. Given the funding likely available, interest to date and other existing commitments, it seems beyond the scope of DFO's Science Branch to be able to tackle the complex issue of cumulative effects on fishery resources on its own. Consequently, the direction being proposed is a partnership with other initiatives already underway.

History of the Development of Cumulative Effects Assessments

A. Scale Considerations

Both spatial and temporal scale are key considerations in modelling cumulative effects. Discrepancies can occur between the scale of management activities and environmental consequences resulting from those activities (Contant and Wiggins, 1993). A major criticism of previous environmental impact assessments has been focus on a single development in only its immediate surroundings over a short time span. This limited view can restrict a thorough understanding of the impact and its interaction with other ecosystem components, which typically occur both locally and off-site (Reid, 1993). In an ecosystem approach, scale conditions vary with the physical or biological issues under consideration. However, it is proving difficult to analyse effects in large-scale ecosystems using the experimental science methodologies that often guide policy and decision processes (Harris and Gosselink, 1990). Attempts to define spatial boundaries are further complicated by jurisdictional borders, land ownership, and the nature of human activity patterns (Cocklin et al, 1992a).

The most common spatial boundary for cumulative effects assessment in the terrestrial environment is the watershed. Watershed analysis has been considered most appropriate for identifying relevant issues and displaying linkages necessary for an understanding of ecosystem processes (FEMAT, 1993), and is the largest practical unit for controlled and replicated studies (Burns, 1991). Watersheds are distinct geographic units in which land use impacts can be represented by changes in flows of water, sediment and nutrients in a downstream direction. Because these watershed parameters are key factors in demonstrating relationships between human activities and fish, cumulative effects assessments and modelling are often focussed on both watershed hydrology and water quality (Gosselink et al., 1990; Burns, 1991; Reid, 1993).

An appropriate time scale must also be defined in cumulative effects analysis. It may initially appear to be adequate to limit temporal scale to the average life span of the species under consideration. However, it can be more appropriate to apply a time scale which encompasses the geomorphic processes associated with forestry, agricultural, urban, and other land uses that determine the physical conditions of the species habitat (Ziemer, 1997). For example, relatively short-term sedimentation impacts in watersheds may not be readily apparent due to the transport processes of entrainment and deposition, which can modify and/or delay responses, resulting in an underestimation of long-term cumulative effects (Ziemer, 1991; Reid, 1993; NCASI, 1999).

B. Model Development and Limitations

To develop a model for cumulative effects, the first conventional step is to define the model’s objectives. Watershed analysis can be very complex depending on variability in characteristics, conditions, processes and issues. It is important to establish desirable objectives within the land use and environmental setting as part of the process to assess key species and habitat requirements at risk (Reid, 1993). Predetermining the desired level of detail and precision will assist in limiting the scope of the analysis within the available resources of data, time and funding. Also, if the model is intended for widespread use, standardisation in data, methodology and product are necessary for the production of consistent, comparable results (Reid et al., In review).

Data requirements and availability are a primary consideration of cumulative effects analysis. Preliminary scoping of relevant issues assists in limiting the number of landscape indices needed to reflect the ecological structure, hydrologic, water quality, and biotic function of the watershed. In general, relevant indices should be simple, measurable, available over time, and representative of ecological process over time and space (Gosselink et al., 1990). Well-defined data collection methodologies ensure there is a standardised level of accuracy and precision, scale of representation, and format for consistent analysis. A large, well-distributed data set is required to cover a wide variety of anticipated conditions. Long term monitoring should also be included as part of an analysis to assist in developing an understanding of the role of extreme natural events, particularly in upper watersheds, where the majority of morphological change is typically in response to large storms (Ziemer, 1994).

In order to assess the accumulation of impacts on resources under consideration, investigators must first properly establish baseline conditions to measure from. Previous cumulative impact assessments have often erroneously considered present conditions as the baseline, neglecting to consider the impacts of any past and present actions that may have already taken place (McCold and Saulsbury, 1996). Some investigators are defining the baseline to be where the resource was most abundant, although other factors such as social goals and data availability may also be important. A lack of background data are often a limiting condition, since monitoring programs may not have been established prior to land use activity, which would have established baseline conditions from which to detect subsequent change (Contant and Wiggins, 1993). If not available, data from other systems in the same ecoregion, with similar climate, geology, terrain, and scale, may be the only alternative source from which to extrapolate relative rates and processes (Ziemer, 1994).

Key to modelling and prediction of cumulative effects is the development of an understanding of the processes and dynamics of the system, including pathways of accumulation and recovery. In order to be able to predict cumulative impacts, there must be an understanding of cause-and-effect relationships associated with them (Cornford, 1986). Scientific knowledge of impact processes is still relatively limited, particularly when impacts cross media or natural systems (Contant and Wiggins, 1993). Prediction is also dependant on knowledge of the response rates of systems to impacts. Rates of change caused by land use impacts and their subsequent recovery are often assumed to be linear. However, in reality this is often not the case (Reid, 1993; Ziemer, 1994). For example, in undisturbed mountainous watersheds, morphological channel change is primarily driven by large infrequent storm events, which drive erosion, sediment transport and changes in bed elevation. At other times, channel morphology is in a state of recovery towards a state of quasi-equilibrium before the next extreme event (Ziemer, 1997). Understanding the interaction between multiple-source impacts is further complicated when their respective rates of response vary over spatial and temporal scale (Beschta et al., 1995). Rates of change can be extracted from retrospective studies using sequential aerial photographs and interpretive maps, and stratigraphic sequences of physical and chemical tracers can be used to show temporal rates of erosion and sedimentation (Sidle and Sharpley, 1991).

Understanding watershed change also requires establishment of thresholds of concern, i.e., the limit of disturbances beyond which the dynamic equilibrium of the system will be disrupted (Coburn, 1989). The establishment of thresholds defined by ‘significant’ impacts can be based on a physical or biological scientific standard utilising available statistical data (Reid, 1998). However, thresholds can also be politically determined based subjectively on social values of perceived risk (Ziemer, 1994).

Recent developments in technology have increased opportunity for not only assessing cumulative impacts from past and present actions, but also to develop models to predict the future cumulative effects of proposed developments. Advances in computer technology, remote sensing capability and GIS can all be utilised to work towards such a goal (Johnston et al., 1988; Sebastiani et al., 1989; Sidle and Sharpely, 1991; Cocklin, 1992b; Reid, 1993). However, there are scale constraints associated with using GIS that can affect the integrity of original data. Although it is important to standardise data to work with GIS, it is important not to let those requirements control analyses and outcomes of a model (Reid et al., In review).

C. Land Use Impacts and Indicators of Cumulative Effects

There have been a number of watershed studies assessing the impacts of multiple or single land uses on water quality. The United States Environmental Protection Agency published guidelines for monitoring water quality parameters in the Pacific Northwest (MacDonald et al., 1991). This comprehensive guide reviews sampling methodology and statistical considerations, and the selection of appropriate monitoring parameters. However, more importantly for the understanding of cumulative effects, the guidelines include a section on the relationships between water quality parameters and various management activities, and the potential interactions between those parameters. Although these guidelines focused on examining the watershed impacts of forestry activities, the scope of the parameters considered and the associated discussion can be applied to a variety of land use activities. A review of forestry-related watershed impacts in Oregon (Beschta et al., 1995) specifically discussed the cumulative effects of land use on water quality and hydrology.

Hydrological indicators are often employed by agencies responsible for the management and protection of aquatic resources (BC MOF/MELP, 1995; WFPB, 1995). However, the use of instream flow measurements alone has been criticised for poorly integrating biological and ecosystem information, and its limited applicability in regions outside of the local study area (Jourdonnais et al., 1990). Simple indices such as mean and median discharge rates have been described as limited summary variables providing relatively low resolution descriptions of complex hydrological patterns, while other complex indices such as discharge-duration curves, spectral analysis and fractal geometry are often too data intensive and difficult to interpret (Nestler and Long, 1997).

Water quality can also be used as a measure of cumulative effects. Water temperature, conductivity, sediment load, and nutrient, bacteria and contaminant levels can all be utilised when assessing the cumulative impacts of land use (MacDonald et al., 1991; Bolstad and Swank, 1997). In order to understand the general level of such effects, assimilative capacity has been suggested as a method to integrate various water quality parameters in both freshwater and estuarine systems. Assimilative capacity is the threshold beyond which natural physical, chemical or biological processes cannot absorb waste or disturbance resulting in environmental degradation (BCMELP, 1995). However, there are concerns about the application of assimilative capacity to assess cumulative effects on an ecosystem (Hyde, 1994). These concerns have continued, causing CEAA to identify assimilative capacity as an environmental assessment scientific challenge that needs to be addressed (Lawrence, 1999).

Sediment load in streams is often used as an indicator of land use activities in watersheds, particularly in those watersheds that experience forest management activity (MacDonald et al., 1991; Binkley and Brown, 1993; Megahan and Ketcheson, 1996; Bolstad and Swank, 1997). Increased sediment loads can have adverse impacts both on fish and aquatic invertebrates and their habitats directly through alterations in channel morphology and bed structure, and indirectly through changes in water quality such as increasing stream temperature and decreasing intra-gravel dissolved oxygen levels. The adsorption of chemicals and nutrients to particle surfaces often results in a correlation between chemical water quality and sediment load, which can also have further impacts from municipal and agricultural uses (MacDonald et al., 1991).

Birtwell (1999) reviewed the effects of suspended sediment on fish and fish habitat and summarised concentration and turbidity guidelines for sub-lethal and lethal impacts on fish. Sediment load monitoring can be conducted by measuring suspended sediment concentration, turbidity, and bedload sampling. However, short-term sediment transport rates typically vary within 1-2 orders of magnitude, and it is common for inter-annual sediment loads to have coefficients of variation of 70-100% (NCASI, 1999). Sediment source variables such as location; particle size, volume and type; and, stream morphology, sediment budgetary state, and alterations in discharge all contribute to lags in sediment transport. To achieve an understanding of the interactions of the complexity of variables requires the proper selection of monitoring locations. Although the accuracy of sediment yield measurements can be improved by also assessing stream type and quantifying channel characteristics, five to ten years of pre/post-monitoring data may be required to assess sedimentary cumulative effects (NCASI, 1999).

In cumulative effects studies focussing on habitat issues, a major challenge is the use and selection of indicator species to represent general habitat conditions within the identified ecosystem. Although several species may be potentially subject to the cumulative impacts of land use practices, issues such as variations in behaviour, habitat preferences, intraspecific competition, and predation often make it difficult to understand impacts at an ecosystem level (Dayton, 1986). Anadromous salmonids have been identified as useful biological indicators of ecosystem change because of their presence in both freshwater and marine ecosystems, their high sensitivity to environmental change during each of several life history stages, and the long time series data available for Pacific stocks. Consequently, salmon observations might be utilised as indicators of ecosystem biodiversity, anthropogenic impacts, and natural large-scale ecosystem changes in global circulation patterns (Hyatt, 1996). However, there are limitations to the use of fisheries abundance data due to high variability in data collection methodologies (May et al., 1997). Benthic macro-invertebrates have been utilised as alternative biological indicators of land use impacts on salmonids because disturbances in physical habitat seem to affect them in a similar way as salmonids; many are long-lived, sedentary and easily sampled; and many are main components of the salmonid food web (May et al., 1997).

The Habitat Suitability Index (HSI) has been used as an alternative to species abundance data as a biological indicator of land use activities in watersheds (Liepitz, 1994; Seaman, 1995). HSIs were developed under the Habitat Evaluation Procedure of the US Fish and

Wildlife Service as a species-specific quantitative model of habitat quality, which when combined with an areal measurement of Habitat Units (HU), illustrates the amount and quality of available habitats. Measurements of physical, chemical or vegetative parameters that are related to the survival, distribution, abundance, behaviour and growth of a species are rated on a suitability index curve with a scale of 0 (unsuitable) to 1 (optimum). In order to assess future habitat conditions, model parameters can be varied based on predicted changes in habitat quality or available HUs, and model predictions can be compared to present conditions (USFWS, 1980). However, for application in a specific area, the validity of habitat models need to be well-tested *a priori*, and must be supported by the availability of sufficient, locally-relevant data (Reid et al., In review).

Use of HSIs for coho and chum on the west coast of Vancouver Island have had mixed results. The coho HSI model (Lamb, 1987) failed to detect statistically significant differences in habitat quality between logged and unlogged reaches because a limited sampling period did not include the extreme conditions that the HSI detects, and the time period was too long between disturbance and sampling. As a result, Lamb (1987) recommended that a HSI is best suited for measuring impacts in only small, recently disturbed watersheds. Statistically significant results for coho and chum HSI models were observed (McMahon, 1987) when the data time series of before, during and after logging disturbances was increased. Suggestions for further improvements were made by calibrating models to local habitat conditions (McMahon, 1987). In the case of anadromous salmonids, it is important for the model to include estuarine and coastal areas in addition to the fluvial system (Ziemer, 1997).

There is further criticism of the use of habitat models that utilise measurements of stream channel parameters and biological targets for the assessment of cumulative effects (Sidle and Sharpley, 1991; Peterson et al., 1992). Models that focus on species high on the food chain may not reflect immediate or short term land use impacts in assessments due to the time lag between managed activities (impacts) and the expression of their effects on species at higher trophic levels. Damage from watershed impacts may also occur in ecosystem components not being monitored**.** As an alternative, by establishing relationships between basic ecosystem components and habitat targets derived from channel conditions in an undisturbed watershed, measurements of parameters such as water quantity and quality might best be used simply as initial indicators of environmental change. Further refinement of the assessment of the system would be a stream classification process to identify other watersheds likely exhibiting similar responses to disturbance (Peterson et al., 1992). The use of habitat models, at the very least, requires testing to verify their applicability to specific areas of study (Reid et al., In review).

In 1997, the International Council for the Exploration of the Sea (ICES) reviewed various biological effects monitoring techniques for potential use in the marine environment, and recommended Scope for Growth (SFG) as one of the applications for monitoring programmes at a national or international level (ICES, 1997). SFG is primarily applied to marine invertebrates to evaluate aquatic environmental quality and test the toxic effects of contaminants. SFG represents a quantitative index of energy available for growth and reproduction, by integrating the physiological responses of organisms through the balance of energy acquisition (feeding and food absorption) and expenditure (respiration and excretion) (Smaal and Widdows, 1994). Blue mussels (*Mytilus edulis*) are commonly used as the indicator species due to their world-wide occurrence and ability to bioaccumulate contaminants. Both field and laboratory studies have found significant, quantitative and predictable relationships between concentrations of contaminants and physiological responses (Martin et al., 1984; Widdows et al., 1987; Widdows and Johnson, 1988). One advantage of applying SFG to cumulative effects studies is the ability to distinguish between natural and anthropogenic impacts through carefully controlled experimental conditions. Another advantage of the technique is the application to both isolated, acute contamination incidents, and long-term, chronic exposure (Smaal and Widdows, 1994).

D. Other Cumulative Effects Studies

The earliest watershed studies assessing land use impacts analysed either the effect of a single land use on a variety of watershed variables (Klock, 1985; Stull and Emery, 1985; Stull et al., 1987a; Stull et al., 1987b; Ziemer et al., 1991; Leibowitz et al., 1992; May et al., 1997) or focussed on the impacts of multiple land uses on a particular ecosystem parameter (Jourdonnais et al., 1990; Bolstad and Swank, 1997; Nestler and Long, 1997). Relatively few studies have attempted to integrate the information from previous watershed studies to model cumulative impacts from management activities. The following discussion gives examples of watershed studies specifically relating to cumulative effects, methodologies employed in cumulative effects assessments, and the land use situations in which they were applied.

1) Hydroelectric Development

Some of the earlier attempts at predicting cumulative impacts were conducted in watersheds subject to proposed multiple hydroelectric developments. The Bonneville Power Administration funded a study to develop a methodology to assess the cumulative effects of multiple hydroelectric developments on fish and wildlife (Stull and Emery, 1985; Stull et al., 1987a; Stull et al., 1987b). For the study area, a list of key species, habitat types, and a summary of the potential impacts they might experience from hydroelectric development was developed. An integrated tabular methodology was then employed to generate an interaction matrix, which was combined with response curves produced from multivariate models that incorporated non-linear and synergistic impacts, in addition to additive effects from multiple projects. Combining the interaction and impact matrices calculated the cumulative effects. A reliance on existing response curves derived from previous studies was recognised as a limitation of the model (Stull et al., 1987b).

2) Forestry

The long period between repeated harvesting rotations in forestry is unsuitable for the short-term experimental study of the long-term cumulative effects of forestry. Therefore, although models have been developed to examine the potential impacts from forest harvesting, they have not been validated. Ziemer et al. (1991) utilised Monte Carlo simulation to model the impacts of varying cutting strategies on watershed erosion and sedimentation in coastal Oregon and California. Predicted patterns of sediment erosion and deposition demonstrated the potential for temporal and spatial variability in long term cumulative effects of forestry in watersheds over a 200-year period. In contrast, the Klock Watershed Cumulative Effects Analysis focussed on a model describing the hydrologic condition of a watershed under alternative scenarios of development patterns over a year. It was concluded that resulting evaluations of potential watershed conditions need to be considered within the context of natural climatic variability and episodic events (Klock, 1985).

The most widely used cumulative effects tools developed in the forest industry in western Canada and the Pacific Northwest use evidence of impacts from past development activity to predict the potential watershed impacts of logging. In both British Columbia (BC MOF/MELP, 1995) and Washington (WFPB, 1995), the respective Forest Service agencies have developed a Watershed Assessment Procedure (WAP) which have been criticised for their reliance on qualitative and quantitative assessments of past harvesting activity to rationalise management decisions to control future potential effects (Collins and Pess, 1997).

In BC, the first version of the WAP was based on hazard indices for peak flow, landslides, surface erosion, riparian disturbance and headwater hazard that were derived from quantitative measurements of varying watershed characteristics (BC MOF/MELP, 1995). However, the procedure failed to model future impacts because it did not incorporate proposed road building and clearcut measurements to develop indices for potential future harvesting effects. In addition, the procedure has been criticised both for relying too heavily on quantitative measurements to produce the hazard indices (P. Teti, BC Ministry of Forests, Cariboo Region, pers. comm.) and for lacking scientific verification of true representation of watershed impacts. Consequently, although quantitative measurements of watershed components are still part of the revised version of the WAP, data produced are no longer converted into a hazard index to signify development impact. Instead, analysis relies primarily on the professional judgement of the assessor to qualitatively determine potential impacts of future harvesting. Furthermore, although revised guidelines now specify that the assessor must consider the cumulative effects of potential impacts from future development on stream stability from watershed level sediment sources, riparian conditions and peak flow increases, and discrete, site specific events, there is no methodology outlined to do so (BC MOF, 1999).

There has also been extensive study of the cumulative effects of conversion of bottomland hardwood forests to agriculture in the south-eastern United States. Loss of wetland habitat has had cumulative impacts on flood moderation and groundwater recharge, water quality maintenance, and indigenous wildlife populations resulting in modification of the function, process and structure of natural ecosystems (Harris and Gosselink, 1990). In response to environmental risks to threatened ecosystems, the EPA Wetlands Research Program developed *A Synoptic Approach to Cumulative Impact Assessment* to assist wetland permit reviews under the Clean Water Act (Leibowitz et al., 1992). The approach follows a five step process: 1) defining goals and criteria; 2) defining synoptic indices; 3) selection of landscape indicators; 4) conducting the assessment; and 5) preparation of synoptic reports. Synoptic indices are relative indicators of landscape quality for readily defined landscape units, such as watersheds. Based on the goals of individual programs, comparisons are drawn between one or more of the following four landscape quality indicators: function, value, functional loss, and replacement potential. Existing data sources are used to estimate values for the chosen landscape quality indices of each landscape subunit, which are then ranked based on calculated synoptic indices and displayed graphically on maps (Liebowitz et al., 1992). An advantage of this approach is its use of existing information sources. However, the trade-off with this approach is a lower degree of precision. The approach is better suited to broad-scale planning rather than regulatory review of development applications. There are plans to develop an improved version of the methodology once researchers have validated models of regional landscape function and tested landscape indicators for the region (Leibowitz et al., 1992). However, until this is developed, the procedure relies on the best professional judgement of the team conducting the assessment.

3) Urbanisation

Several watershed studies have looked at the cumulative effects of urbanisation on aquatic environments. Stream quality in the Puget Sound lowland has been assessed at varying levels of urban development, and data have been used to suggest thresholds for management and protection (May et al., 1997). Level of development was assessed through measurements of forested area, road density, stream crossings, and quality and extent of riparian corridor. However, total impervious area (TIA) was found to be the most representative summary index of urbanisation. Graphical and statistical techniques were utilised to identify relationships between TIA and characteristics of instream habitat, riparian conditions, physical and chemical water quality and biological attributes. The study found that a decline in biologic integrity and physical habitat conditions were initiated at a TIA of 5%. However, chemical water quality was not significantly impacted until TIA exceeded 45% (May et al., 1997).

Olenik (1995) argued the need to translate retrospective analysis like the study of the Puget Sound lowland into tools to predict the cumulative effects of urban development in watersheds. Some models attempted to do so (Dickert and Tuttle, 1985). However, as in the case of the forestry examples, predictive cumulative effects assessments have been criticised for being restricted to a single or a few similar impacts and not having a broad enough overview of potential effects. Early use of computer modelling in evaluations of more complex process systems produced primarily qualitative results with limited scientific basis (Reid, 1993), but there are currently some research programs attempting to deal with those issues (SDRI, 1999; Simenstad, 2000)**.**

The Georgia Basin Futures Project is an alternative approach that predicts the environmental, social and economic impacts of simulated change in an urban setting. Developed by the Sustainable Development Research Institute (SDRI) at the University of British Columbia, this initiative utilises a computer model, GB-QUEST, to generate and analyse a series of alternative future scenarios (SDRI, 1999). The primary objective of QUEST is to be a tool for public consultation, i.e. to educate and inform the public constituency as a means to develop grass roots socio-economic and environmental policy.

Key to the GB-Quest model is its backcasting approach, which involves developing and evaluating the physical consistency and socio-economic feasibility of future end-points. QUEST was not developed to be a direct tool for managers by providing a picture of the most likely futures, nor does it reflect a detailed understanding of all of the complex systems involved. Rather, it tries to teach users about the choices available, and about the linkages between choices and possible consequences (SDRI, 1999).

4) Water Quality

In an alternative to the study of a single land use on various watershed parameters, Bolstad and Swank (1997) studied the impact of multiple land uses on water quality. In order to understand the relative contributions of non-point source pollution from the progression of forest, agricultural, suburban and urban land uses, representative indicators were statistically analysed against water quality parameters measured at five monitoring stations located at various points downstream. Similar to the results of May et al. (1997), there was a high correlation between land use variables in the urban environment. Consequently, one variable, building density within 50 m of a stream, was utilised as the independent landscape variable in simple linear regression models using numerous water quality parameters (Bolstad and Swank, 1997). Total road density and unpaved road density indicators were also regressed against water quality at the five stations. Overall, base flow water quality was found to be high, falling within acceptable biological limits. However, significant differences between base flow and storm flow water quality were evident for some variables, indicating that land use impacts were occurring during storm conditions. Turbidity, bacteria populations, and some inorganic solutes increased downstream with increased human disturbance reflected by changing land use, most likely due to increased overland flow during storm events. However, there was also a general increase in variability for all water quality parameters in storm flow samples (Bolstad and Swank, 1997).

In an alternative approach to gauging land use impacts by assessing specific water quality parameters, some studies have taken a more holistic approach. In recognition of the difficulty in assessing approvals potentially affecting water quality, the Bow River Water

Quality Council (1994) suggested using assimilative capacity among multiple pollutant sources as one of the methods to assess cumulative watershed impacts on the river. In the Saanich Inlet Study (BCMELP, 1995), the collection of baseline information was conducted in order to assess sensitivity to contaminants and marine habitat disturbance, and determine the assimilative capacity of the inlet. The study recommendations were to utilise this information in a cumulative effects approach to the future evaluation of developments, land use and water use.

5) Hydrology

Nestler and Long (1997) developed hydrological indices to describe changes in long-term discharge patterns in a riverine wetland. In their study, harmonic analysis of simple hydrologic indices was used to demonstrate central tendency, seasonality, and annual range of conditions. In addition, comparative time-scale analysis was used to separate seasonal factors such as spring freshet, seasonal rainfall patterns and groundwater recharge. The analysis found that in response to changes in land use over a fifty year period, flow minimums were altered from a stable, aquifer-dominated flow pattern to a flashier, runoff-dominated flow pattern.

To supplement the use of hydrological indicators, Jourdonnais et al. (1990) utilised a hydrological simulation model in conjunction with a multi-attribute trade-off analysis to assess potential cumulative impacts in a regulated river environment. An interdisciplinary working group representing different resource management agencies assigned geographic and importance weightings to ecological and societal resources in the system. A stepwise computation process was used to index impacts and to sum the indices to represent cumulative effects under a proposed regulation scenario. Their analysis predicted the hydrological conditions under which various ecological and societal impacts would be minimised. Not surprisingly, the optimum hydrograph to minimise ecological impacts on fish and wildlife most closely resembled the natural hydrograph for the system. However, this scenario did not support a hydrograph representative of the demands on societal resources, such as flood control, electric power generation, and boating and recreation (Jourdonnais et al., 1990). Consequently, the inclusion of societal demands on resources in a cumulative impact study highlighted the compromises required between various management agencies in resource planning.

6) Biological Indicators

A Habitat Evaluation Procedure was used to measure the cumulative effects of development on the Kenai River in Alaska utilising habitat suitability indices (HSI) for chinook salmon (Liepitz, 1994; Seaman, 1995). Analysis was primarily an additive exercise of summing the loss of habitat units (HU) along a 100 km reach of the river mainstem. In addition, a development trend analysis was conducted by comparing HSIs determined from historical air photographs to current HSIs and using GIS to derive rate of habitat loss on the river. The goal was to assess future impacts through the extrapolation of future development scenarios. However, the procedure was limited to: 1) looking only at additive cumulative impacts and not accounting for secondary, indirect or synergistic effects, 2) its reliance on chinook salmon as the indicator species to represent overall habitat conditions, and 3) the assumption that prior to development, habitat conditions were optimal without verification from baseline data.

7) Marine Environment

The majority of earlier cumulative effects studies in aquatic systems focussed on fluvial as opposed to marine environments. The application of cumulative effects assessment in marine areas has been limited by the need to address new challenges in addition to those faced on terrestrial studies. Properties of marine ecosystems are fundamentally different from freshwater ecosystems due to: 1) the 3-dimensional, fluid nature of the marine environment; 2) heavy reliance on planktonic primary production; and, 3) the dispersal of most benthic marine animals through meroplanktonic larvae (Hinga, 1995). The definition of spatial boundaries is further complicated not only by watershed inputs from the fluvial system, but also by currents and tidal movement in the coastal zone. Potential cumulative impacts on marine organisms could be manifested through alterations in feeding behaviour, fecundity, larval survivorship, habitat selection, and bioaccumulation of contaminants (Dayton, 1986).

More general distinctions include the limited historic records in the marine environment. This relative lack of data restricts ability to establish baselines or determine degree of change over time. In addition, there are relatively few studies on the functional roles of different species, levels of redundancy, and the use of indicator species to gauge ecosystem health (Vestal and Rieser, 1995). This relative lack of scientific knowledge about cause and effect relationships is a critical impediment to the describing of functional relationships in cumulative effects studies. Consequently, the current level of marine environmental science may not allow general predictions of the effects of alterations to the marine environment with the accuracy, precision and confidence desired to support management decisions (Hinga, 1995).

Initiatives are taking place to better understand the linkages between land use and the estuarine and marine environment. The National Oceanic and Atmospheric Administration Coastal Change Analysis Project's (C-CAP) goal is to determine the effect of existing and changing land cover on the abundance, distribution and health of living marine resources (Dobson et al., 1995). Although the project's guidelines mention utilising a geographical database to assess and predict cumulative effects, C-CAP is not directly involved in developing a methodology to do this.

The Puget Sound Regional Synthesis Model (PRISM) project out of the University of Washington is also looking at the effects of land use on the coastal environment (PRISM, 1999). The continuum of water flow modelled in their Distributed Hydrology Soils and Vegetation Model is being carried into Puget Sound by the Princeton Oceanographic Model, which is being utilised to follow circulation transport mechanisms in the estuarine and nearshore environments. The large amount of quantitative data to be used in environmental modelling are being collected through remote sensing, data acquisition and data archives, which when coupled, can hopefully be used to plan for future growth and answer questions about human impact on the environment.

Within PRISM, a technical working group is currently developing NearPRISM, a project that will integrate process models simulating shoreline sedimentation, geochemical cycling of organic matter and nutrients, primary production, and fish and wildlife habitat structures over time on delimited shoreline habitat types. By linking this biophysical model to other PRISM models of watershed and marine dynamics, it is hoped that a tool will be developed to assist planners and resource managers assess the long-term cumulative impact of shoreline modifications to the nearshore environment of the Puget Sound (Simenstad, 2000). The data intensity of all of the models which make up PRISM is highly demanding and complex, and is likely unrealistic under the fiscal constraints of the program. To date, PRISM has acquired $US 3 million dollars in funding to develop the model, and has another $US 4 million dollars in proposals to conduct all of the research that is deemed necessary to gain a thorough understanding of the Puget Sound ecosystem.

Identified Cumulative Effects needs of DFO Resource Managers

In 1988, the CEARC recognised that social and economic factors are the driving force behind management activities that can cause cumulative effects. Therefore, in the long term, changing social values and perspectives with regard to the environment through the use of tools such as GB-QUEST may be the most appropriate method to manage cumulative effects (CEARC, 1988). However, in the short term there is a current need for resource managers to deal with cumulative effects issues in a more immediate context. Cumulative effects issues identified by regional Habitat and Enhancement (HEB) and Oceans managers are summarised in Table 1.

Recent proposal initiatives for development of a model that would permit alternate cumulative effects scenario evaluations by DFO resource managers

In light of the above review, it is apparent that there are no current recognised and accepted methodologies anywhere that would permit aquatic and marine resource managers to evaluate fully either the consequences of proposed actions or to investigate the consequences of past actions in a timely, site-specific and geo-spatially referenced manner. However, recent advances in computer software (e.g. Facet Systems Inc.) and a mid-1990's DFO initiative (Williams et al. 1999) that determined the spatial impacts of upland land perturbations on watercourses, simulated species migration through watercourses, and simulated the effects of water environmental features on species survival rates, etc., was the basis behind a Forestry Renewal BC (FRBC) cumulative effects research submission in late 1996. This submission, developed by this report's senior author, through the Mount Arrowsmith Biosphere Foundation, included many DFO and academic researchers as team members. Its goal was the development of a model that would allow the above, and be accessible through the internet in real time. However, that was unfortunately the time when FRBC funding of new initiatives, particularly relatively costly, multi-year ones, was severely curtailed, with the result that it was not funded. A reduced version was submitted to DFO's Environmental Science Strategic Research Fund (ESSRF); it was not funded in 1999 or in 2000.

Conclusions

The above efforts have been insightful in a number of ways, and have resulted in the following conclusions being drawn re the current ability of DFO to initiate a meaningful cumulative effects program:

1. A comprehensive cumulative effects research effort will, by its very nature, be a complex undertaking and will take a number of years (estimate 4-5 y), involve the development of new approaches, and involve many DFO people in different capacities on both the Science and operational side. As such, many existing funding forums, such as ESSRF, are inappropriate, since they were designed to support shorter term, smaller scale proposals. We suggest that if funded solely within a specific agency like DFO, the proposal would need to be funded as a stand-alone initiative through a direct allocation of funds for this purpose.
2. Because a proposal would be on the cutting edge of Science and will involve the incorporation of many new ideas and methodologies, it has no existing, well-developed advocate base within DFO, beyond a few individual researchers. It crosses

too many conventional research jurisdictions (e.g. chemistry, stock assessment, habitat science, etc.), and as such is not the highest priority of any single group. While everyone recognises their importance, few seem prepared to take a more holistic perspective than encompassed within their own relatively narrow disciplines. To garner the support suggested above, it needs strong proponents at the middle and senior science management level.

3. Because both quantitative evaluations of cumulative effects will not readily be achievable in the near future, and there are only limited resources available within DFO for cumulative effects studies, we suggest that the most cost-effective short term approach is to model discrete systems in a manner that will show managers and the interested public some of the consequences of accepted minor impacts that are cumulatively expressed. The simple act of constructing such models should also advance our understanding of what research priorities might be for the longer-term development of credible, quantitative cumulative effects evaluation methodologies for aquatic and marine systems.
4. Given the above, cumulative effects research submissions of the nature required seem unlikely to be fundable solely within DFO. A more productive alternative might be to become associated with an existing multi-million dollar university-initiated cumulative effects type project, and to build applications on their platform that could begin to address the requirements of DFO resource managers. The down-side of doing this is that DFO's interests will to some extent become subservient to the direction being taken by the larger project, and timeframes over which results will be achieved become more problematic. Nevertheless, this seems to be the only viable alternative at this time if a practical cumulative effects model relevant to DFO is to be developed.

Recommendations

1. If senior managers agree with the research needs for a cumulative effects evaluation process that will be functionally useful to DFO managers in a timely, *a priori* manner,

then direction needs to be provided by them as to how such a complex study should proceed and be funded.

2. Until a plan for obtaining required support is developed, efforts to develop the tools (e.g. electronic processes to merge spatially referenced databases, data assimilation for decision rule development, etc.) that would be required in cumulative effects studies should continue to be developed as opportunities present themselves.

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Table 1: Resource managers comments on how Science might best assist them in dealing with cumulative effects issues, November, 2000.

Agency	**Comment**
HEB	How to meet the requirements of the Canadian Environmental Assessment Act. Where we trigger CEAA, this is required by law. The law, however sets out limitations (basically past projects with no scope for future ones that may or may not go ahead) (G. Ennis, pers. comm.).
HEB	How can we effectively deal with cumulative effects when even things that should be directly impacted and simple to measure are swamped by environmental noise (B. Shepherd, pers. comm.).
HEB	A cumulative effects review of 140 years of human impacts on the Fraser River is needed, what are the future prospects of habitat as related to current trends, and what is the role of restoration etc. in addressing some of those long term impacts (O. Langer, pers. comm.).
HEB	How to define what the cumulative effects of a project are and analyse the impacts. As an example, the Yukon Placer Authorisation is scheduled for review in 2001. The issue of cumulative effects is very difficult, but is required for the review. How does one scope the issue, then how does one determine the impacts of over 100 years of stream disruption? Cumulative effects assessments are currently very qualitative, being difficult to define, and are almost impossible to measure quantitatively. They require a high level of professional judgement. This flies in the face of ongoing attempts to achieve consistency (G. Faulkner, pers. comm.).

Agency	Comment
HEB	Generally when this subject has been raised, it is in the context of land use planning (e.g. physical habitat losses, sedimentation). From our perspective we might want to include water quality issues e.g. • point and non-point sources of effluents (e.g. sewage, pulp mills, mines) • interaction (synergism and antagonism) of various pollutants • cumulatative effects of emerging chemicals (e.g. Endocrine disruptors) and the interaction of these with various contaminants and other "general" pollutants such as pulp mill and mine (metals etc) • consideration of cummulative effects in both the freshwater and marine environments. • cumulative effects of aquaculture (the subject of both east and west coast studies) (W. Knapp, pers. comm.)
Oceans	How to address hydrological and sediment regime shifts as a result of logging coastal watersheds in the North Coast. Fish habitat impacts associated with increases in either flood magnitude or frequency may be particularly important (F. Hietkamp, pers. comm.)

Agency	**Comment**
Oceans	1. As you are aware the perceived lack of protection afforded small streams under the Forest Practices Code (streams classified as S4, S5, S6) has been raised as a provincial concern by DFO. In many respects this is the cumulative effects issue we are dealing with in the fish-forestry interactions file. The damage to a multitude of small streams within a watershed will have a negative effect on larger systems downstream essential to fish production. 2. What are the cumulative effects of logging adjacent to smaller fish-bearing (S4) and non-fish bearing tributaries (S5, S6) to instream habitat within the affected areas and to habitat in larger fish bearing channels downstream? (reach scale, stream channel scale, stream network scale) 3. The rate-of-cut issue is the key cumulative effects question on the Central Coast. How much cutting of a watershed can occur before effects are expressed in the stream channel and negative impacts to fish habitat and fish become apparent. 4. Habitat staff require a greater scientific understanding of watershed level responses to harvesting and tools to comment on forest plans in a meaningful way with specific reference to the size of the watershed and its relative contribution to the larger sub-basin (N. Winfield, pers. comm.).