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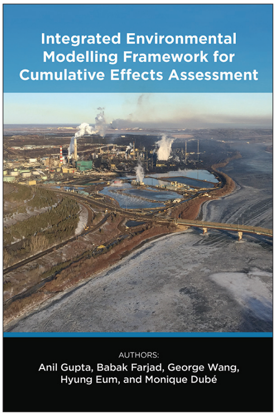

INTEGRATED ENVIRONMENTAL MODELLING FRAMEWORK FOR CUMULATIVE EFFECTS ASSESSMENT

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1.0 INTRODUCTION

Global warming and population growth have resulted in an increase in the intensity of natural (e.g., climate change) and anthropogenic stressors. Investigating the responses of environmental processes to the cumulative effects of stressors – now known as cumulative effects assessment (CEA) – was already being practiced (e.g., groundwater resources described in Schoff & Sayạn, 1969) when the concept of environmental impact assessment (EIA) was introduced in 1969. However, the theory and concept of CEA was defined by the US Council on Environmental Quality (CEQ) in 1978. The concept of CEA has then been gradually described in more detail by other scholars (e.g., Canter, 1999; Ross, 1998; Cooper, 2004), and many well-designed approaches have been proposed in the literature (e.g., Dubé & Munkittrick, 2001; Dubé et al., 2013; Løkke et al., 2010).

There are different definitions for CEA in the literature (Cooper & Sheate, 2002; Bérubé, 2007; Noble et al., 2014). However, it is defined here as *an assessment of cumulative environmental changes due to human and natural stressors over a period of time for the past, present, and future, relative to a baseline or standard*. CEA not only includes analyzing and modelling environmental changes, but it also supports planning alternatives that promote environmental monitoring and management. A variety of methods are used in literature (Table 1) for cumulative effects assessment, such as spatial analysis, network analysis, interactive matrices, and ecological modelling (Smit & Spaling, 1995). In addition to demanding the development of models to help answer policy questions (Castronova et al., 2013), CEA also requires observations (i.e., monitoring) of changes in natural phenomena.

Investigating the complex nature of environmental problems requires the integration of different environmental processes across major components of the environment, such as water, climate, ecology, air, and social aspects. The increasing dissatisfaction resulting from disjointed and narrowly focused environmental management approaches has recently encouraged the use of integrated environmental modelling approaches (Jakeman & Letcher, 2003). Integrated environmental modelling refers to coupling of thematic based numerical or conceptual models to solve complex real-world problems involving the environment and its relationship to human systems and activities.

The concept of developing integrated models first appeared decades ago (Mackay, 1991). However, there has recently been an increased interest in further developing integrated modelling frameworks in response to the emergence of problems related to regional scale land-use management, impacts of global climate change, evaluation of ecosystem services, fate and transport of nanomaterials, and life-cycle analysis. A variety of models have been developed to investigate the processes of each individual environmental component and the way they interact with each other. However, they have failed to consider environmental processes of other components of the environment and their complex interplay within the environment as a whole. Integrated modelling frameworks are often the only way to take into account the important environmental processes, interactions, relevant spatial and temporal scales, and feedback mechanisms of complex systems for CEA. The other obstacle is the uncertainty as to whether an applied modelling system meets its intended purposes and sufficiently represents reality, an issue which is reinforced by a lack of clear understanding of models' mechanisms. In this regard, this book looks at (i) understanding interactions and relationships between environmental components, such as climate, land, hydro, ecology, and resulting responses due to anthropogenic/natural stressors in CEA, (ii) reviewing modelling approaches for each component, (iii) reviewing existing integrated modelling systems for CEA, and (iv) proposing an integrated modelling framework and perspectives for future research avenues for CEA (Figure. 1).

Figure 1. Overview of the Components of this Report

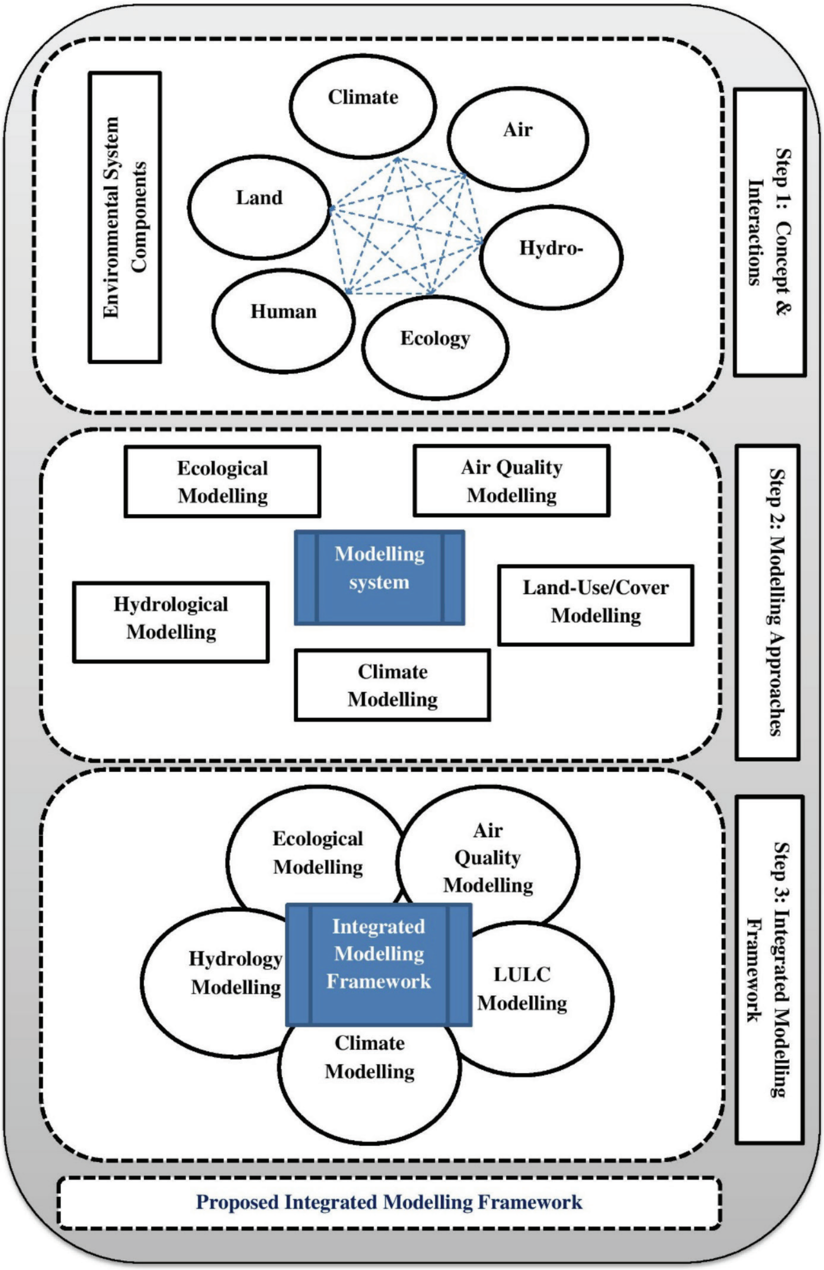

Table 1. Examples of Cumulative Effects Studies

Authors	**Objective**	**Study area**	**Method**	**Indicators**	**Response**
Shrestha et al., 2017	Quantify the impacts of climate change on monthly, seasonal, and annual water balances of blue and green water resources at sub-basin, regional, and basin-wide spatial scales.	Athabasca River Basin (ARB), Canada	Soil and Water Assessment Tool (SWAT), calibrated over 1990-2005 period	Blue (surface freshwater & ground-water) and green water (soil moisture)	Results projected the climate of the ARB to be wetter by 21–34% and warmer by 2.0–5.4 °C on an annual time scale. The annual average blue and green water flow (streamflow and evapotranspiration) was projected to increase by 16–54% and 11–34%, respectively.
Cho et al., 2017	Simulate dry, wet and total deposition of acidifying compounds using four different emission scenarios and provide guidance on possible priorities for oil sands emissions management for addressing acid deposition in the Alberta's oil sand region (AOSR).	Athabasca River Basin (ARB), Canada	Community Multi-Scale Air Quality (CMAQ) model	Annual dry, wet, and total depositions of acidifying sulphur and nitrogen compounds	Average nitrogen deposition increases from the historical to existing and future cases. Sulphur deposition decreases from the historical to existing cases but increases to future cases even though regional SO_2 emission continuously decreases.

Table 1. (*continued*)

Authors	**Objective**	**Study area**	**Method**	**Indicators**	**Response**
Zhang et al., 2016	Provide a quantitative assessment on how forest disturbances affect the components of flow regimes at a large watershed scale.	Baker Creek and Willow River watersheds, British Columbia, Canada	Time series cross-correlation analysis and paired-year approach	Flow regime	The magnitude, variability, and return period of high flows in the Baker Creek watershed were increased on average by 154.3%, 324.2%, and 11 years, respectively, and the timing of high flows was advanced by about 9 days during the disturbed periods.
Ahmed, 2013	Discern and quantify the hydrologic functions of wetlands within the context of the Rideau River watershed.	Rideau River watershed, Ontario, Canada	Numerical modelling techniques (Mike 11)	Low and peak discharge	It was demonstrated that the flood risk would increase if wetlands are removed. The low flow will likely increase if wetlands are removed.

Table 1. (*continued*)

Authors	Objective	Study area	Method	Indicators	Response
Deitch et al., 2013	Predict streamflow impairment caused by 438 small reservoirs in the study area	Sonoma County, California, USA	GIS-based hydrologic model	Streamflow	Results illustrate that impairment caused by reservoirs varies appreciably over space, but as reservoirs fill over time, impairment is lower through most of the drainage network.
Cormier et al., 2000	Assessing ecological risk in a watershed	Big Darby Creek watershed, central Ohio, USA	Conceptual models for exposure of fish and benthic macroinvertebrates, surveys of fish and molluscs, biological indices	Fish and molluscs, water quality, sedimentation, and hydrologic regimes	A decrease in the percentage of Tanytarsini midges along with an increase in the percent of toxic-tolerant invertebrate species found in fish is expected to be consistently associated with an increase in the concentrations of toxic chemicals in the water.