AGRI-ENVIRONMENTAL INDICATOR PROJECT

Agriculture and Agri-Food Canada

INDICATOR OF RISK OF WATER CONTAMINATION: CONCEPTS AND PRINCIPLES

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INDICATOR OF RISK OF WATER CONTAMINATION: CONCEPTS AND PRINCIPLES

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1. INTRODUCTION

The Agri-Environmental Indicator (AEI) Project of Agriculture and Agri-Food Canada was initiated in 1993 in response to recommendations made by a number of agencies, organizations and special studies. The overall objective of the project is to support the larger policy goal of integrating environmental considerations into decision-making processes at all levels of the agri-food sector.

The project aims to develop a core set of regionally-sensitive national indicators that build on and enhance the information base currently available on environmental conditions and trends related to primary agriculture in Canada. The Indicator of Risk of Water Contamination (IROWC) is one such indicator.

Key clients for the information that will be developed and reported through the AEI project include decision-makers in government and industry and other interested stakeholders. The AEIs will yield several benefits, such as facilitating the design, targeting and assessment of policies and programs and assessing the agri-food sector's progress in meeting environmental and resource sustainability objectives.

Water quality has recently emerged as a high-priority environmental issue for agriculture, and the information provided by IROWC will address several policy needs. IROWC will:

- clarify agriculture's potential to impact on this public resource
- facilitate the targeting of remedial policies and programs to areas of higher relative risk of contamination from agriculture
- facilitate the development of predictive models and systems which can assess the potential impacts of agricultural policies and programs on water contamination risks.

For example, data which compares the risk of water contamination associated with conventional and conservation tillage can be used to identify best management practices for protecting water quality and reducing pollution. This information could be incorporated into a programming initiative such as a national soil and water conservation program, or a more regional initiative aimed at environmental farm plans. Over time, as best management practices are implemented, changes in the risk of water contamination associated with agriculture can be measured and reported by IROWC. In this way, IROWC can contribute to the evaluation of agri-environmental actions, programs and policies.

This paper describes the conceptual basis underlying IROWC, and proposes a hierarchical framework to guide the application of a suitable methodological approach to IROWC. It also establishes the focus of IROWC relative to priority contaminants and appropriate geographic scales. These concepts are used to guide the development of a methodology for IROWC in a subsequent paper.

2. SCOPE OF IROWC

The development of a comprehensive IROWC is guided by several aims. These are to:

1. identify and characterize hierarchial levels (e.g., national, regional, local, plot) which are relevant for determining IROWC

2. formulate IROWC based on physical, chemical and biological factors which determine water quality independent of specific water quality standards (societal goals and values)

3. establish clear boundary conditions for IROWC related to the agricultural sector

4. select appropriate geographic scales at which IROWC procedures might be applied and presented

5. define the level, scale and factors which are to be combined into a general, integrated indicator of risk of water contamination to meet the desirable criteria of the indicator (this task is addressed in the subsequent paper on methodology).

In addition to these aims, the development of IROWC should incorporate a set of desirable attributes. IROWC should be characterized by:

1. the integration of key factors which affect the risk of water contamination from agriculture, such as:
   - soil and landscape properties (e.g., soil leaching potential for nutrients and pesticides, susceptibility to erosion)
   - amount and distribution of precipitation
   - prevalence of crop and soil management practices (e.g., buffer strips, conservation tillage, erosion control)
   - intensity of inputs (e.g., application rates, nutrient balance)
   - crop type (e.g., cropland, grassland)
   - other factors

2. a capacity for spatial comparison and temporal analysis

3. an ability to reflect changes in water quality related farm management and production practices

4. a product which is easily communicated to non-specialists and reported in understandable units at the watershed scale (e.g., calculated at the field/farm level and reported at the watershed level)

5. linkages with existing research effort, including use of existing or obtainable data and information.

These characteristics represent ideal attributes. They may be used to evaluate the utility of various methodological approaches to analyze and assess the risk of water contamination.

Finally, although IROWC is distinguished by its focus on water contamination, it is closely related to the other agri-environmental indicators also under consideration. Linkages are apparent through shared conceptual frameworks and methodological approaches, and interdependent databases. For example, the budget approach and data output of a nutrient balance indicator are directly relevant to a risk assessment of water contamination associated with a surplus of nutrients (e.g., fertilizer nitrogen). Pending further development of the nutrient balance indicator, this discussion uses a simplified approach to estimating nutrient surplus. A similar situation is evident between the pesticide risk indicator and IROWC, and only crude approximations of pesticide residue are estimated for this analysis. These linkages suggest a possible integration or coupling of several indicators.

While recognizing the interrelationships among agri-environmental indicators, this paper is focused on the development of a single indicator - IROWC - to address the specific problem of risk of water contamination from agriculture.

3. GENERAL CONSIDERATIONS IN DEVELOPING IROWC

Water contamination implies some change which impairs the chemical, physical or biological quality of the water. A contaminant is broadly interpreted as any material which may be present in water in amounts in excess of that required for sustainable function or use. Water quality is affected by both natural and anthropogenic processes. In this context, contamination can refer to any change in:

- natural chemical and biological constituents (e.g. nutrients and bacteria) or sediment
- agronomic chemicals (e.g.. fertilizers, pesticides or growth stimulants)
- anthropogenic materials (e.g., heavy metals, industrial organic toxics).

Information on change in water quality can be gathered and reported in different ways. One approach is to establish systematic monitoring programs which regularly sample and test water supplies for various contaminants at numerous locations. This approach is used at numerous locations throughout Canada. and is an important component of managing water quality. Another approach is to focus on those human activities which are potential sources of water contamination, based on our scientific understanding of the relationship between these activities and water contamination. Agriculture is one human activity with potential to contaminate surface and ground water supplies from a non-point source. The potential of specific agricultural activities to contaminate water can be measured, analyzed and reported as risk. The development of IROWC is focused on risk to provide a broad assessment of water contamination attributable to agriculture. Data from ongoing monitoring programs are needed to verify and calibrate IROWC.

3.1 Risk

Risk is characterized by two general attributes (Covello and Merkhofer 1993):

1. a possibility of an adverse or undesirable outcome, and
2. uncertainty about the occurrence, timing or magnitude of the undesirable outcome.

Both conditions are necessary for risk to occur. Thus, risk is a function of the possibility of an undesirable outcome (i.e. hazard), and the uncertainty of its occurrence, timing or magnitude (i.e., exposure).

For the purposes of this discussion, the undesirable outcome is water contamination by agriculture, and uncertainty is related to the probability of coincident occurrence of those factors which affect contamination. These factors relate to the properties of a contaminant or agent of risk (e.g.. solubility. mobility, persistence), environmental attributes (e.g., soil texture. slope, precipitation). and land use and farm management (e.g., crop type, intensity of farms inputs). Risk of water contamination by agriculture is a function of contaminant properties, environmental conditions, and specific land use and management practices.

The risk of contamination generally differs between surface water and ground water because of dissimilar processes. The basic processes include:

1. risk of surface water contamination by
   (a) solution (runoff. tile flow, base flow)
   (b) sediment transport
2. risk of ground water contamination by
   (a) leaching below the root zone (shallow ground water) and beyond tile depth
   (b) deep percolation (deep ground water).

Thus, the level of risk of water contamination by agriculture can be analyzed and assessed for surface or ground water. or both. given a set of agricultural practices, environmental conditions, and contaminant properties.

3.2 Type of Contaminants

In general, contaminants originate from farm inputs which are not completely utilized in the production of food and fibre. These inputs differ in their purpose (e.g. addition of plant nutrients, control of pests), and in their physical, chemical and biological properties. This means that the risk of contamination varies for different contaminants. Four main types of contaminants, and their relative importance, are considered below.

3.2.1 Pesticides

While there is an ongoing need to monitor pesticides in the environment, their threat as a water contaminant has decreased (Government of Canada 1991). Pesticides have evolved from general biocides with limited selectivity and high persistence to the current suite of highly selective and concentrated pesticides which have a relatively short period of activity. In addition, the procedures for using pesticides have changed from general, routine prophylaxis to selective use only when required - when the pest infestation will have serious economic and yield consequences rather than just cosmetic effects.

Although technological advances and improved management of pesticides have decreased their environmental risk, there is considerable merit in including them in IROWC. A risk analysis of water contamination by pesticides can itself demonstrate the reduced risk of advanced and properly managed pesticides. It can help to inform a critical public which may erroneously associate the environmental threats of former pesticides with those in current use.

3.2.2 Biological Contaminants

Harvey and Widdowson (1992) point out the need for vigilance against biological contamination of ground water:

> "A major public health concern involving domestic use of untreated ground water is the migration of disease causing bacteria and viruses from contamination sources up gradient, particularly from domestic and municipal waste disposal (septic tanks, waste lagoons, landfills, and on-land application of domestic effluents)".

Major sources of biological contaminants (e.g., pathogenic bacteria and viruses) in agriculture include animal manures and dairy milkhouse wastewater. Generally, the risk of biological contamination can be controlled by discretionary management practices which include protecting wells and aquifer areas from direct contact with wastes. Furthermore, biological contaminants respond well to conventional water treatment procedures.

A similar concern could be applied to surface water for domestic and recreational use (e.g., beaches). Occurrences of biological contamination are potentially numerous in areas of livestock production, but each occurrence is likely to be localized and relatively short-lived, although organisms may travel longer distances and survive longer periods if adsorbed to nutrient rich sediment. The latter are important considerations, but biological contamination of surface waters is generally of local (both temporally and spatially) rather than national scope. Also, where biological contaminants do enter drinking water sources, they are amenable to treatment (e.g., chlorination).

3.2.3 Toxics

Toxics, both inorganic such as heavy metals and organic such as PCB's, tend to be non-agricultural in origin and consequently, beyond the scope of IROWC. Cadmium is a potential toxic associated with phosphate fertilizer, but it is not considered explicitly in this analysis.

3.2.4 Nitrogen and Phosphorous

Nitrogen (N) and phosphorous (P) are essential to agricultural production as plant nutrients. They are applied in organic (e.g., manure) and inorganic (e.g., fertilizer) forms. Nutrient use, in particular uptake by crops, reduces N and P available for contamination, but the risk of water contamination is high because crop requirements and the amount and timing of nutrient application are rarely synchronized so that excess nutrients are potentially available for contamination at certain times. For example, availability of fertilizer nitrogen usually exceeds crop needs at early stages of plant growth (e.g., spring), and again during post-harvest. The risk of contamination is also increased because both nutrients are ubiquitous, have anionic forms, and undergo various chemical and biological transformations which result in their many forms in the environment.

Historically, nutrient contamination of surface waters was dealt with by dilution to concentrations below a critical threshold necessary for a growth response in aquatic plants, or by natural filtration processes in wetlands to remove nutrients (e.g., biomass uptake). Where dilution or filtration do not adequately reduce concentrations of N and P. the nutrients may contribute to the process of eutrophication. A steady decline in wetland area due to the expansion of agricultural land drainage (e.g., Holland Marsh) has decreased the filtration capacity of wetland systems. Dilution continues to be the dominant approach to nutrient treatment, although some farms are constructing artificial wetlands to mimic the natural filtration process.

Both N and P have contaminated surface waters, but nitrates, in particular, have also contaminated ground water in some locations such as farm wells of southern Ontario (Rudolph and Goss 1993) and the Abbotsford aquifer in British Columbia. The natural remediation processes for ground water are limited to dilution and reaction (e.g., chemical precipitation. denitrification).

This brief discussion supports the inclusion of nutrients in IROWC, particularly nitrogen because of its risk to both surface and ground water.

3.3 Contaminant Focus

Based on the above discussion about the relative importance of various contaminants, the contaminant component of IROWC should focus on:

1. common pesticides currently in use, distinguished by type (herbicides, insecticides) and chemical class (e.g., triazines or phenoxy), and
2. basic plant nutrients, particularly nitrogen.

4. IROWC AND HIERARCHICAL LEVELS

As population pressures increase and the requirements for products from land and water resources expand, agro-ecosystems are modified or managed to enhance productivity. The same land must serve multiple concurrent needs. For example, precipitation is needed not only for food and fibre production, but also for recharge of ground water aquifers and surface reservoirs. In addition, many of these same areas are important for recreation and aesthetic purposes, and some have become repositories for waste materials; consequently, most of our agro-ecosystems must be managed to meet a variety of goals related to environmental quality and sustainability.

In past years, many research and land management activities have been carried out sectorally, concentrating on one particular kind of environmental problem or system component. However, to achieve multiple goals, it is generally necessary to study and manage the whole system rather than individual parts. It is also necessary to distinguish between natural and managed ecological systems, and the relationship between them. The concept of agroecosystems incorporates the notion of an ecosystem approach to understanding and management of environmental sustainability in agriculture.

Unfortunately, when we attempt to characterize agro-ecosystems and their management via a comprehensive approach using all possible information and societal objectives, the resulting problem is frequently overwhelming in complexity and detail. In many ways, the task of defining and characterizing the risk of water contamination presents this kind of problem - a complex collection of processes which interact at various scales of time and space.

4.1 Hierarchy Theory

Recently, ecologists have adapted a theory of hierarchial systems to organize complex ecological problems into manageable levels in space and time while retaining a holistic approach to describing the problem (Allen and Starr 1982, Dumanski *et al.* 1993, Kay 1993, King 1993). The concepts of hierarchy theory can be used to structure the problem of defining risk of water contamination into a series of nested levels which can be used to relate our knowledge and understanding of the problem to appropriate levels of detail. These nested levels correspond to the notions of holarchy holons embedded in hierarchy theory.

Basically, hierarchy theory states that everything has sub components and everything is a component of a larger system. At various levels in a system, different characteristics and processes may predominate and constrain each level. Ecological units are defined within a nested hierarchy of spatial and temporal units. Scale defines the entities, structures and processes which are operational at each level. Also, each level is constrained by the processes operational at the levels above it. Consequently, a single level cannot be defined without recognizing the constraints at higher levels.

For the purposes of this discussion, "higher level" refers to a level which bounds a larger area and greater expanse of time than the "lower levels". Map scales are used in the cartographic sense where a larger scale (ratio) refers to greater detail over a smaller area and small scale connotes the opposite.

Grain and extent of observation are two principles which can be used to define hierarchial levels. Grain refers to the resolution of data and is defined by the smallest recognizable entity in the data set. Extent of observation refers to the spatial and temporal scope of the field of observation. It is possible to study the same phenomenon at several levels, however the criteria for observing and characterizing it will change as the grain and extent change. The grain and extent of observation change in going from one level of the hierarchy to another and consequently characteristics or processes which predominate at one level may be of minor importance at a different level. For example, diffusion may be important in characterizing herbicide dynamics at the soil-root interface but irrelevant at the regional level.

From a hierarchial standpoint, it is important to identify the broader level of which IROWC is a component as well as the sub-components of IROWC. As a component of a broader level, the risk of water contamination is one of a series of risks which, when combined, become part of a general assessment of environmental quality and sustainability. As mentioned earlier. IROWC is one of several possible indicators related to agricultural activities.

There are various ways in which subcomponents of IROWC could be characterized (e.g., surface water, ground water, contamination sources). Table 1 shows a suggested assignment of hierarchial levels for IROWC. A nested hierarchy is developed for the major contaminants at risk (i.e., nutrients, pesticides), and for each of the main factors affecting risk of water contamination (i.e., climate, soils, land use, management). Each level of the hierarchy is defined by spatial and temporal scales. Dominant processes of contamination operating at each level are also shown. Finally, examples are given of the kinds of aggregated data which are available or required at each level.

The factors which affect water contamination are likely to differ in their relative importance, or degree of interaction, at each level. Those factors most likely to be differentiated and associated at each level are summarized in Table 2. The type and number of factors incorporated into IROWC increases as spatial and temporal resolution also increases within

Table 2. IROWC Sensitivity by Hierarchical Level and Spatial and Temporal Resolution.

Hierarchical Level	Spatial Extent	Spatial Analysis Units	Temporal Extent	IROWC Sensitivity
Level 7	Canada	Canada	decades to centuries	comprehensive analysis
Level 6	Canada	Province	decades to centuries	population, livestock numbers, kinds of crops, extent and quantities of inputs
Level 5	Ecotone	Ecodistrict	5 years to decades	relative risks from nutrients and pesticides
Level 4	Ecorcgion	SLC polygon	5 to 10 years	relative risks by specific nutrient and class of pesticide associated with specific crops and soil textures
Level 3	Ecodistricts or SubWatersheds	SLC soil polygon or detailed soil map	1 to 5 years	relative risks by specific nutrient and class of pesticide associated with specific crops, soil types and pathways (surface or groundwater)
Level 2	SLC Polygon or farm	detailed soil map polygon or field	season to 5 years	estimated actual risks associated with specific crop, soil and land management conditions with estimates for surface and subsurface pathways.
Level 1	Field or detailed soil map polygon	plot area or pedon	season to 5 years	measured/modelled/actual risks associated with specific crop, soil and land management conditions partitioned to surface and subsurface pathways.

the hierarchy. The sensitivity and reliability of IROWC increases with downward movement through the hierarchical levels.

An implication of the associated factors and constraints at each level is that IROWC must have sufficient flexibility to incorporate the set of factors appropriate to the level of interest. The following discussion considers the set of factors associated with some levels, and their corresponding degree of spatial and temporal sensitivity.

4.1 National Level IROWC - Hierarchy Level 6

Broadly, stated, the environmental goals of the agriculture and agri-food sector are to:

- maximize sustainability of land use and management practices
- minimize undesirable environmental impacts
- recognize and provide other aspects of environmental management in balance with requirements (e.g., adequate wetlands for removal of nutrients).

National indicators are required to monitor how well these goals are being met with respect to risk of water contamination. From a generalized national standpoint, the factors which increase the risk of water contamination can be stated as:

- growing population and associated environmental loading
- increase in livestock numbers
- higher intensity of inputs and cropping.

4.1.1 Population

W.E. Johnson (1972) reports that the increase in urban population from 5.57 to 12.63 million during 1931-1966 contributed an added environmental loading of 10 million pounds (4.5 million kg) of phosphorus from human wastes alone, without any use of detergent or other phosphorus products. Presumably, the increase in urban population to 20.91 million during 1966-1991 resulted in another proportional increase in environmental loading. The relationship between population growth and environmental loading provides the broad context within which IROWC for agriculture is situated.

4.1.2 Intensity of Cropping, Inputs and Livestock

Increased risk of water contamination from agriculture is directly related to intensified cropping and use of inputs, and greater livestock numbers. An increase in the intensity of agricultural production is a response to societal demands (e.g., food supply) and objectives (e.g., grain exports) set at a broader level than the agricultural sector (i.e., a higher level in the hierarchy). Several trends in production intensity are apparent at the national level.

Table 3. Agricultural Land Use in Canada.

Year	Farmland M (ha)	Cropland M (ha)	Total Cultivated M (ha)
1911	64.5	14.4	15.4
1931	66.0	23.6	33.6
1951	70.4	25.2	38.1
1971	68.7	27.8	42.1
1981	65.9	30.9	44.7
1991	67.8	33.5	45.0

Sources: Statistics Canada. 1986. Human Activity and the Environment: a Statistical Compendium. Catalogue 11509E; Statistics Canada. 1994. Human Activity and the Environment 1994. Catalogue 11509E

Table 4. Production of Selected Major Field Crops.

Year	Wheat M (T)	Barley M (T)	Grain Corn M (T)	Fodder Corn M (T)
1931	9.5	2.0	0	1.5
1951	14.7	4.5	0.2	3.8
1971	14.4*	13.1	2.9	9.7
1981	24.8	13.7	6.7	12.1
1993**	27.2	12.9	6.5	n/a

* reflects LIFT program in prairies ** estimated

Sources: Statistics Canada. 1986. Human Activity and the Environment: a Statistical Compendium. Catalogue 11509E; Statistics Canada. 1994. Field Crop Reporting Series Vol. 73 No. 7. Catalogue 22-002 Seasonal

Table 5. Livestock on Farms.

Year	Cattle (1000)	Swine (1000)
1931	7993	4700
1951	8371	4916
1971	13278	8107
1981	13502	9875
1991	12972	10216

Source: Statistics Canada. 1963. Census of Canada. Agriculture. Catalogue 96-530; Statistics Canada. 1981. Census of Canada. Agriculture. Catalogue 96-901: Statistics Canada. 1986. Human Activity and the Environment: a Statistical Compendium. Catalogue 11509E; Statistics Canada. 1992. Agricultural profile of Canada. Catalogue 93-350.

Table 6. Commercial Fertilizer Application on Farmland.

Year	Total applied (1000 T)	Nitrogen content (1000 T)	Phosphate content (1000 T)	Area fertilized (1000 ha)
1970	1539	247	262	6928
1980	3501	731	593	18505
1990	3811	1108	569	21562

Source: Statistics Canada. 1994. Human Activity and the Environment 1994. Catalogue 11-509E.

Table 7. Application of Pesticides on Farmland**.**

Year	Area Sprayed or Dusted	
	herbicides (1000 ha)	insecticides (1000 ha)
1970	8571	913
1980	15220	1652
1990	21599	2774

Source: Statistics Canada. 1986. Human Activity and the Environment: A Statistical Compendium. Catalogue 11-509E Statistics Canada. 1992. Agricultural Profile of Canada. Catalogue 93-350.

Table 8. Quantity of Active Ingredient of Pesticides Used on Field Crops in Ontario.

Year	herbicides (1000 kg)	insecticides (1000 kg)
1978	4075	158
1983	5411	187
1988	4985	127
1993	4144	100

Source: Ontario Ministry of Agriculture and Food. Various years. Surveys of Pesticide Use in Ontario for the years 1978 1983 (Rept. 84-05), 1988 (Rept. 89-08) and 1993 (Rept. 94-01). Economics and Policy Coordination Branch, Toronto.

Table 9. Plant Nutrients in Fertilizers, Animal Manures and Agricultural Crops, 1990.

	Animal [1] Waste (1000 T)	Fertilizer (1000 T)	Total Supplied[2] (1000 T)	Crop Removals[3] (1000 T)
Nitrogen	675	1,200	1,875	1,319
Phosphorus	190	270	460	533
Potassium	450	320	770	481

[1] Data excludes consideration of human wastes

[2] Figures for fertilizer and animal wastes from E. Gregorich, *In* J. Dumanski *et al.* 1994. Status of Land Management Practices on Agricultural Land in Canada. Research Branch Technical Bulletin 1994-3E.

[3] Figures on crop yields for wheat. barley, grain and fodder corn from Field Crop Reporting series Vol 70 #8, Statistics Canada. Values for nutrients harvested from Western Canada Fertilizer Pamphlet. 1992.

Over a period of eighty years, the total area of farmland has remained relatively constant, but its use for annual crops has more than doubled (Table 3). These trends are confirmed by patterns of production of major field crops (Table 4).

Livestock production is also increasing over time (Table 5). The increase in input intensity is evident from data on the use of commercial fertilizer (Table 6). Similarly, the area of farmland sprayed or dusted with herbicides or insecticides is also increasing (Table 7). However, unlike fertilizer, inputs of active ingredients of pesticides have been decreasing in regions such as Ontario since the 1980s, reflecting improved pesticide technology and management (Table 8).

Ultimately, a goal of agricultural production is to achieve a balance between the nutrients available from wastes and fertilizers, and the nutrients used in crops. In some ways the extent to which this balance is achieved provides a broad indicator of IROWC. Excess nutrients not used for crop production may contaminate water supplies, contribute to greenhouse gases, or be taken up by biomass in wetlands. Table 9 shows an approximate nutrient balance for Canada.

4.1.3 National Level IROWC

In addition to the national summary statistics of inputs and production, other possible national level measures related to IROWC include:

1. volume of drinking water treated to inactivate biological contaminants

2. area and distribution of wetlands as a measure of natural filtration capacity associated with agroecosystems
3. estimates of erosion risk (wind and water)
4. estimates of summerfallow area (associated leaching hazard)
5. dollar sales of persistent pesticides
6. estimates of nutrient budget (e.g., Table 9)
7. estimates of human and animal inputs compared to system capacity.

While these measures provide a national level focus for IROWC, they do not meet all the desirable characteristics of the indicator as identified above. They generally lack spatial comparison, and the time frame is quite long. Also, they do not readily relate changes in water quality to farm management or production practices. Nevertheless, they represent the context within which the lower levels must be framed.

4.2. Regional Level IROWC - Hierarchy Level 5

Across the agricultural area of Canada there are clear regional differences. The great plains area has soils developed under grassland, and it has a continental semi-arid climate. Much of the drainage is internal with only a few major waterways providing external drainage. The land use practices for much of the area are based around cash cropping of cereals and oilseeds. Summerfallow is a major land management practice. In the rest of Canada the climate is more humid. In Ontario and Quebec there are large tracts of agricultural land used for activities ranging from cash cropping (corn and soybeans) to livestock based enterprises. In BC and Atlantic Canada the agricultural activities are much more fragmented spatially because of variation in regional climate and soils.

All of the measures presented at the national level for IROWC can be compiled and summarized by region. In addition, it is possible to estimate broad levels of risk associated with these measures.

4.2.1 Previous Regional Studies

Two recent studies demonstrate the potential application of IROWC at the regional level. McRae (1991) has developed generalized maps showing areas where ground water is vulnerable to contamination by pesticides. The study considered the properties of specific herbicides, grouped them into broad classes, and also considered generalized soil properties and cropping patterns. The focus is on areas vulnerable to ground water contamination, but the approach could be adapted to include surface waters by incorporating factors which estimate pesticide transport over the soil surface (e.g., runoff).

A report from the USDA (Kellogg *et al.* 1992) investigates contamination of ground water at the national and regional levels. It states that the principal activities that influence the potential for ground water contamination by agrochemicals are:

- pesticide use
- commercial fertilizer use
- irrigation and chemigation.

This report outlines two possible indicators of risk of ground water contamination:

1. potential of soils to leach pesticides, and
2. potential of soils to leach nitrates.

Again, these indicators provide a useful broad indication of areas which are more or less vulnerable to water contamination. Each of the procedures could be adapted to deal with surface waters. However, the procedures are quite general and rather unresponsive to spatial or temporal change.

These two studies demonstrate that differentiating areas according to their potential to contaminate ground water is feasible at the regional scale. Risk of contamination factors are primarily those related to environmental conditions (soils) and farm management (input intensity). The indicators represent very broad categories of risk, and may not be sufficiently responsive to meet the desirable characteristics of IROWC outlined earlier.

4.2.2 Feasible Regional Measures for IROWC

Feasible measures for IROWC at the regional scale include:

1. proportion and distribution of intensive crops vs extensive and natural vegetation
2. proportion of crops requiring high levels of input
3. proportion of high value crops (e.g. horticultural, tobacco)
4. high concentrations of livestock
5. climate during seasons of application (spring)
6. climate during periods of non-crop growth (e.g., excess NO_3 available for leaching in fall)
7. rainfall patterns
8. drainage pathways (internal or external)
9. moisture deficit seasonally (indication of deep percolation)

Regional data bases are generally available for these measures, or they can be aggregated from lower hierarchical levels in some cases. Many data bases are also available in a digital format useful for geographic information systems.

1. CHEMICAL CONTAMINANTS
    A. Soluble chemical constituents
        a. Inorganic
            i. Reactive
                - Metabolites of plants, flora or fauna
                    - in solution
                    - neutral
                    - net negative charge net positive charge
            ii. Non-reactive
        b. Organic
            i. In solution
                - Biodegradable metabolites of plants, flora and fauna
                    - neutral
                    - net negative charge
                    - net positive charge
            ii. Recalcitrant
                - neutral
                - net negative charge
                - net positive charge
            iii. Adsorbed
                - etc
            iv. Bound
                - etc
    B. Insoluble chemical constituents
        a. Suspended
            - etc
        b. Adsorbed

2. BIOLOGICAL CONTAMINANTS (can be expanded in a similar fashion as above)
    A. Plants
        a. economic
        b. non-economic
    B. Animals
    C. Microbial
    D. Viruses

Figure 1. A Hierarchical Scheme of Properties for Chemical and Biological Contaminants.

4.3 Lower Level IROWC - Hierarchy Levels 4, 3 & 2

As shown in Table 1, hierarchical levels 4, 3 and 2 deal with smaller spatial and temporal units. In most cases, it will not be feasible or practical to characterize them on a consistent basis across the agricultural portion of Canada. It may be necessary to use levels 6 and 5 of the hierarchy to generalize IROWC and, from areas of concern identified at these levels, target specific IROWC measures at greater levels of detail.

Whereas IROWC at upper hierarchical levels emphasize environmental and agricultural conditions, IROWC at lower levels can also focus on the nature of the contaminants. At levels 4, 3 and 2 it is feasible to consider the occurrence of specific contaminants and their associated physical and chemical properties which affect contamination risk. An indication of the additional detail which can be included in IROWC at lower levels is shown in Figure 1. These properties and the classification scheme are representative, and others could be derived. The point is that, at lower levels, more detailed consideration of contaminant properties can be incorporated into IROWC.

5. IROWC AND RELATIONSHIP TO WATER QUALITY STANDARDS

The indicator developed by this project will provide an integrated assessment of the risk of water contamination. Basically, it will estimate the probability, under specified scenarios of land use and management, that the chemical and/or biological properties of water become increasingly different from those of a baseline condition. This condition may be defined as pure water, the existing state of water quality, or some target agreed upon. Change in the indicator will be interpreted against some values established by society for desirable water quality.

There are a wide range of values or water quality goals which could be chosen. The ecotoxicological sections of Health Canada and Environment Canada are working on some guidelines and rationalizing them with international efforts in this area. For some potential contaminants there are maximum allowable levels for drinking, recreation, fish and wildlife, industry, and various agricultural uses ranging from washwater to irrigation. In many cases these standards are further qualified by whether or not the water is treated.

Usually, water contamination is attributed to human activities. However, the level of water quality differs among water supplies with no or minimal human interference. There are also natural exceptions to the norm. For example, Johnson, (1972) cites several examples in the great plains area where major rivers were contaminated by buffalo which fell through weak ice in springtime. One example was estimated to have added over 20,000 kg of phosphorus to the Qu'Appelle River. Recent examples of "natural" causes include contamination of beaches by large numbers of gulls and geese.

The IROWC should be appropriate for assessment against some or all of these values for water quality. An important consideration for the indicator is the degree to which it will be integrated over space and time. It may not be sensitive enough to detect differential instances of contamination, such as a pulse of NH_3 sufficient to cause fish kill, or small areas of contamination over aquifer recharge areas (e.g., Regional Municipality of Waterloo, Oak Ridges Moraine, Abbotsford).

6. BOUNDARY CONDITIONS FOR IROWC

The indicator is restricted to activities and areas associated with **primary** agriculture. The location of contamination risk is immediately adjacent to the agricultural activity (i.e., at the edge of the field, at the point where the tile line empties into the stream, or within the soil below the rooting depth). The indicator considers natural sources of contaminants (e.g., soil nitrogen), but does not include contaminants from industrial or urban sources.

Artificially drained areas (tiled) will be difficult to characterize. The tile line shunts water percolating through the soil to surface drains and, for intensively managed areas, may tend to protect ground water through the removal of flow in periods of flush. The water at these times may well be high in nutrient content. Drainage information is available for some lower hierarchical levels (e.g., farms. municipalities, counties) and some provinces (e.g., Quebec, southern Ontario). In other regions. soil classification may provide an indication of the location and extent of tile (i.e., agriculture in gleysols will normally be drained).

7. SPATIAL SCALES (GEOGRAPHIC) AND IROWC

There are two main sources of data: the census of agriculture and the land resource inventories. Both are appropriate for use at scales of 1:1 million or smaller (less detailed). Regional and detailed studies are possible using information for selected areas.

The census of agriculture characterizes land use and management as potential sources and causes of contamination. The data are collected and aggregated to a level which can be displayed at a map scale of about 1:1 million. Data have been compiled on administrative areas (e.g., census subdivisions) and recompiled on natural units (e.g., soil landscape polygons).

The land resource inventory data can be interpreted to show the capacity of a land area to limit the release of contaminants into the water moving off-site. Land resource data are available in a consistent format at 1:1 million for Canada. It has also been generalized into higher level ecological units (i.e., ecodistricts, ecoregions, ecozones).

There are regional or county soil survey maps for much of Canada available at scales of

1:20,000 to 1:125,000. The coverage is not complete and not consistent in format. It may well be useful for studies of limited area. The census of agriculture contains Canada-wide land use and management information. Only for selected study areas or project-specific survey areas is there detailed information on land use and management.

Based on the above, an upper and lower geographic scale is recommended for IROWC. The region (level 5 of the hierarchy) is proposed as the upper geographic scale for IROWC, and the drainage basin or watershed (levels 4 and 3 of the hierarchy) are suggested as the lower geographic scale.

8. SUMMARY

This paper describes a conceptual framework for developing indicators of risk of water contamination (IROWC). The purpose of IROWC is to express change in the risk of water contamination by agriculture over time and across space. Key theoretical constructs which make up the conceptual base of IROWC include:

1. a hierarchical framework. based on hierarchy theory, which organizes and classifies the various components of IROWC into a series of nested hierarchies defined by temporal and spatial attributes. The suggested upper and lower spatial and temporal scales for calculation and reporting of IROWC are those of levels 5 and 3 of the hierarchy.

2. a risk-based approach to water contamination from agriculture. Risk is a function of three factors affecting contamination: i) contaminant properties, ii) environmental attributes (e.g.. climate, soils), and iii) management and land use. The relative importance of these factors, and the degree of interaction among them, varies throughout the hierarchical framework.

3. integration into IROWC of the risk factors and the probability of their coincident occurrence or reliability. An estimate of IROWC is enhanced at lower hierarchical levels because of an increased level of confidence in the individual risk factors and their probability of coincident occurrence at these levels.

4. a unit of expression which measures change in risk over time and across space, relative to some standard acceptable level (e.g., drinking water standard).

These concepts are used to guide the development of a methodological approach to IROWC in a companion paper.

REFERENCES

Allen, T.F.H. and T.B. Starr. 1982. *Hierarchy: Perspectives for Ecological Complexity.* University of Chicago Press, Chicago.

Covello, V. and M. Merkhofer. 1993. *Risk Assessment Methods: Approaches for Assessing Health and Environmental Risks.* Plenum Press, New York.

Dumanski, J., W. Pettapiece, D. Acton and P. Claude. 1993. Application of agro-ecological concepts and hierarchy theory in the design of databases for spatial and temporal characterization of land and soil. *Geoderma* 60:343-358.

Government of Canada. 1986. *The State of Canada's Environment.* Ottawa. Government of Canada. 1991. *The State of Canada's Environment.* Ottawa.

Harvey, R.W. and M.A. Widdowson. 1992. Microbial distributions, activities and movement in the terrestrial subsurface: experimental and theoretical studies. *In* R.J. Wagenet, P. Baveye, and B.A. Stewart (eds.). *Advances in Soil Science - Interacting Processes in Soil Science.* Lewis Publishers. pp. 185-225.

Kay, J. 1993. On the nature of ecological integrity: some closing comments. In S. Woodley, J. Kay, and G. Francis (eds.). *Ecological Integrity and the Management of Ecosystems.* St. Lucie Press. pp. 201-212.

Kellogg, R.L., M.S. Maizel and D.W. Goss. 1992. *Agricultural chemical use and ground water quality: Where are the potential problem areas?* United States Department of Agriculture. Washington, D.C.

King, A. 1993. Considerations of scale and hierarchy. In S. Woodley, J. Kay, and G. Francis (eds.). *Ecological Integrity and the Management of Ecosystems.* St. Lucie Press. pp. 19-45.

McRae, Blair. 1991. *The characterization and identification of potentially leachable pesticides and areas vulnerable to ground water contamination by pesticides in Canada.* Issues, Planning and Priorities Division, Pesticides Directorate, Agriculture Canada.

Rudolph, D. and M. Goss (editors). 1993. *Ontario Farm Groundwater Quality Survey: Summer 1992.* Unpublished report. Agriculture Canada, Ottawa.

Table 1: Proposed Hierarchial Levels for Indicators of Risk of Water Contamination.

Hierarchial Level	General agent of risk	Specific agent of risk	Management	Land Use	Climate	Soils, Topography, Drainage	Processes
Level 7 National Environment Strategy for Agriculture	Indicator 1 . Indicator 12 Green Plan and other programs						
Level 6 National (nominal map scale of 1:7.5 M to 1:50 M) time: 10 to 5 years	**Plant Nutrients (N and P)** **Pesticides**	- Fertilizer - animal wastes		**agricultural intensity** **- proportion of farmland in crop**	temperate (normals data)		
Level 5 Regional provincial or ecozone (Mixed Woods Plain) space: 1:5 M to 1:1M time: 5 to 1 year	Plant Nutrients (N and P) Pesticides	**- fertilizer** **- animal wastes** **- urban sources** **Classes of Herbicides** **Classes of pesticides**	general levels of intensity and contiguity; General management and conservation practices	**general practices** **- cash cropping, summer fallow livestock** **General class of crop e.g. grain corn, spring wheat**	**Meso or small order Macro (e.g. monthly or seasonal rainfall and moisture deficits)**		

Level 4 Major drainage basin or ecological region (Lake Erie lowlands) or land resource region (LRA) space: 1:1M to 1:250K time: annual to seasonal	Plant Nutrients (N and P) Herbicides Insecticides Nematocides	- fertilizer - animal wastes by livestock enterprise - urban and rural by specific centres Groups of similar compounds e.g. phenoxy	**mix of management practices (e.g. conventional and no-till), general times of field operations**	**mix of farming systems with defined crops and rotations**	Meso (e.g. monthly or daily climate including spatial and temporal variability across the area)	Great groups, associations thereof. Broad groups of texture and parent material **Topography and drainage**	- Surface water by runoff; - Surface water by sediment; - ground water
Level 3 Watersheds (Lower Thames River watershed) or soil landscape polygons (SLC) space: 1:250K to 1:50K time: seasonal to monthly	Plant nutrients (N and P Herbicides Insecticides Biological pathogens	**- fertilizer general amounts of specific carriers,** **- specific kinds of operations** **- specific pesticides** **- livestock source** **- wildlife source (e.g. gulls)** **- human source**	specific mix of tillage operations, input sources and methods of application	- specific mix of farming systems, crop types and rotations	Meso to small order micro (e.g. daily data on climate events)	**Subgroups or associations thereof. Limited ranges of texture class and parent materials**	Surface water, by water course for solution and sediment - ground water related to specific aquifers - general information on the **extent of sub-surface tile drains**

Level 2 Farm/Field scale (farm unit, ecosite) space: 1:50K to 1:5K time: monthly to daily	Plant Nutrients (N and P) Pesticides Biological pathogens	- **source, form, and amounts for fertilizer amendments and/or animal wastes** **Specific compounds, rates etc** source for human and livestock - localized area for wild	specifics of timing, equipment, conservation tillage, buffer strips, etc	Specifics of farming operation, crop type and variety by land management parcel	Micro **- specifics of events daily or smaller time steps as required**	Families of related soils to soil series (specific textures of surface and parent material, known mixture of soil profiles)	- Surface runoff, tile flow, base flow - wind erosion vs water erosion - ground water levels to specific depths and connected to known aquifers - water retained in the soil and used by plants
Level 1 Plot scale (experimental plot, ecoelement) space: 1:5K to 1:1K time: daily to hourly	as above	as above	as above with specific experimental treatment(s)	as above with specific experimental treatment(s)	small order micro	Soil series or homogeneous soil (to the extent possible)	**- runoff, sediment and tile flow by field** **- ground water by field** **- flow paths e.g. preferential** **- soil reaction, surface faunal activity, etc specific processes e.g. rill vs sheet erosion**

The items in **bold** represent constraints which have been added at the various hierarchial levels. The complete set of constraints at any level include those in bold and all the bold constraints from the higher levels. In some cases, the constraints represent increased specificity of a particular kind of constraint, in other cases they are additional kinds of constraints.