

GRAPH THEORY APPLIED TO EVALUATION OF WATER SCIENCES RESEARCH SYSTEMS*

DENIS COUILLARD

Professor

Institut National de la Recherche

Scientifique (INRS-Eau)

Sainte-Foy, Québec

ABSTRACT

Many procedures have been proposed over the past years for evaluating the degree to which the objectives pursued by research are realized. However, none of these has succeeded in entirely encompassing the problem. Thus, a new approach that is likely to improve on already existing procedures has been sought. After presenting a typology of the diverse methods used in the evaluation process, this article describes a technique which permits one to systematically determine the relationships in a system of research execution and to rapidly identify the principal components. The use of coherence graphs has facilitated the achievement of these objectives. As a case study, the method has been applied to qualitatively describe a system of university research in the water sciences. In the preliminary step, the objectives pursued by university research and the disciplines necessary for realizing projects have been itemized. The second stage involves the construction of a coherence graph by establishing relationships between the elements. A schematic representation of the relationships making up the research system is thus obtained. The graph consists of five levels: objectives, sources of financing, places where research is conducted, programs, and project disciplines. This graphic representation allows one to identify among the multiple requests for funds those that have the greatest potential to provide the desired results in accordance with the objectives retained.

Research has always existed for purposes of expanding the frontiers of knowledge and the limits of perception. It has long been applied to the cure of poorly understood diseases, the identification and development of tools and techniques to facilitate individual lives, and the discovery of new geographical areas as well as new modes of transportation, and has undergone continual

* The financial support of the Natural Sciences and Engineering Research Council of Canada (Grant A3711) is gratefully acknowledged.

renewal while improving life and society. There is nothing false in presuming that research has long been with us, and has developed and provided innumerable results principally because of the sustained efforts of vast numbers of individuals over time. These results, now assimilated in modern lifestyles, have often been obtained despite the obstructions of elite forces governing society, even if certain of them are among the most innovative [1].

Today, the need to undertake the evaluation of research has become a constant in modern society [2-5]. The various intervenants in the research system all undertake, in their own way and to different degrees, a certain formal or informal evaluation of components of the system. However, it seems evident to the observer that informal evaluations are all too frequent, and noticeably less transparent to the public eye.

Ideally, what is required is a simple method of evaluation having the flexibility to adapt to all types of systems (human, environmental, social) [6], and affording a balanced consideration of their interactions which is not limited by an overly normative disposition. Intuition must share a proportionate role with logic in the evaluative process. This method should be amenable to integration into an interesting visual format which encourages decisionmakers and others to take account of the multiple repercussions implicated [7]. What is not needed is "cut and dried" methodology with standards and principles that cannot be abrogated; rather, a guide or a general approach is called for, one which permits the identification and evaluation of the different repercussions.

This basic approach, more intuitive than normative at the outset, could, with practice, eventually lead to the establishment of a fixed method. The present study is therefore oriented towards the specification of an evaluation method with the greatest possible universality of application.

METHODS OF EVALUATION

There are numerous existing methods that can be used for purposes of evaluation. The majority have originated in the United States and were developed for management needs in crucial sectors (e.g., space research, high technology industries, military strategy, and land management). The spectrum of techniques is diversified, ranging from the most rigorous of statistical methods (variance analysis, simulation, and *a priori* probability) to those termed discontinuous (creativity methods, future studies, and even science fiction), including the more classical methods such as cartography and matrices. The existence of these numerous techniques confirms the fact that a need is felt to evaluate repercussions, and that there is still room for research and experimentation to yield a standard method. An initial classification of existing methods reveals the varying modes of identification: checklists, matrices, cartographic methods, networks, statistical methods, Delphi, methods of scenarization and conceptual representation, and creativity methods. The fields of application of these classes are presented in Table 1. In Table 2, sixteen methods are described

Table 1. Classification of the Principal Existing Methods of Evaluation

<i>Method</i>	<i>Applicability</i>	<i>Remarks</i>
Checklist	A method where a fixed list of parameters is most often evaluated from the point of view of what can be discovered in their environment.	<ul style="list-style-type: none"> • Very normative methods which include the possibility of weighing the parameters. • Methods can include different aspects to evaluate: <ul style="list-style-type: none"> – ecological; – economic; – social.
Matrix	A method where one establishes relationships between the repercussions of a project in terms of direct or indirect or major or minor relations. It is possible to define beforehand likely existing relationships, and it only remains to evaluate the intensity.	<ul style="list-style-type: none"> • Bidimensional plane limits the applicability of the methods to some degree. • Methods are moderately reproducible.
Cartography	Methods especially pertinent to highway projects. These methods must be considered as inapt for quantifying and explicitly identifying repercussions.	<ul style="list-style-type: none"> • These methods require particular enthusiasm on the part of the analyst. • It is possible to employ automated cartography in these methods.
Network	Methods which establish a cause-condition pattern. The scope of evaluation can be diversified.	<ul style="list-style-type: none"> • Method reproducibility is apparently weak. • Methods permit tracing the pathways that produce the repercussions.
Statistical Methods	These are more forecasting methods than methods of pure impact assessment.	<ul style="list-style-type: none"> • While pertinent to some fields of evaluation, these methods are rather limited in social evaluation.

Table 1. (Cont'd.)

<i>Method</i>	<i>Applicability</i>	<i>Remarks</i>
Delphi	Methods which proceed more from intuition than from rationality. They are a form of controlled subjectivity.	<ul style="list-style-type: none"> • These methods can have a general as well as a sectorial range of application.
Scenarization and Conceptual Representation	Scenarization and conceptual representation depend greatly upon the intuition of the authors. However, these methods retain a rational character.	<ul style="list-style-type: none"> • Weak scientific representation. • The field of application is general and often vague, and encompasses above all the political and social fields.
Creativity Methods	These methods almost exclusively involve the field of intuition. The objective of these methods is to control and direct intuition towards a practical application.	<ul style="list-style-type: none"> • The orientation of creativity methods is essentially exploratory. • Creativity techniques apply more to limited and precise fields than to more vast fields.

Table 2. Description of the Principal Existing Methods for Evaluating Environmental Impact

<i>Method</i>	<i>Methodology</i>	<i>Applicability</i>	<i>Remarks</i>
Smith, L. [9]	<ul style="list-style-type: none"> • Checklist. • This method is based on the concept of supply and demand using probabilities. • One seeks to identify the alternative which minimizes social costs in terms of environmental resources and maximizes the social benefits in terms of resources. • A supply and demand probability is assigned to each element of the evaluation and each zone in the range of study. • The field of evaluation is very limited. 	<ul style="list-style-type: none"> • Pertinent mostly in judging alternative highway projects. • Resource requirements are difficult to determine. • Areas of the evaluation related to ecology, pollution, and sociology are not fully considered. • A limitation with this method is the implicit equal weight of each element of the evaluation. 	<ul style="list-style-type: none"> • Of doubtful reproducibility due to the difficulty of evaluating probabilities of supply and demand. • The method provides a unique "aggregated" indicator for each alternative.
McHarg, I. (1968, 1969) [10, 11]	<ul style="list-style-type: none"> • Cartographic survey. • This method employs cartography and transparencies of environmental characteristics (11 to 16) that are represented by one of three levels of compatibility with the project alternatives. 	<ul style="list-style-type: none"> • Pertinent for highway projects. • Of limited application to other projects. • Moderate resource requirements. • The method requires special analytical work. • The method is of little use in explicitly identifying and quantifying impacts. 	<ul style="list-style-type: none"> • This method can serve well for a preliminary view of environmental impacts.

Table 2. (Cont'd.)

Method	Methodology	Applicability	Remarks
Little, A. D. (1971) [12]	<ul style="list-style-type: none"> • Checklist. • This is not a complete and elaborated method but rather an identification and discussion of potential impacts and measurement techniques. • The importance of impacts and effects on the population is subdivided among them. • The categories of identified impacts are quite varied and general. 	<ul style="list-style-type: none"> • Pertinent to highway projects. • The approach can be useful for other types of projects. • The aggregation of individual impacts is not considered. 	<ul style="list-style-type: none"> • This method is not well described and appears to be imprecise as to how the study unfolds.
Atkins, W. C. and Burke, D. (1971) [13]	<ul style="list-style-type: none"> • Checklist. • A relative system of evaluating alternatives (-5 to +5) with a subjective process. • Environmental, sociological, and economic factors are considered. 	<ul style="list-style-type: none"> • Especially applicable to road and highway projects. • Social considerations are confined to community services and facilities. • The environmental impacts are ecologically deficient. • The social and economic approach can be useful for other types of projects. • With impact estimation being relatively subjective, necessary resources are variable. 	<ul style="list-style-type: none"> • The relative project vs. no project evaluation is made in relation to the future state of the area without the project. • The mode of presenting the relative estimates of impact, by category and by the range -5 to +5, is of interest.

- Institute of Ecology, University of Georgia (1971) [14]
- Checklist of 56 environmental components.
 - Varied range of impacts includes: land use, sociology, esthetics, economy.
 - A method which ranks individual impacts as a function of the greatest potential impact.
 - The weight of consideration increases with the duration of impact.
- Leopold, L. B., Clarke, F. E., Hanshaw, B. B., and Balslev, J. R. (1971) [15]
- A matricial approach where 100 potential activities related to a project are interrelated with 83 environmental characteristics or conditions.
 - Each identified impact is evaluated in terms of amplitude and importance.
 - Ecological and physico-chemical impacts are considered.
- Sorensen, J. C. (1971, 1973) [16, 17]
- Network.
 - Not so much a complete methodology but a guide to identify impacts.
 - Impacts are presented in a
- Especially useful for highway projects.
 - Extension to other types of projects is undesirable due to the choice of components.
 - The statistical approach used can be useful in other methods applied to water resource projects.
 - Elevated resource requirements (computer).
- Pertinent to any project with a minimum of adaptation.
 - Social and economic aspects, along with indirect impacts and secondary consequences, are considered little if at all.
 - Resource requirements are variable due to the subjectivity of the impact evaluations.
- While applicable as to projects in the littoral zone, the approach can also be used for other types of projects; in this case, the method must be
- A statistical treatment of variables and weights greatly improves the subjective basis of the method, hence its reproducibility.
 - Statistical treatment also permits one to test the significance of the total impacts of alternative solutions.
- Weak reproducibility.
 - Room for much subjectivity and ambiguity.
 - The method is especially useful for identifying potential impacts and for communicating results.
- Reproducible.
 - One strength to this method is the identification of ways in which impacts are generated.
 - Certain types of data are

Table 2. (Cont'd.)

<i>Method</i>	<i>Methodology</i>	<i>Applicability</i>	<i>Remarks</i>
	<p>hierarchical form: — use (project); — causal factors (project activities); — 1st, 2nd, and 3rd order changes in conditions; — effects.</p> <p>• A varied range of evaluation.</p>	<p>adapted by developing the appropriate networks. • Very competent human resources would be required for an adaptation.</p>	<p>suggested for the analysis of identified effects.</p>
Central New York Regional Planning and Development Board (1972) [18]	<p>• Matrix. • This method evaluates project activities in terms of impacts: — direct or indirect; — major or minor. • The scope of evaluation covers mostly physical impacts to the environment for: — 9 types of watersheds; — 14 types of activities.</p>	<p>• Pertinent for water resource projects (reservoirs, etc.) • Of limited interest because of the limited scope of evaluation. • Moderate resource requirements.</p>	<p>• Moderately reproducible. • Uncertainty and risk factors are not considered. • Spatial and temporal differences are not considered, reducing the authority of a study based on this approach.</p>
Dee, N. (1972) [19]	<p>• Checklist. • Oriented towards the quantification of 78 parameters chosen in advance. • Parameters cover four specific categories of impact: — ecological; — environmental;</p>	<p>• Especially applicable to major water resource works, also to a wide variety of projects. • Economic aspects are not covered explicitly. • Sociological aspects are partially covered under human impacts.</p>	<p>• Highly reproducible results. • Spatial and temporal factors are explicitly considered. • Public participation is not considered. • Uncertainties and major risks are not taken into account. • A "red flag" feature permits</p>

- esthetic;
- human.
- The method employs a system of “environmental quality units” calculated using indicators and formulas unique to each parameter.
- Automated cartography.
- The environmental characteristics considered are especially varied in land use and physiographic characteristics.
- Environmental data banks are constructed using geographic support units of 1 km².
- Impacts are evaluated by enumerating the squares intersected by repercussions of the project and by weighting each on the basis of environmental characteristics.
- A high level of resources is required for quantification, which makes the method particularly applicable to large projects.
- Especially useful for highway projects.
- The method is adaptable to major water resource projects on condition that the area can be delineated well and impacts are relatively localized.
- High resource requirements, unless the data banks already exist.
- The method has several advantages unique to its particular character; it:
 - reveals which environmental characteristic is the most important for a given alternative;
 - uses a readily comprehensible graphic representation;
 - considers several alternatives without appreciably increasing costs;
 - employs data banks that are increasingly available in North America.
- Analyses are subjective; however, with a programmed method, several alternative lines of analysis can be pursued.
- The method has several advantages unique to its particular character; it:
 - reveals which environmental characteristic is the most important for a given alternative;
 - uses a readily comprehensible graphic representation;
 - considers several alternatives without appreciably increasing costs;
 - employs data banks that are increasingly available in North America.
- one to assign priority importance to certain types of impacts (e.g., extinction of a species).

Krauskopf, M.
and Bunde, D. C.
(1972)
[20]

Table 2. (Cont'd.)

<i>Method</i>	<i>Methodology</i>	<i>Applicability</i>	<i>Remarks</i>
Multiagency Task Force (1972) [21]	<ul style="list-style-type: none"> • Checklist. • Pre-established categories of environmental components are considered. • Impacts are either measured quantitatively or subjectively evaluated, according to the possibilities. • The scope of evaluation includes different aspects of pollution as well as biological, physical, cultural, and historical resources. 	<ul style="list-style-type: none"> • Pertinent to a wide range of projects, especially in agricultural areas. • Resource requirements stem mainly from the formation of an interdisciplinary work group. • Socio-economic aspects are not covered. 	<ul style="list-style-type: none"> • Weak reproducibility. • Several ambiguous points in the evaluation. • Consideration of uniqueness and irreversibility are included. • Several means are suggested to facilitate the presentation of results. • The "without project" alternative is evaluated as perceived in the future. • It is suggested to avoid aggregating the impacts and to consider each individually without reference to a cost-benefit approach.
Stover, V. (1972) [22]	<ul style="list-style-type: none"> • Checklist. • This approach uses a quantitative evaluation of the impacts linked with the activities of a project. • Impacts are evaluated by using a fork with 7 possibilities ranging from very beneficial to very negative repercussions. 	<ul style="list-style-type: none"> • Pertinent to a wide range of projects. • Resource requirements are fairly high, due especially to the interdisciplinary consultative committees. • Provides no indication about the aggregation of sub-parameters. 	<ul style="list-style-type: none"> • Reproducible. • Possibility for ambiguity or subjectivity. • Differentiation and comparison of short and long term impacts. • Areas of impact are implicitly afforded an equal importance. • A major strength is the presentation of the relative

- A methodology is suggested for identifying the optimal alternative.
- The scope of evaluation is sufficiently diversified.
- Fifteen parameters of general impacts to which are added an indeterminate number of sub-parameters of specific impacts.

Tulsa District,
U.S. Army Corps
of Engineers
(1972)
[23]

- Provides no spatial differentiation.

- An attempt is also made to integrate the deliberation of the impact evaluation into a more global process which considers, for example, the concept of ecological stability.

- Useful for reservoir construction projects.
- May be adapted to other types of projects.
- Certain impacts, although important, can only be described with difficulty as positive or negative.
- Impacts are not directly related (in the presentation) to project activities.
- Necessary resources are variable:
 - interdisciplinary teams;
 - computers.

- Checklist.
- Within certain large categories of evaluation, the pertinent factors, along with indicators when measurable, are described.
- Impacts are evaluated using a relative assessment of one alternative to another, along with a subjective weighting of the characteristics.
- The “without project” alternative is considered null for this assessment.
- The scope of evaluation is divided into three sectors:
 - environmental quality;
 - “quality of life”;
 - economy.

- importance of impacts as a function of the alternatives.
- Very weak reproducibility.
- Impacts are summarized in a matrix constructed so as to permit a rapid comparison of alternatives.
- The weighting of characteristics is accompanied by an estimate of error which, in conjunction with statistical manipulations, permits a more significant differentiation of the impacts of alternatives.

Table 2. (Cont'd.)

Method	Methodology	Applicability	Remarks
Dee, N. (1973) [24]	<ul style="list-style-type: none"> • A composite of: <ul style="list-style-type: none"> — checklist; — matrix; — network. • Impacts are considered within a hierarchy of: <ul style="list-style-type: none"> — 4 categories; — 19 components; — 64 parameters. • The categories include the following impacts: <ul style="list-style-type: none"> — ecological; — physico-chemical; — esthetic; — social. • Impacts on each parameter are assigned a value between 0 and 1. 	<ul style="list-style-type: none"> • Especially pertinent to waste-water treatment projects. • May be applied to other projects but is of limited use. • Economic aspects are not considered explicitly. • Moderate resource requirements; however, the analysts must be highly trained. 	<ul style="list-style-type: none"> • Highly reproducible results. • This procedure is very technical and is hard to explain to an uninitiated group; the results are vulnerable to being belittled or contested. • The method, beyond its universality, is very well defined as to the procedures to follow. • The method permits flexibility in the choice of available data.
Moore, L. (1973) [25]	<ul style="list-style-type: none"> • Global impact is quantified using a weighting system. • Network. • This method establishes a "cause-condition-effect" chain for each activity of potential impact. 	<ul style="list-style-type: none"> • This method was developed to evaluate manufacturing activities in the littoral zone. • The proposed indicators can be applied to other types of 	<ul style="list-style-type: none"> • Weak reproducibility. • The method is very useful in providing a visual synthesis for the use of the population and at times of decision.

- The scope of evaluation is as large as desired by the analyst.
- Impacts are expressed in terms of damages:
 - elevated;
 - moderate;
 - minor;
 - negligible.

- activities.
- Low resource requirements.

Couillard, D.
(1976)
[26, 44-46]

- Network.
- This method establishes a "cause-condition-effect" chain for each activity of potential impact.
- Impacts are presented in a hierarchical form (causal factors, order changes in conditions, effects).
- Spatial temporal factors are implicitly considered.

- The scope of evaluation is as large as desired by the analyst.
- A varied range of evaluation.
- Pertinent for water resource projects (reservoirs, etc.).
- A limitation with this method is the implicit equal weight of each element of the evaluation.
- Environmental, sociological, and economic factors are considered.

- Moderately reproducible.
- Guide to identify potential impacts and for communicating results.
- This method is very useful in providing a visual synthesis for the use of the population and at times of decision.
- Reveals which characteristic is the most important for a given alternative.

specifically, and their methodology, applicability, and position in the above classification are discussed. Several of the methods presented in Table 2 are applicable to a diversity of human activities and could be integrated into decisional processes necessary for the orientation and execution of research.

PROPOSED METHOD

The method proposed herein aspires to a certain extent to be a composite of several techniques; the coherence graphs provide the underlying framework which organizes these components [26]. The fundamental principle of the coherence graph is based on the gradual decomposition of the proposed action in ever greater detail. In fact, the coherence graph is a formal framework that permits the interrelationships existing between the components of an action, as well as the consequences of this action, to be visualized schematically. The notation of these interrelationships allows the resulting graph to be treated quantitatively. Along with the theoretical and analytical bases of the method, this article discusses its application to the system of research undertaken in the water sciences in Quebec, as well as methods of notation for the links uniting the different elements of the coherence graph.

THEORY OF THE COHERENCE GRAPH

The essence of the theory consists in representing on a graph of several levels (Figure 1) the causes, conditions and effects brought about by an action. The first principle is the decomposition of the action from bottom to top through each level, from the first level of components to the final level of action results. The interrelationships progress from a low to a superior level (level "1" to level "N"). Each of the elements at the different levels are connected by lines drawn to one or several elements of the superior levels. The quality of the connection between a given level and a superior level may eventually be made the object of a numerical evaluation. The most important aspects in the application of the theory are the correct identification of the indicators employed and the assurance of coherence between indicators at the same level.

The structure of the graph thus corresponds to a representation of the unique relationship whereby an element i of a level M contributes to a change in an element j of another level N . The notation of this relationship involves a numerical translation, if appropriate, of the intensity of the contribution linkage.

It may happen that, for purposes of enhanced comprehension, one or several additional levels are introduced in order to make the cause-condition-effect relationships more explicit. Obviously, the number of levels must be limited so as not to overburden the schematic representation. As with other methods (e.g., matricial methods), it is desirable that the graph be accompanied by a text which explains the multiple relationships under scrutiny.

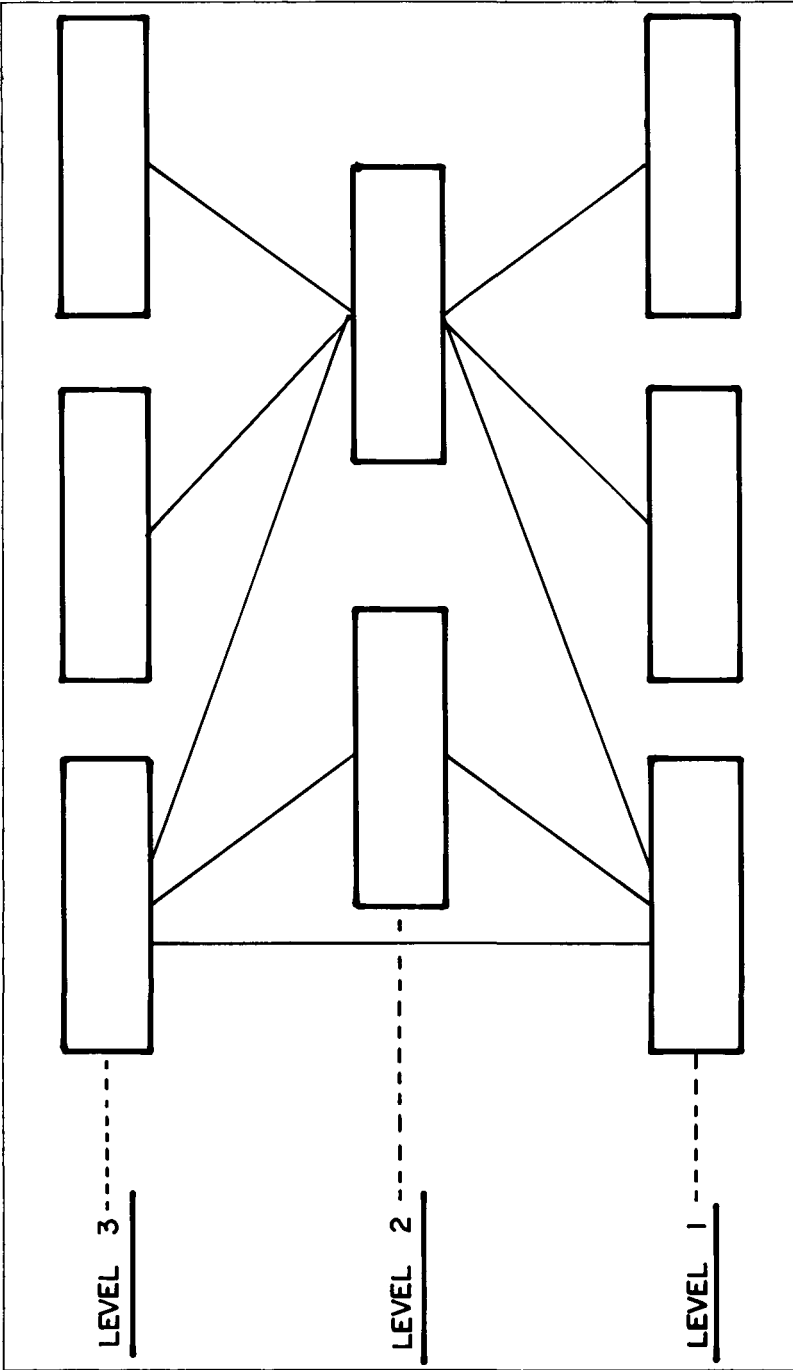


Figure 1. Schematic representation of the coherence-graph method in one plane.

NOTATION OF THE LINKS UNITING DIFFERENT ELEMENTS

Another interest of the coherence graph method rests in the possibility of assigning a numerical notation to serve as an indicator of the quality and intensity of the linkages under study. One must envision several different notation methods, based on the implicated systems and the nature of the parameters. Notation requires an appreciation of the value of the connection relating an element i of a level M to an element j of a level N . Each element of the level N plays the role of an objective against which the contribution of the related elements of the level M is judged. Depending on the systems studied, many situations can occur. In the best of cases, the two variables connected by a line are measurable and a law can be found to relate their evolution. In this instance, one can obtain a relation of the type:

$$A = f(B)$$

In other systems, the linkages are characterized by precise statistics; however, it often happens that there is no known applicable law and the variables cannot be measured. In these cases, an ordinal scale must be used.

The Scale of Values in Matters of Administration

Initially pre-occupied with the evaluation of linkages which can only be measured indirectly, the majority of administrators have established these relations in a cardinal system of evaluation where the common denominator is economic profitability [27]. Thus, only the cost benefit analysis becomes the decision factor.

This scale of values is not always the best for evaluating the repercussions of an action. One cannot always expect to evaluate the repercussions using a system of cardinal evaluation [28]. The solution rests in the possibility of employing an ordinal system of values [29, 30].

It is only under this condition that one is enabled to measure the repercussions of a decision. Advantages inherent to an ordinal system permit the classification, ordering and comparison of items or phenomena which, at first, appear unmeasurable with a cardinal system.

Considering that the fundamental problem of the administrator is one of choice [31], he is continually confronted with a multitude of decisions: to perform or not perform certain actions, or, given a problem for which there are several possible solutions, to choose an "optimal" solution given the constraints imposed on his realm of administration. In view of this dilemma, technocrats have applied themselves to the development of systems to aid in decision-making [32]. These systems permit an optimization of the decision-making process while at the same time being impregnated with the search for "objectivity." Such systems must play a balancing role where, for a given situation, one can

“weigh” (evaluate) the influence of each of the implicated parameters [33]. It is only after this that one can even classify the possible solutions, and this is the ultimate goal of evaluation: to rank the solutions.

Notation of Linkages with the Delphi Method

The principle of this method is to permit a group of specialists to express themselves on precise questions through the use of well-defined schedules. An application of the method is effectuated through a series of questionnaires in which one wishes to unite extreme positions in convergence around a mean. To accomplish this, the responses of the first trial are compared. Distribution functions are then obtained from these responses as well as the different moments of these distributions. These results are then communicated to the participating specialists and those with more extreme positions are asked if they maintain their positions or if they wish to modify them in relation to the mean. In the event they do not change their response, it might even occur that they be asked to justify it. These justifications are then introduced as arguments within the new questionnaire distributed. This process may be repeated for as long as the specialists continue to modify their responses by taking cognizance of the results of the other group members.

Notation System Used by Morin and Trudel

The studies of Morin and Trudel were undertaken with the goal of creating an understanding of the relative importance of an enterprise on the economy of a city and a region (Saint François River drainage basin) [34]. The study presents economic impact by enumerated parameters which reflect the amplitude of impact. Each enterprise is characterized using a variety of parameters: direct and indirect employment, value added. A relative weighting system is established for each parameter used; for example, private manufacturing employment or city manufacturing employment. The relative weights are then each qualified with a rating of the parameters themselves. The evaluation system thus permits the establishment of a global value for each parameter:

Notation of a first order parameter –

$$C_i = P_i N_i$$

where:

- C_i : global value of a first order parameter
- P_i : relative weight of the first order parameter used
- N_i : rating of the first order parameter used
- i : industry chosen for first order

and:

$$0 < C_i < 100$$

$$0 < P_i < 10$$

$$0 < N_i < 10$$

Notation of a second order parameter –

$$C_i^1 = P_i^1 N_i^1$$

where:

C_i^1 : global value of a second order parameter

P_i^1 : relative weight of the second order parameter used

N_i^1 : rating of the second order parameter used

i : industry chosen for second order

and

$$0 < C_i^1 < 50$$

$$0 < P_i^1 < 10$$

$$0 < N_i^1 < 5$$

With this method, a maximal global value represents an extremely important economic impact for the city and/or region. Finally, it is possible to compare and class the group of enterprises on the basis of the global value.

Notation System Used by Provencher

The study of Provencher sought to develop a tool for interpreting water quality data while taking into account the diverse needs of different users of the resource [35]. A methodology for determining the potential use of a given water body was developed by comparing observed water quality with the criteria for different uses. Seventeen different classes of water usage were chosen among three principal types (industrial, social, ecological).

For a given use the evaluation of water quality is based on physical, chemical, and biological characteristics. Thus, for each of the seventeen classes, a list of independent parameters is established to serve in the calculation of a quality index. A complementary list of parameters is added to the classes which takes into account social and ecological needs. They are employed in the calculation of the quality index only when they represent deviations from technical standards of quality.

Once the list of quality parameters (Table 3) associated with a precise usage is chosen [36], the relative importance of each parameter must be evaluated. This evaluation is represented by a weighting coefficient P_i . This factor is independent of the concentration of the parameter and takes account uniquely of its importance relative to other parameters used to characterize a water body. The weights can be assigned following a literature search or from consultations

Table 3. Notation in the Provencher System:
Parameters of General Water Quality [36]

<i>Parameter</i>	<i>Units</i>	<i>Weight</i>	<i>Standard</i>
		$\Sigma = 1$	
Total Solids	mg/l	0.073	300
Temperature	°C	0.100	-4.5, 3.4
Turbidity	J.T.U.	0.082	21.5
Fecal Coliforms	org./100 m	0.158	18
B.O.D.	mg/l	0.105	3.8
Nitrates	mg/l	0.100	6
Dissolved Oxygen	O/O satu.	0.172	60, 150
pH	units	0.111	6.0, 8.7
Phosphates	mg/l	0.100	0.5

with experts in the field. Thus, through the weighting process, the parameters are classed in order of importance for a given water usage. The weighting coefficient varies from 0 to 1.0 such that the sum of the coefficients of the same class totals 1.0:

$$\sum_{i=1}^n P_i = 1.0$$

where:

i : chosen parameter “i”

n : number of parameters in the use class

P_i : weight of parameter “i”

and

$$0 \leq P_i \leq 1.0.$$

After having determined the relative importance of the parameters, one must establish the relationship between the concentration of a parameter and water quality. This function is traced on the basis of data available in the literature [37-40]. The appreciation of the water quality corresponding to a parameter concentration is made by referring to Table 4. The notation system of Provencher thus permits the establishment of a global value of water quality for a chosen usage class. There are two ways to formulate this evaluation:

additive method:
$$C_i = \sum_{i=1}^n P_i (fQ_i)$$

Table 4. Levels of Quality Associated with Parametric Values

<i>Quality Rating</i>	<i>Interpretation</i>
100	Excellent water quality
> 85	Very good water quality
> 75	Good water quality
60-75	Satisfactory water quality
< 60	Poor water quality; must be treated (aeration, chlorination, etc.) prior to use
0	Very poor water quality; any improvement in water quality would require complex and costly treatment procedures

multiplicative method:
$$C_i = \prod_{j=1}^n (fQ_j)$$

where:

fQ_i : quality function for the parameter "i"

and:

$$0 \leq Q_i \leq 100$$

$$0 \leq C_i \leq 100$$

Several other methods exist which permit the comparison and ranking (evaluation) of different situations as a function of an objective; and this is usually done with an ordinal system. These methods can be used for evaluating the relative importance of impacts brought on by an action by conducting a notation of relationships between the elements of the graph (Figure 1).

EXAMPLE OF THE USE OF COHERENCE GRAPHS

The method described herein can be employed in different ways depending upon whether or not the decisions to be made concern an entirely new system (descriptive and prospective) or an existing system requiring changes in certain components (descriptive, decisional). Graph notation, as well as the method of combining the diverse elements, varies according to the type of decision. In order to present a better appreciation of this method, the results of a case study in which the coherence graph was used is reviewed: impact of evaluating policies concerning the execution of research in a given sector [1].

Research in Water Sciences

The example presented concerns the system of research execution in the water sciences in Quebec (Canada). The principal goal pursued is to describe the system and identify the most significant characteristics. The process followed for the elaboration of the coherence graph (Figure 2) is based on Fiscal Year 1973-1974 data obtained from official documents describing the activities of the various agencies which support and/or perform research in the water resource sector in Quebec. This information permitted the identification of the elements of the system of Quebec university research in water sciences on a coherence graph (Figure 2) consisting of five levels. The graph connects sources of financing and the objectives pursued at performing institutions and in the various disciplines associated with the realization of research in this sector.

Description of the Graph

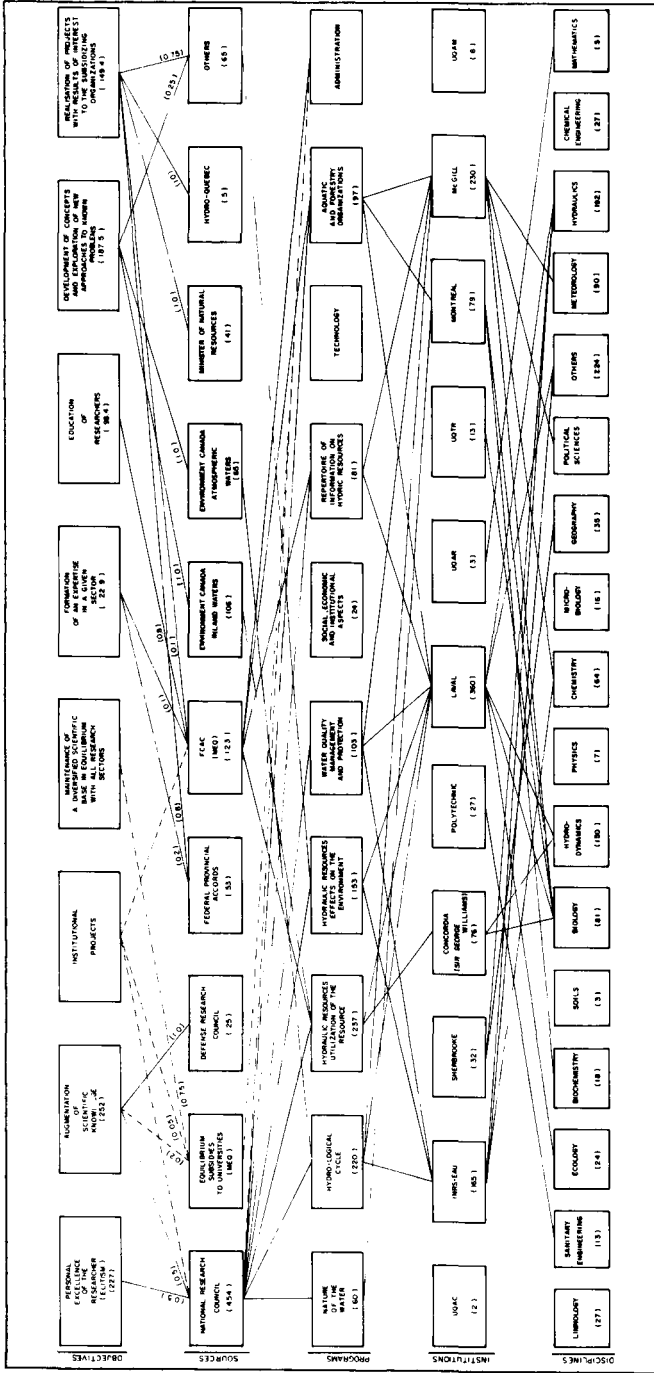
The coherence graph presented in Figure 2 is composed of five levels of elements, the elements being defined by the properties and responsibilities shown. The levels are numbered from 1 to N such that each element of a level J contributes to the obtention of elements of level J-1; the final level N is that of the elements to be ranked. In this case, the disciplines and/or institutions and research programs are obtained in relation to elements of the OBJECTIVES level. Each level represents either a body of elements that one seeks to realize or a series of elements indispensable for following the progression of the effect of elements of level N through to level 1. The generality of this type of coherence graph is such that the levels can be removed or introduced according to the goals of utilization. In our study, we have chosen to include five levels in order to facilitate comprehension of the problem, and also because the data needed to link a level J in relation with another level (J-1) were available with a high degree of precision for the 1973-1974 fiscal year [41, 42].

Description of Graph Levels

The graph presented schematizes the research system in a three-dimensional space in which each plane represents the five following functional levels:

1. the objectives of research;
2. the sources of research financing;
3. the sectors (programs) of research execution;
4. the institutions performing research; and
5. the disciplines associated with research execution.

The OBJECTIVES level groups the majority of objectives pursued by agencies financing research, and the body of elements at this level represents the politics of science existing at a given time. The formulation of elements comprising the body of objectives can be done through different processes according to the type



- Notes:**
- 1) Dashed linkages indicate existing relations for which specific amounts cannot be identified in the scope of this analysis.
 - 2) The numbers in parentheses on lines leading from financial sources to specific objectives are an evaluation of the order of priority observed by the subsidizing organizations.
 - 3) The numbers in parentheses indicate the "mils" of financing obtained or allocated by each of the elements of this graph (a mil is equivalent to \$2,287.00 of financing).

Figure 2. Coherence graph connecting the sources financing research in the water sciences (for the year 1973-74) in Quebec with the objectives pursued, the programs realized and the performing universities.

of community that establishes them. In totalitarian countries and developing countries where investments are directly or indirectly public in nature, the elements of this level are generally clearly identified in triennial or five-year development plans. On the other hand, in western industrialized countries, the elements of this level are defined by each group sharing a portion of research funds. Each of these groups identifies itself with elements of the SOURCES OF FINANCING level presented in Figure 2. Adequation between elements of the levels OBJECTIVES and SOURCES OF FINANCING occurs through the intervention of criteria governing the conferment of grants and research contracts. It is thus with the aid of an elaboration of the formal criteria for conferment that the effect of the body of elements forming the politics of science can be discerned.

The third level identified in Figure 2 represents the analytical elements of the efforts made in the water sciences in Quebec. Each of the projects uncovered in documents available for this study has been classified according to the type of general research program of which it is a part. The fourth level groups all the universities performing research in the water sciences in Quebec which had obtained direct financing for research in the 1973-1974 fiscal year. The fifth level classes the identified projects according to the disciplines associated with the execution of the research.

Notation of the Coherence Graph

The preceding sections have presented diverse methods for the notation of a coherence graph. Thus, it is possible to appraise and quantify the connections between elements of the different levels and, therefore, to note using different combinative methods each of the paths flowing from elements of the SOURCES OF FINANCING level to those of other levels. This first step of the evaluation, delineation of the respective weights of each of the objectives, permits response to a preliminary body of questions that can be posed regarding university research and that are pertinent to the objectives guarded by those providing funds. In other words, before being able to consider the question of efficiency and the performance of university research results, one must beforehand delineate the objectives preferred by financial sources.

The funds directly allocated to water sciences research in the Province of Quebec were at that time in the order of thirty-three million dollars. The numbers in parentheses on the linkages between levels IV and V represent the thousandth portion (mil) of financing obtained or distributed in the diverse disciplines considered. The percentages of the objectives favored by financial sources are indicated in parentheses on the linkages between level I and II. In the graph shown in Figure 2, one can already recognize the relative importance of the different pathways proceeding from the elements of the OBJECTIVES level to those of the DISCIPLINES level, and that these various pathways can be ranked. The notation of the critical pathway can thus be introduced and used

to signify the connection which represents the greatest or smallest total of mils, according to the specific case, by taking for granted that each level is appraised in the same fashion.

The graph of university research financing presented in Figure 2 permits a distinction to be made concerning the influence of objective and subjective data in all evaluation processes. In effect, the linkages between elements of the RESEARCH PROGRAMS and SOURCES OF FINANCING levels represent objectives; existing statistical data on the amounts distributed by one or another organization under various forms of financing are objectively verifiable data which can be easily quantified. It is possible to use this data according to their absolute value (thousands of dollars granted) or relative value (percentage of financing), or to rank the financing according to its position on a scale graded at three, five or eleven positions. Nevertheless, the linkages between the SOURCES and OBJECTIVES levels of university research financing are subjective because it is necessary for any observer to appreciate if, for example, a provincial council finances its projects toward objectives of increasing knowledge and the formation of researchers in exclusion to those regarding solutions to identified problems. It is also necessary to appraise financing between two highly regarded objectives: is the distribution 50-50 on a percent scale of 70-30?

These considerations cast a little more light on the type of evaluation applicable to the results of university research. This evaluation will be more and more qualitative as the preferred objectives of financing bring together classes of scientific and emerging objectives in opposition to those of a utilitarian nature. This orientation of financing objectives partially defines the mission of research projects and programs, and at the same time, the type of evaluation and the importance of real or expected results. It is thus that programs most associated with augmenting knowledge and the formation of researchers will be evaluated according to their contribution to knowledge and an increase in researchers for a certain discipline or a certain field of interest. Evaluation methods using a jury of experts conform well to the evaluation of these types of results. On the other hand, research leading toward more utilitarian ends must respond to specific evaluative criteria regarding their more immediate results, the elaboration of new concepts, or the production of new products and methods. This is also the case with the evaluation of governmental interventions in a specific field. Evaluations of the "cost-benefit analysis" type conform better to first results while different experimental protocol are better adapted for the second approach. These observations apply as well to criteria for the distribution of funds.

OTHER EXAMPLES

Several other examples of the potential for using coherence graphs as a tool in the evaluation of impact can be mentioned. In particular, the study of Morin

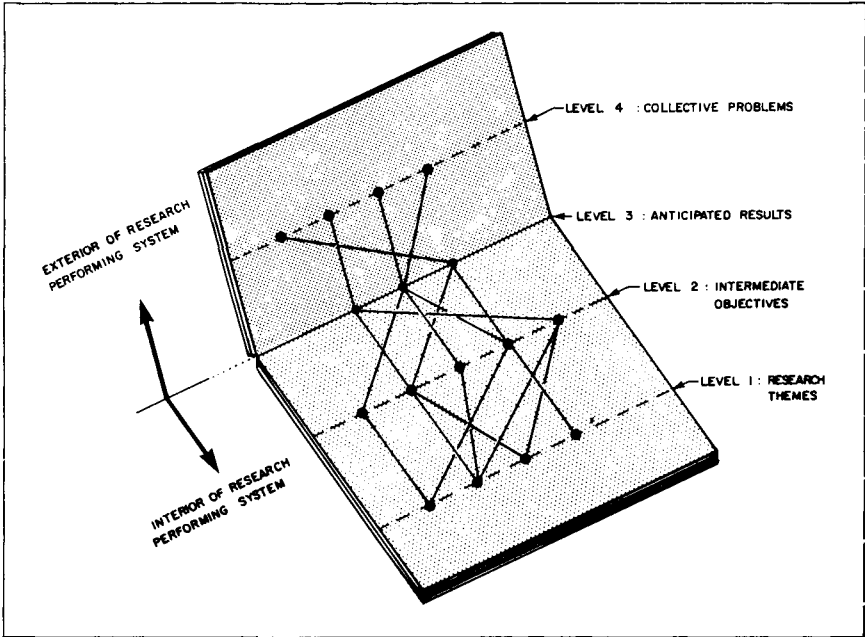


Figure 3. Coherence graph representing the relation of the performance of research in an institution and the external service utilizing the results.

and Trudel aspired to illuminate the relative importance of diverse enterprises for the economy of the municipality or region in which they are established [34]. Certain parameters such as value added, direct employment and indirect employment are represented in this report by a relative weighting system. Accompanied by the determination of parameters, this procedure affords a characterization of the enterprises in combination and an evaluation of their relative impact.

Another example of the potential use of a coherence graph is in the choice of research programs pursued by an institution or an entire national system. Such an approach was employed for programming the department of agronomy of the I.N.R.A.-France (Institut National de la Recherche Agronomique, Versailles, France). The resulting graph, depicted in Figure 3, implies four levels, each one grouping objectives of an increasing degree of generality: research themes, disciplinary objectives, results anticipated, and technical problems encountered. This last type of graph introduces a new dimension in the use of graphs for the evaluation of policies. In effect, it demands that communication between the interior and the exterior of an organization executing research pass through the level of results (anticipated or obtained), a level represented by the intersection of two planes reciprocally defining the internal and the external elements of the

system of research execution. This notion is primordial to the elaboration of a method for evaluating policy related to the financing of research [43].

A final example is the application of the coherence graph to the ecological impacts pursuant to the establishment of an integrated forestry complex (sawmills and bleached Kraft pulp factories) on the Chamouchouane River, an inlet of Lake St. John, Quebec [44, 45]. The coherence graph permits preliminary conclusions to be drawn through a schematic representation of the interrelations between the actions posed in the establishment of an integrated forestry complex and the environments which are influenced [46]. It thus facilitates a very rapid identification of serious repercussions (avoidance effects, presence of phenols, contact time, etc.) on the survival of *Salmo salar ouananiche*.

CONCLUSION

Despite an appearance of simplicity, the proposed method nevertheless possesses some difficulties which appear during analysis and programming. The first pitfall to be encountered resides in the discernment of the problem. With a method this flexible, one must know how to fix the optimal number of levels as well as to respect the necessary coherence in the choice of elements comprising each level. The aspect of numerical evaluation is also a point of litigation lending criticism to the method. In order to render the application of this method more objective, it would be preferable that it be effectuated by a multi-disciplinary team.

The graphic presentation is certainly one of the most important advantages among those offered by the method. It provides a comprehensive overview of the relations made apparent and in this way affords the user a valuable opportunity for effective communication. This schematization also plays a role in the synthesis which confers the method with a very interesting functional character.

The coherence graph method aspires to be an intuitive method, couched in a rational aspect conferred to the method by the rigor with which the intuition is directed. As has been shown, the method is exploratory at the outset. The normative point of view, however, is absent only insofar as it will eventually establish itself with practice. The universality of the method is also greatly advantageous. It is applicable to virtually any subject, from the most extensive to the most refined.

REFERENCES

1. D. Mascolo, *Introduction à une démarche évaluative de la recherche: application au système universitaire*, Ministère de l'Éducation, Gouvernement du Québec, Québec, Canada, 1980.

2. C. O. Jones, *An Introduction to the Study Policy*, Duxbury Press, 2nd Edition, pp. 205-206, 1978.
3. A. Greycar, Political Issues in Research and Evaluation, *Evaluation Quarterly*, 3:3, pp. 460-471, 1979.
4. M. C. Alkin, Evaluation Theory Development, *Evaluation Comment*, 2: 1, pp. 2-7, 1969.
5. P. Hesseling, Principles of Evaluation, *Social Compass*, 11:1, pp. 5-22, 1964.
6. D. Couillard and P. Trudel, Modèle de la gestion du territoire et des ressources et scénario d'évaluation des impacts, *Eau du Québec*, 11:1, pp. 9-13, 1978.
7. D. Couillard, Quality of Life: The Importance of Man-Environment Relations and a Tentative Conceptual Model, *Journal of Environmental Systems*, 12:2, pp. 163-184, 1982-83.
8. M. L. Warner and E. H. Preston, *A Review of Environmental Impact Assessment Methodologies*, Report No. 68-01-1871, Office of Research and Development, U. S. Environmental Protection Agency, Washington, D.C., 20460, 1974.
9. W. L. Smith, *Quantifying the Environmental Impact of Transportation Systems*, Van Doren-Hazard-Stallings-Schnacke, Topeka, Kansas, mimeographed, undated.
10. I. McHarg, *A Comprehensive Highway Route-Selection Method*, Highway Research Record, Number 246, pp. 1-15, 1968.
11. _____, *Design with Nature*, Garden City, Natural History Press, pp. 31-41, 1969.
12. A. D. Little, *Transportation and Environment: Synthesis for Action: Impact of National Environmental Policy Act of 1969 on the Department of Transportation: Vol. 3: Options for Environmental Management*, prepared for Office of the Secretary, Department of Transportation, 1971.
13. W. C. Atkins and D. Burke, *Interim Report: Social, Economic, and Environmental Factors in Highway Decision Making*, research conducted for the Texas Highway Department in cooperation with the U. S. Department of Transportation, Federal Highway Administration, College Station, Texas, Texas Transportation Institute, Texas A & M University, 1971.
14. Institute of Ecology, University of Georgia, *Optimum Pathway Matrix Analysis Approach to the Environmental Decision-Making Process: Test Case: Relative Impact of Proposed Highway Alternatives*, University of Georgia, Institute of Ecology, Athens, Georgia, mimeographed, 1971.
15. L. B. Leopold, F. E. Clarke, B. B. Hanshaw, and J. R. Balsley, *A Procedure for Evaluating Environmental Impact*, U. S. Geological Survey Circular 645, Washington, D.C., 13 pages, 1971.
16. J. C. Sorensen, *A Framework for Identification and Control of Resource Degradation and Conflict in the Multiple Use of the Coastal Zone*, Thesis, Department of Landscape Architecture, University of California, 50 pages, 1971.
17. J. C. Sorensen and J. E. Pepper, *Procedure for Regional Clearinghouse Review of Environmental Impact Statements Phase Two*, report to the Association of Bay Area Government, 1973.

18. Central New York Regional Planning and Development Board, *Environmental Resources Management*, prepared for department of HUD, NTIS PB 217 517, 1972.
19. N. Dee, *Environmental Evaluation System of Water Resources Planning*, Report of the U. S. Bureau of Reclamation, Battelle Memorial Institute, Columbus, Ohio, 1972.
20. T. M. Krauskopf and D. C. Bunde, *Evaluation of Environmental Impact Through a Computer Modelling Process*, *Environmental Impact Analysis: Philosophy and Methods*, R. Ditton and T. Goodale (eds.), University of Wisconsin Sea Grant Program, Madison, Wisconsin, pp. 107-125, 1972.
21. Multiagency Task Force, *Guidelines for Implementing Principles and Standards for Multi-Objective Planning of Water Resources*, Review Draft, U. S. Bureau of Reclamation, Washington, D.C., December 1972.
22. L. V. Stover, *Environmental Impact Assessment: A Procedure*, Sanders and Thomas, Inc., Miami, Florida, 1972.
23. Tulsa District, U. S. Army Corps of Engineers, *Matrix Analysis of Alternatives for Water Resource Development*, draft technical paper, 1972.
24. N. Dee, *Planning Methodology for Water Quality Management: Environmental Evaluation System*, Columbus, Ohio, 1973.
25. J. L. Moore, *A Methodology for Evaluating Manufacturing Environmental Impact Statements for Delaware's Coastal Zone*, Report to the State of Delaware, Battelle Memorial Institute, Columbus, Ohio, 1973.
26. D. Couillard, Systems Analysis for Description of Environmental Pollution, *Water Supply and Management*, 5, pp. 183-194, 1981.
27. J. K. Stanley, A Cardinal Utility Approach for Project Evaluation, *Socio. Econ. Plan. Sciences*, 8, pp. 329-338, 1974.
28. J. P. Guilford, *Psychometric Methods*, McGraw-Hill, New York, 597 pages, 1954.
29. W. J. Baumol, The Newmann-Morgenstern Utility Index – An Ordinalist View, *J. Polit. Econ.*, 59, pp. 61-66, 1951.
30. R. N. Shepard, Metric Structures in Ordinal Data, *Journal of Mathematical Psychology*, 3, pp. 298-315, 1966.
31. R. H. Irving and S. F. Love, Evaluation and Choice – An Engineering Approach, *Engineering Digest*, pp. 31-33, November-December 1975.
32. D. J. Etzold, Benefit-Cost Analysis: An Integral Part of Environmental Decisioning, *Journal of Environmental Systems*, 3, pp. 253-256, 1973.
33. L. Prati, R. Pavanello, and F. Pesarin, Assessment of Surface Water Quality by a Single Index of Pollution, *Water Research*, 5, pp. 741-751, 1971.
34. J. F. Morin and R. Trudel, *Évaluation de l'impact économique de l'activité manufacturière du bassin de la rivière Saint-François*, Report No. 0302-21(7), Direction de l'aménagement, Division de l'affectation, Ministère des Richesses naturelles, Gouvernement du Québec, Canada, 1976.
35. M. Provencher and M. P. LaMontagne, *Méthode de détermination d'un indice d'appréciation de la qualité des eaux selon différentes utilisations*, Service de qualité des eaux, Ministère des Richesses naturelles, Gouvernement du Québec, Canada, 1977.

36. N. I. McClelland, *Water Quality Index Application in the Kansas River Basin*, U. S. Environmental Protection Agency, Kansas City, Kansas, Report No. EPA-907/9-74-001, 227 pages, 1974.
37. Environmental Protection Agency, *Quality Criteria for Water*, U. S. Environmental Protection Agency, Washington, D.C., 256 pages, 1976.
38. _____, *Water Quality Criteria*, Environmental Studies Board, U. S. Government Printing Office, Environmental Protection Agency, Washington, D.C., Report No. 5501-00520, 594 pages, 1972.
39. Communauté Économique Européenne, Direction du Conseil concernant la qualité requise des eaux superficielles destinées à la production d'eau alimentaire dans les états membres, *Journal officiel des Communautés européennes*, L-194, pp. 26-31, 1975.
40. _____, Avis sur une proposition du Conseil concernant la qualité requise des eaux douces aptes à la vie des poissons, *Journal officiel des Communautés européennes*, C-77, pp. 2-5, 1977.
41. Ministère de l'Éducation du Québec, *La recherche subventionnée et commanditée dans les universités du Québec, 1972-73 et 1973-74*, Direction générale de l'enseignement supérieure, Ministère de l'Éducation, Gouvernement du Québec, Québec, Canada, 1976.
42. D. Healy, L. Dion, and B. Neatby, *Rapport de la commission d'enquête sur les études supérieures dans les sciences humaines*, Conseil de recherches en sciences humaines du Canada, Gouvernement du Canada, Canada, 1978.
43. D. Maquart, Introduction à l'organisation de la décision, *Annales agronomiques INRA*, Versailles, France, 1971.
44. D. Couillard, D. Bourret, and G. Thibault, *Graphe de cohérence appliqué aux impacts économique et écologiques de l'implantation d'une usine de pâtes et papiers à Saint-Félicien, Lac Saint-Jean, Québec*, presented to the 14th Canadian Symposium on Water Pollution Research, University of Ottawa, INRS-Eau, University of Quebec, Quebec, Canada, Internal Report No. 75, 1978.
45. D. Couillard, Évaluation des impacts environnementaux dus aux rejets d'une usine de pâte kraft sur le *Salmo salar ouananiche* à l'aide d'une nouvelle méthode: le graphe de cohérence, *Environmental Pollution, Series B*, 2, pp. 145-161, 1981.
46. _____, Évaluation de la pollution et des répercussions des rejets des industries des pâtes et papiers sur la vie aquatique, *The Sciences of the Total Environment*, 14, pp. 167-184, 1980.

Direct reprint requests to:

Denis Couillard
 INRS-Eau, Université du Québec
 C. P. 7500
 Sainte-Foy, Québec G1V 4C7
 Canada