Lake Como

A study at IIASA has helped resolve a conflict of interests between upstream residents and downstream water users supplied from the reservoir at Lake Como in Italy. The software developed now forms the basis of a decision support system in daily use by the reservoir manager.

Managing reservoirs to meet water needs for different purposes invariably involves distributing costs and benefits. Inevitably, there are gainers and losers, and this fact of life can lead to conflicts between the groups affected. Such conflicts arise partly because different groups have their own priorities in assessing management plans: economic efficiency, environmental quality, distributional (equity) considerations, or risk factors, for example. There is a need for scientifically sound but relatively simple computer-based procedures and policy-oriented methods for resolving conflicts in resource allocation, and IIASA has done methodological work in this area. The systems-analytical approach is well illustrated by the Institute’s work on Lake Como in Lombardy in northern Italy.

Lake Como stretches for almost fifty kilometers (thirty miles) beneath the spectacular peaks of the central Alps near Italy’s border with Switzerland. By June each year the lake is filled with the snowmelt from a catchment area in the Alps of over 4,500 square kilometers. Over the hot dry summer the lake is drained by the River Adda.
which flows 140 kilometers across the Padana plain south-east of Milan before merging with the River Po. In autumn the lake is refilled by the rains.

Since Roman times this typically alpine cycle has benefited farmers downstream from the lake, where the yields of wheat, corn, and forage from 144,000 hectares of agricultural land can be greatly improved by using the waters of the River Adda for irrigation. The users remained subject to the caprices of nature, however, until the Second World War, when a dam was constructed at Olginate. The dam was built to regulate the lake’s outflow for agricultural purposes over the summer and to increase the power production of the seven downstream hydroelectric plants, which have a total generating capacity of 92 megawatts.

**Como’s Sinking Square**

In the 1960s, the main square in the town of Como at the southern end of the lake began to subside, probably as a result of over-pumping from the underground aquifer. It is now about 60 centimeters below its 1946 level, and this has greatly increased the flooding of the square during the periods of high inflows due to snowmelt in the early summer and rainfall in the autumn. In the first twenty-five years of the dam’s operation, only three floods lasted longer than five days; between 1972 and 1981 there were ten such floods. In 1976 one flood lasted twenty days, and the square was under water for a total of thirty-seven days in 1977. Since the main square is the commercial center of Como, and the lakeside road links the eastern and western parts of the town, which has a population of about 100,000, flood protection has become a matter of great concern. It has been the subject of much discussion between the Municipality of Como and the manager responsible for the day-to-day operation of the dam at Olginate.

IIASA’s involvement in the management of Lake Como dates from 1981, when the Institute held a summer study on the real-time management of hydro-systems, at which Como was the primary practical concern. The work at IIASA followed two separate but inter-related lines of research. In the first, with the support of the Italian National Research Council, Professor Sergio Rinaldi, Dr. Rodolfo Soncini-Sessa, and Dr. Giorgio Guariso, all of the Center for Systems Theory at Milan Polytechnic, developed a new computer-based approach to the management of the lake. The second study elaborated a “risk-averse” approach to the management of hydro-systems in general. This approach was initially developed by Dr. Sergei Orlovski and others at the Computing Center of the USSR Academy of Sciences in Moscow.

Professor Rinaldi explained the purpose of the study: “Managing Lake Como is a process of making tradeoffs between conflicting objectives. Retaining water in the reservoir to irrigate agricultural land in the summer and to generate hydroelectric power in the winter runs the risk of disruptive flooding in Como and around the lakeshore when the inflows suddenly increase. There are mathematical means of dealing with such problems of storage control with multiple objectives, but these are often too abstract and sophisticated to be of much practical help. We wanted to develop a simple and heuristic, but scientifically sound, method of reservoir management that would take into account the experience and preferences of the manager.”
since 1946, which showed that the two statistical analysis of all the floods means that we can just consider the generation, a sound indicator is the maximum generating capacity; the indicators are highly correlated. This means that we can just consider the number of days of flooding per year without distorting the picture. This has averaged about ten days in the past (see figures), whereas the natural figure for the same period, had the dam not been built, would have been about twenty-three days." Estimates indicate that the cost of one day of flooding is not great in comparison with the economic gains in agriculture resulting from improved irrigation; however, the number of people directly involved in farming is rather small.

The dam at Olginate is operated subject to the terms of a government licensing act which specifies that the manager decides the release each day provided that the lake level lies between two fixed limits. This range defines the so-called "active storage", which is the volume of water the manager controls. The figure for Lake Como is about 250 million cubic meters. Since the lake is filled twice during the year, first by snowmelt and later by rainwater, the manager is responsible for a total "budget" of 500 million cubic meters of water a year. When the level reaches the lower limit, the manager must release no more than the inflow into the lake, so that the level does not drop further to jeopardize navigation and cause sanitation problems. At the upper limit, the manager is obliged to open all the dam gates to alleviate flooding of the lake shore.

Three Remedies

The HASA group studied three complementary ways of mitigating flood damage to Como and improving the water supply to downstream users in agriculture and hydroelectric power generation. The first was to develop a decision support system for the manager operating the dam. Secondly, appropriate amendments to the licensing act were proposed. Thirdly, the analysts investigated the merits of raising the sunken part of Como.

Professor Rinaldi explains how they set about the first of these. "For water levels between the set limits, the manager decides the water release necessary each day to achieve a satisfactory compromise between the conflicting objectives. We examined the historical data relating to the entire operational life of the reservoir, since 1946. These data showed that there are three distinct zones in the range of water levels between the two limits. In the lowest zone the primary concern of the manager is to satisfy the water requirements of the farms on the Padana plain. In the middle zone the manager also takes into account the water needed for hydroelectric power generation, while when the level nears the upper limit, flood protection becomes the overriding objective." In other words, the manager follows an implicit operating rule relating the daily release to the lake's water level and the time of year. This operating rule can be expressed as a mathematical formula.
duced the mean number of days of flooding between 1946 and 1981 from at least 45 million cubic meters. This improved rule would essentially make more intensive use of the lower part of the reservoir’s active storage, and would open the dam gates fully before the upper limit was reached.

Before this operating rule was proposed to the manager, it was analyzed in detail by modeling its performance over the whole of the reservoir’s operational lifetime. Historical droughts and floods were then compared with those resulting from the storages and daily releases given by the computer model using the proposed operating rule. “The volumes of all water deficits generated in the simulation were lower than the corresponding historical values,” states Professor Rinaldi, “and flood peaks and durations would have been reduced in every single episode of the entire thirty-five years of operation.” (See figure on page 5).

Neither flooding nor water deficits can be eliminated completely. The simulation showed that, in present circumstances, at least four days of flooding and an agricultural water deficit of at least 45 million cubic meters are unavoidable, however the dam is operated. Furthermore, these are independent minima, not attainable simultaneously. Flooding could only be minimized at the cost of high deficits, and vice versa.

In 1982 the proposed operating rule was programmed onto a microcomputer, and this has since been used by the reservoir manager to support his daily decision on the water release.

Flood Protection in Como

The second proposal was a simple reduction in the statutory upper limit of the active storage to reduce flooding. This would be a convenient and costless method of keeping high water levels down. The proposed operating rule suggested that at certain times of the year the dam gates should be fully opened 30 cm below the lake water level at which the licensing act stipulated they must be fully opened to protect against flooding. It was found that this new measure could cut the number of days of flooding by up to a third without unacceptable consequences for agriculture. A few months after the presentation of these results, the Italian Ministry of Public Works decided to reduce this upper limit by 30 cm and also to reduce the lower limit in partial compensation to the downstream users. This revision to the act obliges the manager to follow the proposed operating rule by opening the dam gates fully when the lake reaches this water level.

The third proposal to alleviate flood damage was to restore, at least partly, the conditions in 1946, when the square was over 60 cm higher. The Italian team made a study of the degree of protection required. Professor Rinaldi summarizes the results. “We found that raising the square to its original level, in conjunction with the new operating rule, could limit the flooding to less than one day per year on average. On the other hand, if the square sinks further, flooding would increase drastically. Twenty days a year under water would be unavoidable if the square sinks by a further 20 cm. This makes protection of the square virtually mandatory if the subsidence worsens, even under present conditions, it seems desirable.” These results were presented to the Municipality of Como. Funds have now been allocated to raise the square and the lakeside road, and the work should soon be done.

The manager occasionally deviates from the release suggested by the microcomputer, when he has information relating to likely future inflows, or about actual water demands — a forecast of a long dry spell, for example. Together with Dr. Esko Kuusisto of the National Board of Waters in Finland, the group
made a study of the improvement in the operation of the reservoir that could be expected if information on the state of the catchment area were available to the manager in real time; that is, if the manager had an indication of the likely inflows before he decided the release. Important factors are the snow cover in the Alps between February and June, the depth of the water table all year round, and the previous two days' rainfall between March and November. They found that information on each of these three factors would help the manager, and the use of information on all three together would be almost as good as having a perfect two-day forecast of inflows. Revised software that incorporates these three factors as inputs was then proposed to the manager and programmed onto his microcomputer.

The regional authority in Lombardy has recently earmarked US$300,000 to develop an automated information-gathering network, to buy a mainframe computer that will be online twenty-four hours a day, and to automate the operation of the dam gates. The computer cannot replace the manager, however, since there will always be other subtle factors that he must take into account.

The Risk-Averse Approach

The discussions between the scientists and the reservoir manager revealed that the manager is often most concerned with avoiding extreme failures of the system during severe hydrological episodes, even at the cost of a somewhat worse performance in terms of the average values of the indicators. In the second study at IIASA, together this time with Dr. Sergei Orlovski, the analysts developed another operating rule that took into account this risk-averse attitude.

This study followed an approach first used in managing the multiple reservoir system in the Volga river basin in the USSR. The approach was termed a "min-max" approach, because the objective is to minimize the maximum ill effects rather than to achieve the optimum mean values of the indicators. "This gave us a two-objective optimal control problem in which the longest-lasting flood and the greatest water deficit were to be minimized," says Dr. Orlovski. "Obviously, the manager's decisions depend on what future inflows he expects. Rather than using statistical methods to represent these, we modeled the manager's image of the future using a set of yearly inflow sequences that included the most critical hydrologic years in the reservoir's operational history."

The operating rule obtained with the min-max approach gave worse long-term mean values of the indicators (see figure on page 3), but it did perform marginally better in severe episodes. It does guarantee the avoidance of drastic failures, and it will be programmed onto the microcomputer so that the manager can consider the releases suggested by both operating rules before making his decision.

An Effective Systems Analysis

Building the dam in 1946 made it possible to improve on Providence. However, when the square in Como began sinking in the 1960s, drastically increasing the flooding, criticism inevitably mounted. This caught the manager between the conflicting interests of the residents and authorities in Como and the agricultural water users. The very effective study at IIASA made the tradeoffs involved explicit, and the new approach to managing the reservoir that was developed has succeeded in both alleviating flooding and improving the water supply for irrigation. It also established the importance of information on the state of the catchment. Furthermore, the study makes a significant contribution to the theory of storage control problems with uncertain supply and multiple objectives.

Derek Delves

Further information on the Lake Como management study can be found in the following papers, available from IIASA: The Management of Lake Como, by Giorgio Guariso, Sergio Rinaldi, and Rodolfo Soncini-Sessa; The Value of Information in Reservoir Management, by Giorgio Guariso, Sergio Rinaldi, and Przemyslaw Zielinski; and A Risk-Averse Approach for Reservoir Management with Application to Lake Como, by Giorgio Guariso, Sergei Orlovski, and Sergio Rinaldi.
Quality Control in the Service Sector

Giandomenico Majone offers some suggestions on improving the quality and productivity of the organizations and bureaucracies providing our social services.

Quality in economic life generally has not been sufficiently explored, while in the service sector quality control must surely be ranked among the most important, and least understood, problems facing analysts, policy makers, and the public. The reason for this lies in the peculiar characteristics of the services.

Most industrial products are easily measurable in physical units, are highly standardized, and can be unambiguously categorized as "good" or "defective". The products of many of the services are intangible, with a high degree of variability in quality and efficacy. For many services, particularly the personal services which are so important for the general quality of life, clear quality standards are not available. The lack of standardization is related to the inherent variability of the "human inputs" and to the intrinsic complexity of the product. Thus, everything a medical doctor does is some combination of technology — using the products of medical science that are effective in preventing or altering disease — and acts that provide reassurance or support to the patient. The two functions may be separated conceptually but they are combined in practice, so that the quality of the service depends crucially on both components. Even if the technological component could be standardized and objectively evaluated, this would not provide an adequate measure of overall quality. Such factors explain why the techniques of statistical quality control used in industry have found only limited application in the services.

Another characteristic of the services is that there is no well-defined "production function", no standard technology transforming inputs into desired outputs. This characteristic is related to the phenomenon of producer ignorance, illustrated in the development of many of the services provided by the modern welfare state. For a variety of reasons, ranging from ideology to the influence of foreign models, a strong demand for some particular service arises, with pressures on the government to make adequate provisions. As soon as funds are made available, people step forward claiming to have the skills needed to produce the new service. In many cases this leads to the creation of new professions or quasi-proessions, with special academic training, journals, and officially recognized administrative positions. What has happened is that demand for a service has arisen in advance of real knowledge of how to satisfy it. As Professor Albert Hirschman points out, the problem here is not so much one of protecting or educating the consumer, as in the case of consumer ignorance, but of educating the producer, by providing the means of evaluating performance and learning from mistakes.

Another consequence of the lack of a well-defined production function becomes evident when the supply of certain services is suddenly expanded. Whereas in industry or agriculture production can be expanded only if certain basic proportions among the factors of production are respected, the provision of many human services can be expanded even in the presence of serious bottlenecks and imbalances in input proportions, as shown by overcrowded classrooms, long waiting times for med-
The closeness of the relationship between producer and consumer is another distinctive feature of the services. In fact, in many cases the relationship is so close that one may speak of coproduction — the final outcome is jointly determined by the input of the primary provider of the service and the input of the client. This makes it difficult to evaluate the separate contributions. One can never rule out the possibility that an unsatisfactory result may be due not so much to deficiencies of the producer as to inadequacies of the consumer, such as insufficient cooperation, noncompliance, inability to provide relevant information, lack of trust, and so on. Coproduction not only complicates the task of quality evaluation, but also introduces an element of moral hazard in the producer—consumer relationship: the possibility of shifting part of the blame for a failure to inadequacies of the coproducer may induce the primary producer to do less than the best.

Coproduction usually, and somewhat paradoxically, appears in conjunction with another characteristic of many services: the fact that information is asymmetrically distributed among producers (for example, doctors or teachers) and consumers (patients, students). Some sociologists define the professions as those occupations in which *caveat emptor* cannot be allowed to prevail. The need for trust in the relationship between professional producers of services and their clients is directly related to the fact that the former have considerably more knowledge about their products than the latter.

At the same time, trust in the technical competence and moral integrity of the producer of a service implies at least a partial surrender of consumer control. This situation sets the stage for one of the classical dilemmas of professionalism — how to preserve the moral authority of the professional while providing sufficient protection to the client.

To sum up, intangibility and lack of standardization of the products, producer ignorance, coproduction, asymmetric distribution of information, and the need for trust in the producer—consumer relationship are essential characteristics of most services and pose serious problems of quality control. But, of course, different methods of quality control are available.

**Alternative Modes of Evaluation and Quality Control**

The term control is used here to denote a process of monitoring and evaluating performance in terms of some standards of quality. In assessing the performance of people and their technologies there are basically only three elements that can be controlled, monitored, or evaluated: the inputs, the processes or behaviors that transform those inputs, and the resulting endstates or outputs. Correspondingly, we can distinguish three basic modes of control — by inputs, by process (or behavior), and by outputs.

In comparing these three modes the starting point is essentially arbitrary, but it is perhaps natural to take output control as the basic mode. Indeed, for many people output control is control tout court. It seems obvious that if one is interested in evaluating the quality of a certain performance, one should look at its consequences, its outputs, its results. What is less clearly understood is the stringency of the conditions that have to be satisfied for this mode of control to be feasible. First, it must be possible to evaluate the outcome by unambiguous and easy-to-apply criteria. In addition, the output measure should be a "sufficient statistic" with respect to the relevant measure of performance: the measure must contain all the information necessary for a full evaluation. In the case of joint or interdependent activities, it should also be possible to measure separately the individual contributions to the final output. Finally, in situations when one wants to distinguish between good and bad managerial or professional decisions, it may be necessary to separate
results that are due to chance from those that can be attributed to foresight.

In a competitive market situation all these conditions are satisfied, at least approximately. Hence market transactions are readily evaluated by the price system. But most professional services are not carried out exclusively on the basis of an impersonal cash-for-service exchange as in pure market transactions. As Professor Kenneth Arrow has remarked, doctor and patient behave more like coworkers than like a large manufacturer and his remote and unseen customers.

The temptation to insist on output evaluation regardless of the particular nature of the situation may actually produce disfunctional consequences in terms of the quality of performance. If the number of clients interviewed, for example, becomes the sole evaluation criterion, the interviewer may try to see as many clients as possible, not try to provide the service that is the true objective.

Similarly the practice of using preset output goals in evaluating medical services carries with it the danger that the goals are interpreted, not as guidelines, but as commandments to be violated at the physician’s risk. The physician begins to practice “defensive medicine”, being afraid of departing from the codified conventional wisdom.

What can be done when output control is unsuitable? Careful monitoring of process (or behavior) seems to be the natural candidate as the second-best solution to the control problem. In fact, given complete knowledge of the production function of an organization, process control is just as effective as output control: the quality of the output can be correctly predicted by observing the production process. The choice between these two control modes depends on considerations of relative costs, administrative convenience, the human factors of morale, atmosphere, burden on supervisors, and so on.

Ceteris paribus, output control is more efficient since (a) it requires less information; (b) it evaluates performance less obtrusively as there is less direct interference with people’s activities; and (c) it is relatively less susceptible to hierarchical attenuation since, being typically expressed in quantitative terms, it can be more easily compared across hierarchical levels and across functions.

On the other hand, evaluation based on direct observation of process can be more subtle, flexible, and informative. An experienced observer can evaluate process in terms of the entire strategic situation in which it takes place, can distinguish foresight and skill from mere chance, and can appreciate style and elegance of execution in a way that no quantitative output measure will ever be able to match. However, the subjective qualities of this mode of assessment may cause severe problems of communication (since the conclusions cannot be easily transmitted across hierarchical and functional lines) and of morale (the evaluation may appear to be unfair or ill-informed) unless the personal judgments can be related to a well-developed system of principles of professional or craft practice. Moreover, process control presupposes that process can be directly observed and interpreted by an outside evaluator. But when the essential criteria and methods of work are not only qualitative but are even difficult to articulate in explicit terms, outside evaluation must be replaced or at least complemented by internalized methods of control.

In the professions, in scientific research, and in education the key mechanism for the evaluation of quality is peer review and control. Performance evaluation takes place through the kind of subtle reading of signals that is possible among coworkers sharing the same values and a specialized language, but which cannot be translated into specific, objective measures. This means that there is sufficient information to promote learning and effective cooperation, but that the information is largely “tacit” and cannot be articulated in explicit standards and rules of behavior. For this reason the collegium must rely on careful screening of its members (a form of input control), on long apprenticeships and other socialization processes, and on widely shared values and beliefs.

Actual organizations usually rely on more than one mode of control. For example, the for-profit firm, being internally organized along hierarchical lines, makes use of a number of standard bureaucratic control devices while its research department may be organized along collegial principles. Nevertheless, the essential control on the firm is the external one exercised by the market; every activity, therefore, must ultimately be submitted to the final test of profitability. As long as the market can unambiguously assess the value of the firm’s products, the process by which those products are obtained is largely immaterial: only results count. Hence, rules and procedures are adhered to only as long as convenient, and are modified on an ad hoc basis if the situation seems to demand it.

A public bureaucracy does not usually face a market for its outputs and, consequently, the prevailing mode of control is different. Rules and procedures must be scrupulously respected, even when efficiency considerations would suggest deviations. On the other hand, professionals working in bureaucratic organizations aspire to self-evaluation and self-control according to collegial principles. This explains the continuous tension between the professional and the bureaucratic orientation, and the emergence of a “community within a community”.

Professor Giandomenico Majone holds the Chair of Mathematical Statistics at the University of Calabria, Italy. A former consultant to the National Institute of Planning in Italy, he joined IIASA’s health services project in 1974. Since returning to IIASA in 1982 after teaching in Italy, Canada, and the USA, Professor Majone has led the research undertaking on the service sector.
Because elements of each control mode are present in most actual organizations, the problem of control design is finding the right mixture for any given set of tasks and environmental conditions. At the present time, and for a variety of reasons having to do both with technological developments and with broad social changes in modern societies, we are witnessing a shift of emphasis from market and bureaucratic modes of control toward forms of self-evaluation and self-coordination clearly inspired by the model of the collegium.

**Matching Structure and Function**

The comparison of alternative modes of evaluation and control strongly suggests that there cannot be any single approach to the issue of quality control in the services. Rather, the institutional problem is finding the right mix — one which matches mode of control and organizational form with the special characteristics of each individual service activity. Mismatches are unavoidable when the same institutional arrangements and evaluative criteria are imposed on qualitatively different activities.

An example is the bureaucratization of professional work when the services are sponsored by the state acting as "third party" mediator between professionals and clients. The immediate consequence of mediation for the professionals is the creation of a guaranteed clientele.

Under state mediation, a service is made available on the basis of citizenship or some other characteristic, such as need, typically determined through administrative tests, rather than by the professional or the client. The personal, fiduciary relationship between professional and client is thereby weakened, and technical and ethical questions tend to be removed from professional control. Professionals are increasingly incorporated within the organizational framework of governmental agencies, with a corresponding multiplication of administrative duties. One of the important consequences of bureaucratization is the superposition of hierarchical organizational forms over collegial relationships, and the consequent weakening of autonomous professional controls.

The ideology of state mediation stresses overall efficiency of the service delivery system rather than quality of the individual treatments, and social service rather than the personal service orientation of professionalism. The emphasis is on quantitative measures of outcomes, on extensive recording, and on elaborate statistics. Thus, as the evolution of the institutions of the welfare state indicates, state mediation may lead, sooner or later, to the bureaucratization of professionals, to standardization of their tasks and work roles, and to the depersonalization of the professional–client relationship. Predictability of results and adherence to rules become the overriding criteria of evaluation and control. I argue that it may be possible to reconcile the social goals sought by state mediation with the preservation of essential professional values and attitudes, by making greater use of the nonprofit form in the organization of personal services.

The nonprofit goal reduces the tension between the pursuit of professional excellence and the requirements of economic management. Work control in many nonprofit organizations, such as teaching hospitals and private schools, is largely in the hands of the professionals, who also have a major role in running the organization and hiring and promotion decisions. The nonprofit nature of a service organization tends to reinforce the fiduciary component in the relationship with clients. Professional mobility is also favored by the emphasis on a qualitative product.

This is not to say that all professional services ought to be organized in this way. The frontier of professional research and experience is continuously expanding, leaving behind large areas of practice where standardization of methods and procedures is possible. In such cases an efficient market for certain types of professional services may develop, with access for the poorer members of the community ensured by special arrangements like vouchers or subsidized insurance. The conditions under which professionalism, as a specific type of occupational control, is socially and ethically desirable must be submitted to constant verification.

High quality service is not automatically assured by shifting to the nonprofit form as an alternative to governmental and private for-profit service provision. Market incentives and "voice" — protest, criticism, persuasion — may still be needed to push the organization to produce at the highest level of quality consistent with the available resources.

Decentralization, citizens' participation in decision making, systematic performance evaluation, and interagency competition can be effective means of improving service quality within a governmental system of service provision. Nor are these solutions mutually exclusive. In fact, quality control is best assured by a plurality of organizational modes — for-profit, nonprofit, and governmental — and of control mechanisms — market, bureaucratic, professional, political. Any improvement in the match between institutional arrangements, controls, and individual preferences leads to an increase in social efficiency.

<table>
<thead>
<tr>
<th>Mode of control</th>
<th>Organizational type</th>
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<tr>
<td>Output</td>
<td>Market transactions; for-profit firms</td>
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<tr>
<td>Process/behavior; Input control</td>
<td>Public bureaucracies, and bureaucratic components of for-profit and not-for-profit organizations</td>
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<tr>
<td>Collegial</td>
<td>Professions, crafts, nonprofit organizations</td>
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Various modes of control and evaluation related to the institutional arrangements in which they are most commonly found.

This is an adaptation of a presentation by Professor Majone at the IIASA International Forum Meeting "Structural Change in the Service Sector" held at the Institute in July 1983.
Climate and Energy Systems

Jill Jäger analyzes the possibility of undesirable — and perhaps even irreversible — climate changes due to energy conversion and use in her book *Climate and Energy Systems: A Review of Their Interactions* (John Wiley and Sons, © 1983 IASA), excerpts from which follow.

The climate system is very complex. It consists of the atmosphere, the oceans, the ice and snow cover, the land surface, and the terrestrial biota. These components interact with one another through processes such as evaporation and wind stress. For example, the atmosphere exerts wind stress on the ocean surface; the ocean surface water evaporates into the atmosphere; the land surface exchanges sensible heat with the atmosphere, and so on. Because of these interactions, changes in one part of the climate system can lead to changes in another part. For instance, changes in the ocean surface temperature in a particular region can lead to changes in the atmospheric storm tracks, leading to changes in temperature, rainfall, and other climatic variables downstream. Thus climatic variations can be a result of feedbacks between the variables within the air, water, and ice. One feedback loop that is often described is the ice-albedo feedback loop, in which an increase in the amount of solar radiation leads to a decrease of ice cover, giving a lower reflectivity, so that more radiation can be absorbed and more ice melts. This is a positive feedback loop. There are also negative feedbacks.

As a result of natural forcing mechanisms, climate has changed and is changing on all time and space scales. On the global scale the climate is known to have changed on a very long (geological) time scale. About 20,000 years ago the earth was experiencing a glacial period with large continental ice caps in North America and Europe. On a shorter time scale the northern hemisphere was on the average somewhat cooler during the first half of the nineteenth century than at present, a warming occurred until 1940, a cooling followed until the middle of the 1960s. Since then there is some evidence of a warming trend.

Present understanding of the complexities of the climate system and knowledge of the changes that have occurred in the past indicate that the climate can be sensitive to natural and anthropogenic changes in climatic boundary conditions. The question then arises: Will energy systems also perturb the climate system? We have found that such changes could occur because of waste heat release, additions of carbon dioxide (CO₂) and other gases and particles, or because of changes in characteristics of the earth's surface such as wetness, roughness, or reflectivity.

Energy systems could affect climate on the local, regional, or global scale. We have already observed that, on the local scale, climatic variables (for example, temperature and cloudiness) can be changed in the vicinity of a power plant. On the regional scale, urban-industrial areas influence precipitation and cloudiness, not only overhead, but also several tens of kilometers downstream. On the global scale there is no evidence that man's activities have influenced the climate.

One reason for concern about the potential effects of energy systems is the possible undesirability and irreversibility of climatic changes. Thus, we want to be able to predict the effects of energy systems before embarking on an energy strategy that has unwanted environmental consequences.

Unfortunately, it is not possible at present to predict with any reliability the climatic consequences of particular energy strategies or scenarios. It is, however, possible to investigate the sensitivity of the climate system to certain imposed changes and thus to compare the magnitude of the influences of different factors. The main tool for making such sensitivity analyses is the numerical climate model, although climatic analogues can also be useful in sensitivity analyses.

Carbon Dioxide

At present the effect that is thought to be potentially the most serious arises from the release of CO₂ by fossil fuel combustion. Since 1958 accurate measurements of the amount of CO₂ in the atmosphere have been made. The annual average concentration of CO₂ measured at Mauna Loa in Hawaii has increased from just over 315 parts per million (ppm) in 1958 to 338 ppm in 1980. The increase in atmospheric CO₂ concentration is a global phenomenon. It is believed that part or all of this increase is due to the release of CO₂ into the atmosphere by burning fossil fuels (coal, oil, and gas). It has been argued recently that the release of CO₂ as a result of deforestation and soil deterioration, especially in the tropics, has also contributed to the observed CO₂ increase.

The four reservoirs of carbon are the atmosphere, the ocean, the biota, and sediments. There are two possible sinks for the CO₂ released into the atmosphere by fossil fuel combustion: the ocean and land vegetation. The capacity of the oceans to store carbon is tremendous, but the transfer to the deep ocean is slow. Terrestrial vegetation can act either as a source or as a sink of carbon. The main storage is in the forests; it has been claimed that clearing forests is a source of CO₂.

The carbon cycle is very complex. There are a number of reservoirs of carbon with chemical, physical, and biological processes linking them. Numerical models of the carbon cycle are necessary so that predictions of the future concentrations of atmospheric CO₂ can be made. Although there are many uncertainties in the models of the carbon cycle, it is possible to make predictions of the future atmospheric CO₂ concentration, particularly for a period of twenty to thirty years from now. There is a general consensus among oceanographers on how much fossil fuel CO₂ the oceans can remove from the atmosphere. The
role of the biosphere is more uncertain. Deforestation, especially in the tropics, has been a source of atmospheric CO$_2$. Regrowth of forests, particularly in temperate latitudes, and enhanced growth due to atmospheric CO$_2$ increases have been acting as a sink for atmospheric CO$_2$. Theoretical and observational studies of the ocean and terrestrial vegetation suggest that the biota cannot at present be a net source of CO$_2$ as large as the fossil fuel source.

Many studies have made projections of the future use of fossil fuels and the consequent atmospheric CO$_2$ increase. Most projections of the future levels of atmospheric CO$_2$, generally based on models of the carbon cycle and assumptions about energy supply and demand, envisage a continued increase in the amount of atmospheric CO$_2$ due to burning fossil fuels. Many projections suggest that a doubling of the preindustrial CO$_2$ concentration will occur within the next one hundred years. Many studies made with climate models of varying complexity have shown that increased atmospheric CO$_2$ produces a warming of the earth’s surface and of the lower atmosphere. This warming is due to the fact that CO$_2$ is a good absorber–emitter of long-wave radiation. The surface warming is therefore caused by the increased downward emission of long-wave radiation from the CO$_2$ in the lower atmosphere.

Calculations show that doubling the atmospheric CO$_2$ concentration would lead to a net heating of the lower atmosphere, oceans, and land by a global average of about 4 Watts per square meter. There is relatively high confidence that this net heating value has been estimated correctly to within plus or minus 25 percent. Greater uncertainties arise in estimates of the change of global mean surface temperature resulting from the change in heating rate. The present best estimate is that the global mean surface temperature change would be 1.6–4.5 °C for a doubling of the atmospheric CO$_2$ concentration.

A number of measures have been proposed for preventing or removing a “CO$_2$ problem.” They involve reducing the use of fossil fuels, removing CO$_2$ from the gases in power plant stacks, removing CO$_2$ from the atmosphere or ocean, and adopting methods to cause a global cooling to counteract the potential global warming due to CO$_2$. Results of studies made with models of the carbon cycle suggest that reducing CO$_2$ emissions from fossil fuel combustion could have a considerable effect on the atmospheric CO$_2$ concentration. Varying assumptions regarding the level of fossil fuel use were shown in one study to give an atmospheric CO$_2$ concentration in the year 2100 ranging between 1,500 ppm (by volume) and less than 400 ppm (by volume). Several technologies are available to reduce emissions of gases and particles from power plants; however, they generally add to the cost and reduce the efficiency of the power plant. Technologies are also available to remove CO$_2$ from the atmosphere and ocean, but for most of the processes more CO$_2$ would be generated than recovered if a coal-burning power plant were used to supply the required electrical power. Options for disposing of captured CO$_2$ include disposal in the deep ocean, burial in oil and gas fields, fixation in natural clay, or disposal in outer space.

A further approach to CO$_2$ control is to recover CO$_2$ and reuse or recycle it. The most discussed use of recovered carbon is its conversion into liquid or gaseous fuels using a nonfossil energy source. Most of the suggestions for manipulating climatic boundary conditions to counteract a CO$_2$-induced warming are speculative and the engineering feasibility has not been thought out. Since it is impossible to predict at the present time what the effects of any large-scale modification scheme would be, it would be irresponsible to tamper with the climate system deliberately.

If the atmospheric CO$_2$ concentration continues to increase and climatic changes either occur or can be reliably predicted, there are a number of potential responses. In any event, the climatic changes would not be uniform over the globe and questions of equity arise because some regions may be seen to benefit (such as by more rainfall in presently arid areas), while others may be seen to suffer (such as by less rainfall or higher temperatures in hot, arid areas). The CO$_2$ question is an interdisciplinary issue that needs international cooperation.

### Waste Heat Release

When averaged over the globe, the amount of heat released by human activities is a small fraction of the solar radiation absorbed at the earth’s surface. The global average energy use is one ten-thousandth of the solar energy absorbed at the earth’s surface. However, at individual places on the earth’s surface the heat release due to human activities is of the same order of magnitude as or larger than the absorbed solar energy. Assuming the unlikely values of a global population of 20 billion with a per capita consumption of 20 kilowatt-years per year, we find that the global average heat release would be about 0.5 percent of the global average solar radiation absorbed at the earth’s surface, giving a global average surface temperature increase of around 1 °C.

Since, however, waste heat release is and will be concentrated in certain regions, it is more important to look at the effects of such sources than at the effect of a globally distributed source.

There are several published reviews of the atmospheric effects of power plants on the local scale. The most frequently observed change is due to low stratus or fog formation in the plumes from cooling ponds and towers. There are only a few reports of precipitation enhancement in the vicinity of power plants, and temperature effects also appear to be negligible. The maximum amount of electrical power currently generated at a single power station is about 3 gigawatts (thousand megawatts) electric (GW(e)) and the atmospheric effects of current heat dissipation rates are not serious problems, especially beyond the confines of the power station, provided that efforts are made to design the facility such that downwash is eliminated, drift is minimized, and plume rise is maximized.

In contrast to the present dispersed sites for power generation, some proposals have been made to build more than one
The Effects of Particles and Gases Other Than Carbon Dioxide

In addition to releasing CO₂ and waste heat into the atmosphere, energy systems can influence the atmospheric concentrations of other gases and particles. Combustion of fossil fuels releases particles directly into the atmosphere; particles are also formed from the gaseous products of combustion. The effects of particles on the earth-atmosphere radiation balance, and thus on such variables as global surface temperature, are extremely complex. They depend on characteristics of the particles, such as shape, size, and radiative properties. The location of the particles with regard to their height in the atmosphere and the radiative properties of the underlying surface are also important. Particles also can change horizontal and vertical temperature gradients. For instance, man-made particles in the lower atmosphere generally (all other factors being constant) warm the lower atmosphere and cool the earth's surface, thus changing the vertical stability. Particles also influence the reflectivity of clouds formed with the particles as cloud condensation nuclei. The entire set of radiative, thermodynamic, and dynamic effects of particles can be assessed ultimately only with the aid of suitably detailed climate models, which can predict cloudiness and consider cloud-radiation interactions. Particles can act as cloud condensation nuclei; there is evidence of increased cloudiness and precipitation as a result of increased atmospheric particle loading.

Sulphur dioxide (SO₂) is also added to the atmosphere by man's activities, including burning fossil fuels, and it can have climatic effects. It has been estimated that, if sulphate from sea spray is ignored, 60 percent of the atmospheric sulphur is anthropogenic. Calculations have shown that the scattering of radiation by sulphate aerosols is equivalent, when spread over the northern hemisphere, to a cooling of 0.03–0.06 °C. However, more detailed studies, taking into account such factors as infrared radiation, cloudiness, and radiation absorption by sulphate-containing aerosols, are required before an evaluation of the climatic effects of regional concentrations of SO₂ particles can be made.

A further gas with potential climatic impacts is nitrous oxide (N₂O). It has been calculated that by the year 2000, the greenhouse effect due to increasing atmospheric N₂O from using fertilizers and burning fossil fuels may be about 40–50 percent of that due to increasing CO₂, while by 2050 it may be about 20–30 percent of the CO₂ effect. Other man-made trace gases also have a greenhouse effect and could cause a warming of the earth's surface if their concentration continues to increase. The gases N₂O, methane (CH₄), and ammonia (NH₃) from fertilizers and fossil fuels and the chlorofluorocarbon gases used in spray cans and as refrigerants have the most significant potential effect. This is, however, less than that calculated for CO₂ and water vapor. Further studies have shown that tropospheric ozone also increases owing to fossil fuel sources of carbon monoxide (CO), nitrogen oxide (NO), and CH₄. Tropospheric ozone also has a greenhouse effect. It is estimated that the combustion of fossil fuels is a source of CO, CH₄, and NO that is about 25 percent of the natural source. A continuation of the present growth rate of emission of these gases has been calculated to lead to doubling the tropospheric ozone concentration in the next century, giving a global average surface temperature increase of 0.9 °C. It has been estimated that anthropogenic sources of trace gases other than CO₂ may contribute as much as 40 percent of the surface warming to the combined surface warming effects of CO₂ and these gases. It is therefore obvious that trace gases other than CO₂ could play a significant role in any potential climatic changes due to man's activities...

In the case of the evaluation of the effects of man-made particles, the studies are much more preliminary and even the direction of potential global changes remains uncertain. The potential effects of trace gases also have been studied mostly with one-dimensional climate models. However, the predicted effects are essentially an enhancement of the CO₂ effects, so that the lack of depth of study is not as serious as it is in the case of particles.

Effects of Changes in the Earth's Surface Characteristics

A number of technologies exist or have been proposed for the use of renewable (mostly solar) energy sources. Many of these technologies involve changing the earth's surface characteristics. For example, solar thermal electric conversion (STEC) using the “power tower” concept involves installing arrays of steerable mirrors on the ground. They would change the surface
energy balance, surface roughness, and perhaps the surface wetness if the area were paved. Likewise, hydropower production could require flooding an area, with consequent changes in surface characteristics. Biomass conversion could require large plantations of trees, or irrigation.

The question then arises of whether these changes in boundary conditions could be large enough to influence local, regional, or global climate. Since many of the solar energy conversion schemes are likely to be deployed only on a small scale in isolated regions, the effects are likely to be very localized and to be very dependent on local conditions.

For the effects of STEC plants, rough estimates suggest that the effects on the surface energy balance would not lead to a change in the amount of heat added to the atmosphere but in the manner in which it is added. The influence of such energy balance changes has been investigated using a two-dimensional mesoscale model of the atmosphere. It has been found that a hypothetical STEC plant in southern Spain, generating about 30 GW(e), increased local cloudiness and precipitation in summer simulations.

Photovoltaic cells could be deployed in a number of ways, ranging from arrays of cells on roofs of houses to modules of all arrays for a central power station. At present the use of photovoltaic conversion in a decentralized fashion appears to be the preferred option, in which case local climate effects would not differ in magnitude from those currently observed in urban areas.

Biomass can be converted to solid, liquid, and gaseous fuels from numerous sources and by many technologies. This diversity means that no simple evaluation of the local and regional climatic effects of biomass conversion can be made. Probably the largest effects could be expected to occur with forest plantation areas, since forests have a significant influence on the exchange of water between the earth's surface and the atmosphere and a large dynamic interaction with the atmosphere. Particle emissions to the atmosphere due to biomass conversion schemes would probably not contribute significantly to the presently estimated anthropogenic inputs to the atmosphere.

The main effect on local climate of wind energy conversion systems is likely to be on a microclimatological scale unless huge turbine arrays are considered, which seems unlikely. It has been suggested that there might be some slowing of the wind for a short distance downwind of an array of windmills, but that the wind would rapidly accelerate because of the downward transport of momentum from the stronger winds aloft.

Since most renewable energy conversion schemes that could be used on a large scale are still in the development stage, their deployment on a scale large enough potentially to influence global climate will, in any case, occur in the distant future. Moreover, the detailed physical characteristics of potential large-scale systems are not well defined. It is, therefore, unrealistic to examine potential climatic effects of specific scenarios for the large-scale use of these technologies. It is possible, however, to describe the general types of effect that could arise due to large-scale changes in surface energy balance, roughness, and hydrological characteristics (due, for instance, to large-scale use of STEC, photovoltaic conversion, or biomass plantations) or due to large-scale changes in ocean surface temperatures from ocean thermal energy conversion (OTEC) systems. A number of model studies have indicated that large-scale decreases in surface albedo lead to increased cloudiness and rainfall over the perturbed area with further effects on the general atmospheric circulation. Large-scale roughness changes could influence the atmospheric circulation due to changes in the transfers of momentum, heat, and moisture in the boundary layer. Large-scale anomalies in surface wetness could lead to effects on the upstream and downstream atmospheric circulation. Model and observational studies indicate that large-scale ocean surface temperature anomalies, which could occur with deployment of OTEC systems, can have a significant influence on the atmospheric circulation.

Since most renewable energy conversion will be on a small and decentralized scale with different locations being more suited to particular conversion systems (such as windy areas to wind energy conversion, or sunny areas to direct solar energy conversion), it seems likely that the effects on climate will be at most very localized. The large-scale deployment of some systems, which would take place in any event in the distant future, could cause more extensive and thus more significant changes in the earth's surface boundary conditions and thereby have a larger climatic effect.

How to Cope

With regard to the present state of knowledge about the interactions between energy systems and climate, it is clear that there is much uncertainty and the tools for studying the climate system have many shortcomings. If the climate were to change as a result of man's use of energy, present studies suggest that the most likely political response would be adaptation, because it does not require investment now to prevent or compensate for changes in the future. If mankind is going to adapt to man-made climatic changes, one may ask whether it is necessary now to put in a large effort to remove uncertainties about potential changes. The answer must be yes! An improved understanding of the potential consequences of human activities would mean that the world would be able to cope better with future climatic changes and might be warned in time of potentially irreversible and undesirable changes. An improved understanding of the effects of climate would help to reduce international tensions in the event of a man-induced climatic change; international cooperation will be required to achieve this improved knowledge. The present uncertainty about the effects of energy systems on climate suggests that energy strategies should be kept flexible and open, so that any changes that might be deemed necessary can be taken into account. Simultaneously, all efforts at energy conservation will reduce the effect of energy systems on climate.
Profile: IIASA Secretary, Jean-Pierre Ayrault

"IIASA is such an important example of international scientific cooperation on the main issues faced by mankind. It is an honor, as well as a pleasure, for me to join the Institute," declares the new Secretary to IIASA.

Jean-Pierre Ayrault, a graduate of the École Polytechnique in his native France, specializes in applied mathematics and data processing. He joins IIASA from the Intergovernmental Bureau for Informatics in Rome, Italy, where he was Deputy Director General.

M. Ayrault has considerable experience in international relations concerning scientific, technical, economic, and industrial matters. He first learned about IIASA as Scientific Attaché at the French Embassy in Moscow, USSR from 1968 to 1971, during discussions with the future IIASA Council Chairman Academician Jermen Gvishiani.

From 1972 to 1977, in France as Assistant to the Director of the Research Institute for Informatics and Automation, in charge of international scientific relations, he helped establish the European Informatics Network.

M. Ayrault was Deputy Chief of the International Service, Directorate for Electronics and Information at the Ministry of Industry from 1980 to 1981, and was a representative of the French Government and delegate to several European Community Commission committees as well as to several Commissions on bilateral cooperation with socialist countries.

Profile: Chester L. Cooper
Special Advisor to the Director

Dr. Chester L. Cooper, with wide experience in international affairs, American policy formulation, and research management, has joined the Institute as Special Advisor to the Director. He takes on the responsibilities of former Deputy Director Allan Hirsch, who has returned to the US Environmental Protection Agency, and he is also leading the forthcoming IIASA Forum on Science and Public Policy.

Meetings

The Institute was one of the sponsors of the International Conference on the Sensitivity of Ecosystems and Society to Climate Change held in Villach, Austria. Research findings were reported by the IIASA project investigating the impacts on food production in marginal agricultural areas from short-term climatic variations and the likely long-term effects of carbon-dioxide-induced climate change. This project is an integral part of the World Climate Program of the United Nations Environment Programme, which also sponsored the Conference with the International Council of Scientific Unions, the World Meteorological Organization, and the Austrian Ministry of Health and Environmental Protection.

A report is being prepared on the IIASA work assessing the socioeconomic impacts of climate changes in cold marginal areas.

Planning organized by IIASA and the Institute for Regional Economic Planning of Tuscany (IRPET). The just-completed IIASA Tuscany case study was presented, with an international appraisal of methods and practical experiences from IIASA regional development case studies of Notece, Poland; Skåne, Sweden; Silistra, Bulgaria; and Tuscany, Italy.

On-line demonstrations of decision support systems, including the IIASA-developed DIDIASS, were featured during an International Workshop on interactive decision analysis held at the Institute, which discussed the use of several operational systems and theoretical mathematical work for further developments in this new field.

At a seminar sponsored by the USSR Academy of Sciences, the Lenin Agricultural Academy, and IIASA at the Agricultural Research Institute in Stavropol, USSR applications to the Stavropol region of models developed by IIASA and Soviet scientists for agricultural planning and development were presented. This is one of the case studies in an investigation of the technological transformation of agriculture in terms of the interaction of resource limitations, technological options, and environmental consequences.

The Fourth IIASA Task Force Meeting on Input-Output Modeling, including the international network involved with the INFORUM system of models, emphasized inter-industry structural change and how individual sectors have adapted to recent changes in the economic environment. The proceedings will be published shortly.

Teams from collaborating organizations and agencies met with IIASA scholars in the Forest Sector project in Sopron, Hungary through the courtesy of the Hungarian NMO to discuss the development of the global model of forest resources, production, and trade in forest products. A preliminary version of this model is expected to be operational at the beginning of 1984.

A short course in the new multistate demographic methodology developed at IIASA was given in Primorsko, Bulgaria for population analysts in the centrally planned economies. The Bulgarian NMO, which sponsored the course with the Institute, is also publishing a Russian course handbook.

IIASA, the Finnish NMO, and the Technical Research Center of Finland, with five Finnish companies -- NOKIA Machinery, Oy Stromberg AB, Kone Corporation, Velmet Automation, and Imatron Voima -- jointly sponsored a Task Force Meeting of international experts in Helsinki to consider Human Factors in Innovation Management within industrial enterprises.

Industry officials, analysts, and scholars met at an Institute Workshop to explore the effects on the international coal-fuel minerals market of the rapid growth of state enterprises in developing countries for mineral mining and processing. A book is being prepared.

New Titles

IIASA Collaborative Proceedings Series


Research Reports

RR-83-19 Trade-off Between Cost and Effectiveness of Control of Nutrient Loading into a Water Body. I. Bogardi, L. David, and L. Duckstein.


All IIASA publications can be ordered from the Publications Department, IIASA.
Director's Corner: **Surprise?**

Why should an applied institute, like IIASA, indulge in a mathematical and empirical analysis of the dynamics of biological macrosystems?

It seems unarguable that the rule for applied research should be that he who pays the piper calls the tune. Certainly in the past decade, many countries have developed policies that emphasize the consumer-supplier relationship for short-term benefit. But however much pays the piper calls the tune, it is equally a policy that reinforces tradition. If initiated at a time when changes and innovations are needed, its very success can simply produce more and more efficient dinosaurs, and larger and larger surprises.

Much of the past decade of research and development has this character. Its consequence is transparently evident in the economic difficulties and resource and environmental issues of recent years. The result has been increased perception of surprises by expert, policy maker, and citizen. It has led many to lose their sense of certitude.

Surprises of this kind are ones of perception. They emerge as reality departs from expectation. They emerge because the very success of traditional methods and concepts generates not only products but paradox. As the paradoxes accumulate, the world begins to seem increasingly complex, vulnerable, and ungovernable.

Perhaps that is the time, if not earlier, for some modest "countercyclical" investment in research - so not much with an emphasis on application to achieve better solutions, but on paradox to provide new understanding.

That is scarcely a luxury or intellectual indulgence. Now more than ever, the key issue for man's future concerns the ways to deal with surprise - with the unknown and the unexpected.

The history of applied science has been one of trial-and-error approaches to the unknown. Theory and concepts have suggested the questions to pose, the form of the trials, and the kind of results to interpret. The errors, when they are detected, provide additional information for modification of subsequent efforts. Such "failures" provide the experience and information upon which new knowledge grows. But the increasingly intensive and extensive nature of our trials threatens errors larger and more costly than society can afford. We need either new questions, or smaller errors.

We seem, however, to have little choice. What were once local environmental problems have become international. Acid rain is an example. And what once were international problems promise to become global ones. The possible effects of increasing CO₂ concentrations on climate is an example. Similarly, the web of international economic dependencies has expanded. The past motivation has been to achieve stability of national economies. The present fear is for the vulnerability of the whole interrelationship.

And I have not spoken of the pathology of nuclear arms policy.

Reality is not perceived, it is conceived. Many of our perceptions of surprise, of complexity, and of vulnerability emerge from our conceptions of stability - of the way the systems we live with and manage respond to unexpected events. A system which is globally stable is admirable for blind trial-and-error experimentation. It will always recover from any perturbation. It is a paradigm of an infinitely forgiving Nature.

But if the system in fact has several regions of stability, then Nature can seem to play the practical joker rather than the forgiving benefactor. Policies, trials, and management will seem to operate effectively so long as the system remains within known stability domains. However, if the system moves close to a stability boundary, incremental disturbances can precipitate radically altered behavior.

In some instances that can be seen as a "sharp" surprise detected by many. Examples include efforts to control eutrophication, pest outbreaks, flood damage, and forest fire. In each instance the original policies were often classically myopic. They succeeded in the short run but at the price of increased vulnerability to the very problems the policies were meant to control. But however sharp and extreme the failures, their consequences were largely local. Both the visibility of the failures and their localized nature permitted constructive learning.

But there are other instances which ultimately produce sharply altered behavior where changes accumulate slowly. They can accumulate so slowly that man's remarkable adaptive capabilities hide the underlying pathology. The system evolves to become less and less resilient and threatens larger and more extensive failures.

This represents not simply a localized and mischievous Nature. Rather it demonstrates the resilient character of Nature and the consequences of losing that resilience. Systems not only have different stability regions; these regions evolve as a consequence of successful action to constrain variability. Once the resilience is reduced, they can only be sustained by increasing subsidy, increasing knowledge, and increasingly error-free control. They are systems not well matched to human and institutional frailties.

The combination of biology and mathematics has developed striking representations and examples of the full range of such structures. Many are so striking that they have become part of man's world view. As such they have become metaphors for action. Darwinian evolution, the stability of genomes and the development of species, for example, captures the imagination by its very order and explanatory power. So much so, that attention has long been concentrated on the equilibrium and on regulation about it.

But more recently, interest, example, and analysis have shifted from the equilibrium to the limits of regulation, to the existence of stability structures, and to the role of instability and variability in releasing opportunity. That role is best displayed, more rigorously examined, and more useful as a metaphor for understanding in biology than in any other area of science or policy. It provides the basis for understanding present paradoxes and future surprises in an environment somewhat detached from the emotionalism and polarization that characterize so much of present debate.

Why examine the dynamics of macrosystems? Not, certainly, to provide solutions immediately. Rather, to provide better questions.

C.S. Holling