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BOUNDARIES OF ECOLOGICAL SUSTAINABILITY OF PRAIRIE LAKES AND RESERVOIRS

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NWRI Contribution No. 92-55

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MANAGEMENT PERSPECTIVE

This report is a summary of Dr. Barica's presentation at Waterscapes '91 Conference in Saskatoon, June 1991, based on his past work in Western and Northern Region, as well as a recent involvement in ecosystems sustainability research. It suggests that due to high natural input of nutrients from agricultural land and advanced eutrophication, the carrying capacity of many prairie lakes and reservoirs is almost fully utilized and leaves little room for further loads from population, industry or agriculture. This may impose serious constraints on development in the region unless more stringent waste control policies and recycling are introduced. In order to sustain ecosystem integrity, some threshold values of significant parameters are not to be exceeded (i.e., allowable nutrient concentrations and loadings, salinity, algal biomass, mean depth, etc.). The ecological sustainability of prairie lakes can be assessed by examining algal growth. Examples of unsustainable aquatic ecosystems and their breakdown of structure and function were presented, and warning signals and limits of ecological sustainability identified.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Le présent rapport est un résumé de l'exposé de M. Barica lors de la Conférence Waterscapes '91, tenue à Saskatoon, en juin 1991, et qui portait sur ses travaux antérieurs dans les régions Ouest et Nord de même que sur sa participation récente à des recherches sur la viabilité des écosystèmes. Il semble qu'en raison d'un apport naturel élevé de matières nutritives des terres agricoles et d'une eutrophisation avancée, la capacité de nombreux lacs et réservoirs des Prairies est presque atteinte et laisse peu de place à d'autres charges provenant de la population, des industries ou de l'agriculture. Cette situation peut imposer d'importantes contraintes au niveau du développement de la région à moins que l'on applique des politiques plus rigoureuses en matière de contrôle des déchets et que l'on recycle. Afin d'assurer l'intégrité de l'écosystème, certaines valeurs seuils de paramètres importants ne doivent pas être dépassées (c'est-à-dire, les concentrations et les apports de matières nutritives autorisées, la salinité, la biomasse algale, la profondeur moyenne, etc.). La viabilité écologique des lacs des Prairies peut être évaluée par l'étude de la prolifération des algues. L'auteur cite des exemples d'écosystèmes aquatiques non viables et indique la ventilation de leur structure et de leur fonction, et détermine des signaux d'avertissement et des limites de la viabilité écologique.

ABSTRACT

The dynamics of algal growth and algal bloom development in eutrophic prairie lakes and reservoirs offers an opportunity to assess the negative consequences of exponential growth and its sustainable and unsustainable phase. Extreme situations of ecological perturbation and instability, where the structure and function of an aquatic ecosystem breaks down, are demonstrated using summary results from lakes undergoing collapse (crashes) of algal blooms or winter anoxia as a result of unsustainable productivity. Algal blooms provide warning signals during their development and indicate various levels of ecological sustainability. Phytoplankton biomass was found to be a measure of ecological sustainability with chlorophyll a levels less than 50 μg/L being sustainable and over 100 μg/L unsustainable.

Due to high natural input of nutrients from prairie soils and advanced eutrophication, the carrying capacity of many prairie lakes and reservoirs is often fully utilized and leaves little room for further loads from population, industry or agriculture.

RÉSUMÉ

La dynamique de la prolifération algale et de la formation d'efflorescence dans des lacs et des réservoirs des Prairies offre la possibilité d'évaluer les conséquences néfastes d'une croissance exponentielle et de sa phase viable et non viable. Des situations extrêmes de perturbation et d'instabilité écologiques, où la structure et la fonction d'un écosystème aquatique se rompent, sont révélées à l'aide de résultats sommaires provenant de lacs en voie de subir un effondrement des proliférations d'algues ou d'une anoxie hivernale en raison d'une productivité non viable. Des proliférations d'algues constituent un signal d'avertissement pendant leur développement et indiquent divers niveaux d'intégrité écologique. La biomasse du phytoplancton est une mesure de l'intégrité écologique avec des teneurs en chlorophylle a inférieures à 50 ug/L qui sont viables, et plus de 100 ug/L, qui ne sont pas viables.

En raison d'un apport naturel élevée de matières nutritives des sols des Prairies et d'une eutrophisation avancée, la capacité de nombreux lacs et réservoirs des Prairies est souvent presque atteinte et laisse peu de place à d'autres apports provenant de la population, des industries ou de l'agriculture.

INTRODUCTION

Most lakes and reservoirs in the Canadian prairies are naturally eutrophic due to high nutrient loadings from agricultural land, high solar energy input in combination with their shallowness. They frequently develop dense algal bloom in mid-summer, composed mostly of nuisance blue-green algae (usually *Aphanizomenon fl.-aquae, Microsystis* and *Anabaena* species) which seriously limits use of the water use. Some lakes undergo "crashes" of their algal bloom in mid-summer resulting in oxygen depletion and fish die-off (summerkill), while others develop winter anoxia causing the same adverse effect on fish populations (winterkill). Algal blooms can also cause taset and odour problems in drinking water, clog filters in water treatment plants and produce algal toxins which are deadly to cattle and other domestic animals. These catastrophic events provide some indication of the boundaries of ecological sustainability, beyond which the lake ecosystem structure and function breaks down dramatically with devastating impact on lake biota.

Both these phenomena place serious constraints on development in the region where there are already acute water shortages and salinization problems as a consequence of semi-arid climate. This paper presents an overview of the author's previous studies conducted in western Canada, with a focus on sustainable development in the prairie region and the possible implicationsof water quality deterioration from excessive, uncontrolled and unsustainable productivity.

ECOLOGICAL CATASTROPHES IN PRAIRIE LAKES AND RESERVOIRS

Collapses of Algal Blooms (Algae "crashes", summerkill)

Due to high natural nutrient input from the drainage area, all major Canadian prairie lakes and reservoirs are eutrophic. For example, the annual phosphorus loadings for fishing lakes in Saskatchewan range from 3.3 to 25.0 $g/m^2/yr$ (Allan and Kenney, 1978a), which is far in excess of major eutrophic lakes in Europe (2.5 to 4 $g/m^2/yr$, Barica, 1987a). Of this, 2.2 $g/m^2/yr$ (Pasqua Lake) to 6.2 $g/m^2/yr$ (Misson Lake) is natural P loading from the land drainage (Cross 1978). Vollenweider's (1968) limit for eutrophication of lakes with similar mean depth (5 to 15 m) is about 0.5 $g/m^2/yr$ of P. At the same time, spring total N:P ratios, which are characteristically high for oligo- and mesotrophic lakes (10 to 30 in Lake Ontario, Stevens and Neilson, 1987) are low in eutrophic prairie lakes (on average 3 to 6, Barica, 1990). This indicates a severe nitrogen deficiency and suggests why nitrogen-fixing blue-green algae dominate the lakes in the summer.

The growth of algae follows a hyperbolic curve which can be described by the Monod equation describing Michaelis-Menten kinetics (Reynolds, 1984):

$$V_s = V_{smax}S/K(K_s + S) \tag{1}$$

where V_s is the rate of uptake, V_{smax} is the maximum rate of uptake and S is the nutrient concentration; K_s (the half saturation coefficient) represents the nutrient concentration at which the rate of uptake, V_s, is one half of the maximum rate (i.e., $V_{smax}/2$). Comparative growth rates (in terms of cell doublings per day, or the rate of specific increase in cell biomass per unit time, k') have been assumed (and in many cases shown) to conrorm with the Monod equation; thus,

$$k' = k'_{max}S/(K_s + S) \tag{2}$$

Since the nutrient supply and light input is abundant on the prairies, growth of algae progresses exponentially as the number of algal cells doubles about every day. Figure 1 presents three generalized patterns of algal population development in an oligo- to mesotrophic lake (curve 1) a eutrophic lake (curve 2) and a hypereutrophic lake (curve 3). The initial phase of all three growth curves is smooth, progressing from the initial logarithmic stage in the spring to the maximum biomass level, which can be sustained by the given nutrient supply and light input to each lake. Curve 1 represents a steady-state system which, after reaching its maximum biomass and levelling off in mid-summer, gradually declines in magnitude with the season as the meteorological conditions advance toward the fall.

In contrast, curve 2 shows an advanced eutrophic system which exhibits signs of instability as it begins to oscillate, i.e., undergoes partial die-off of the bloom, regenerating some nutrients, which is followed by their quick recovery (Barica, 1974). This erratic system has obviously reached the level of sustainability or surpassed it, and is becoming vulnerable to any external factors (i.e., reduction of light, temperature and/or nutrient supply).

Curve 3 illustrates the ultimate stage of bloom development where the nutrient and energy supply becomes inadequate to sustain the magnitude and the physiological requirements of the bloom (no surface runoff from the basin during the dry season to provide additional nutrients, and limited flux of regenerated nutrients from the anoxic lake sediments). Under these conditions, the entire mass of algal biomass (bloom) collapses and the whole system undergoes dramatic alterations, affecting living conditions of lake biota. This process eventually ends in a catastrophic collapse of the algal bloom with the resultant anoxia leading to total die-off of fish populations and some zooplankton species in the affected lake.

We have studied the mechanism of algal collapses (also termed "crashes") in detail on numerous occasions and arrived at a generalized pattern presented in Figure 2, highlighting changes in the most significant parameters during and after algal collapse. The algal biomass reaches its exponential phase rapidly and continues the growth in this fashion, with the maximum chlorophyll a values exceeding 100 to 200 μg/L. The oxygen levels are high (at supersaturated levels) and the Secchi transparency drops down to only 0.2 to 0.4 m. The ammonia and the soluble reactive phosphate are at near-zero levels at this stage. It is very significant that at this point algae show an acute nutrient deficiency in their cellular composition, and their primary productivity decreases sharply. Within a few days after reaching the maximum, the bloom suddenly dies off and the mass of algae starts sinking to the bottom of the lake. The water clears downward from the surface. Simultaneously, a dramatic drop of dissolved oxygen concentration to zero levels is observed, accompanied by a sudden increase in NH_3-N concentrations (up to 2000 $\mu g/L$ and over), which may reach toxic levels to fish, depending on temperature and pH conditions.

The weather appears to determine when a the dense algal bloom is going to collapse. Healey and Hendzel (1976) showed that *Aphanizomenon flos-aquae* blooms in the advanced stage of their development experience an acute P deficiency. This is accompanied by visible signs of their poor physiological condition, such as pale yellowish colour, clumping of the filaments and water turbidity. This condition may persist for a long or short period of time before a collapse occurs. At this stage, algal cells may respond to any unfavourable change in the environmental conditions by a massive die-off. Normally, sunny and warm prairie weather with short summer nights provides optimum conditions for the blooms to exist even in the nutrient-deficient systems. If these favourable conditions change at this stage, either by a sudden drop in water temperature, or by wind and heavy overcast reducing input of solar energy, the bloom cannot exist any longer at this density and collapses on a massive scale. This "crash" is followed by rapid bacterial decomposition of dead algal cells resulting in partial or total oxygen depletion and fish kill.

Winter Oxygen Depletion (Winterkill)

This phenomenon is common in shallow lakes and reservoirs on the prairies as a consequence of high summer production, low depth and mainly a six-month-long ice and snow cover. This effectively cuts off input of atmospheric oxygen to the lake surface, as well as limits the photosynthetic activity during this period through light reduction. Algae continue to grow and produce oxygen for some time under the ice at low temperatures as long as some light is available. At about 20 to 30 cm of snow cover, primary production practically ceases, algae die off and bacterial processes take over. The organic matter, accumulated during the previous productive period (mostly dead algal cells), undergoes a rapid decomposition and mineralization (Figure 3).

By mid-winter, these factors eventually cause a dissolved oxygen depletion to near-zero levels and a total extinction of fish stock (winterkill). Temporary winter oxygen depletion is associated with drastic changes in water chemistry, namely the release of ammonia, CO_2 and H_2S from decomposition processes in the sediments (Barica, 1987b).

A good correlation was found between the mean depth of the lakes and daily oxygen depletion rates. It was established that the winterkill process affects only the shallowest and the most stagnant lakes (mean depth less than 3 m; Barica and Mathias, 1979). However, shallow parts of deeper lakes and reservoirs can be affected if the flushing rates are low.

The winter anoxia persists until mid-March; then, as daylight becomes longer and ice-snow cover diminishes, the oxygen conditions return quickly to normal.

A Lesson From Algae

Growth of algae in prairie lakes offers suggestive examples of varying degrees of ecological sustainability. Curve 1 in Figure 1 shows a truly sustainable growth, i.e., the situation where the magnitude of the nutrient pool and the rates of nutrient and light energy supply are adequate to sustain the bloom at the corresponding V_{max} level (equation 1). Curve 2 presents an unstable oscillating system, where the limits of sustainability are being surpassed. Curve 3 represents an unsustainable growth. The nutrient supply at this ultimate stage is exhausted and the fluxes from the sediment are inadequate to satisfy requirements of the bloom. This is noticeable by the deteriorating physiological state of the bloom, namely diminishing cellular P content and increasing cellular P-debt. At this stage, any external factor (i.e., weather disturbance) can trigger a catastrophic event for the entire lake. This can be demonstrated by application of the catastrophe theory to our data, as shown by Van Nguyen and Wood (1978), who confirmed that a crash of algal bloom exhibits a proper abrupt change as desired by the theory, which depends upon the interaction with light flux density, nutrient level near the algae mass and the respiration rate factor. This integration can be modelled and predicted using the cusp catastrophe model (Figure 4). The catastrophe theory fully supported our own conclusions on the triggering factors for the algal crash. The cusp catastrophe model also confirmed that the physiologically weakened system must adjust itself by experiencing a jump (crash) under appropriate conditions to regain a better stability. In general, the equations defining the unstable (and unsustainable) system contain clearly the structure of a cusp catastrophe.

Algal bloom collapse (crash) and the winterkill can therefore be considered to be truly catastrophic events resulting in a destruction of ecological integrity, as well as structure and function of the lake ecosystem, ending with the elimination of entire populations (phytoplankton, fish, and some zooplankton). This also suggests that the limits to growth - in the case of phytoplankton - are finite and growth beyond these limits ends in a catastrophe. This also provides some warning analogy to uncontrolled growth of human population as presented by the Club of Rome's classic project (Meadows et al., 1972).

Development of algal blooms in prairie lakes of different trophic status, as shown in Figure 1, can also provide some warning signals to indicate levels of ecological sustainability. The chlorophyll a concentrations up to 20 to 30 μg/L are apparently safe and the system is ecologically sustainable (curve 1), and provide an early warning signal. Any further increase in biomass (to around 50 to 60 μg/L of chlorophyll a) brings the bloom into an unstable, vulnerable state (the system develops oscillation patterns with significant fluctuations in algal biomass as a result of partial die-off of unsustainable portions of the bloom; Barica, 1974). This provides a "serious warning signal" indicating that the ecosystem is in danger. The levels close to and over 100 to 150 μg/L present a late warning signal, indicating at least 50% probability that the bloom will collapse.

Room for Development in the Prairie Region

Considering the low human population densities on the prairies and the available space, compared, say, to the Great Lakes region, it would appear, on the surface, that the conditions for economic development are limitless. This is a misleading notion, as the water resources in the region are limited not only by quantity, but also by quality. Many lakes on the prairies are saline (Hammer, 1986), exceeding the sea-water salinity levels and therefore not suitable for any municipal, agricultural or industrial use. What is left are lakes in an advanced eutrophication state with most of the nutrients of natural origin and therefore uncontrollable. There is very little room left - if any, to accommodate further loads. If we accept the advanced eutrophic and hypereutrophic level as unacceptable, we are left with very little or no carrying capacity (i.e., capacity to assimilate additional nutrient loads), to be filled by additional nutrients from growing population or agriculture (Figure 5). Therefore, any future development of settlements around the lakes on the prairies must be conducted under stringent controls, using both the ecosystem approach to water management (Vallentyne and Hamilton, 1987) with emphasis on prevention of pollution, and maximum recycling of nutrients, as well as application of the best available wastewater treatment technology to cope with growing population pressures.

Introduction and enforcement of zero-discharge policies will be crucial not only for the toxic contaminants as in the Great Lakes basin (IJC, 1989), but also for nutrients from human population and agriculture. This would call for a total recycling of any newly generated nutrients in the lake basins. It can be expected that despite lower population pressures, it will be difficult to secure ecological sustainability of the prairie lakes because of their already advanced eutrophication state.

In conclusion, due to high input of nutrients from prairie soils and advanced eutrophication, the carrying capacity of many prairie lakes and reservoirs is almost fully utilized and leaves little or no room for further loads from population, industry or agriculture. This may impose serious constraints on development in the region unless more stringent and effective waste control measures are introduced. In order to sustain ecosystem integrity, some threshold values of significant parameters are not to be exceeded (i.e., allowable nutrient loadings and nutrient concentrations, salinity, algal biomass, mean depth, etc.; Table 1). The need for a pragmatic approach to water management, responding to the specific conditions and needs of a semi-arid region using all available approaches to water management and lake restoration will be essential (Barica, 1991).

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TABLE 1: Critical levels of significant parameters to ensure ecological sustainability of prairie lakes and reservoirs. (Based on separately published reports and works by Barica, 1987a,b and Barica and Mathias, 1979)

Sustainable algal growth:	
Maximum summer chlorophyll a	<50 μg/L
Maximum mix-winter ammonia-N	<600 μg/L
Annual phosphorus loading	$<3\ g/m^2/yr$
Minimum dissolved oxygen	>4 mg/L
Total dissolved solids (salinity)	<2000 mg/L
Avoidance of winterkill:	
Mean depth	>3.0 m
Snow cover	<10 cm

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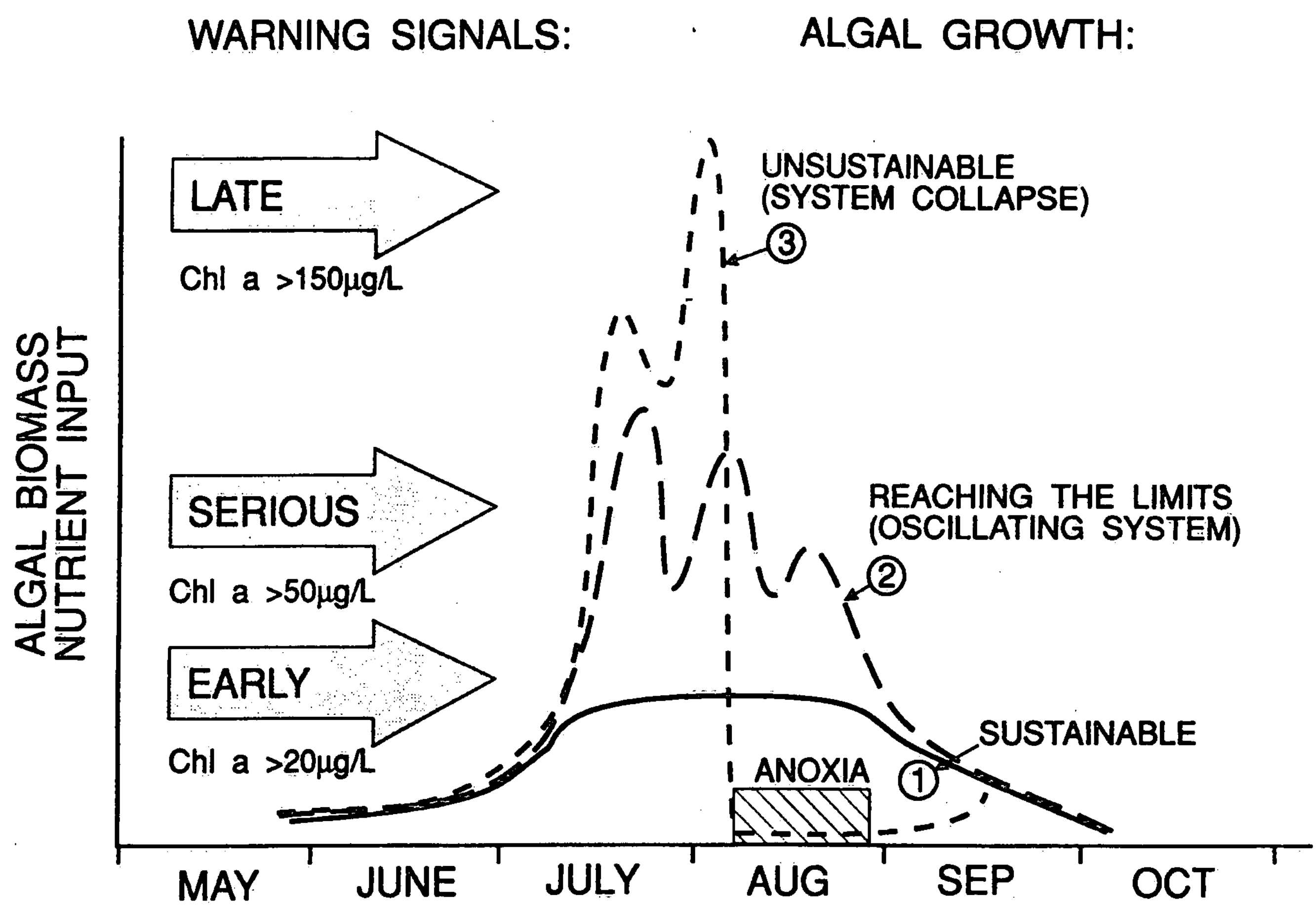

Figure 1: Generalized pattern of algal growth in an oligo- to mesotrophic lake (1), eutrophic lake (2) and a hypereutrophic lake undergoing bloom collapse (3), in regard to its sustainability. Differences mainly due to increasing nutrient loadings.

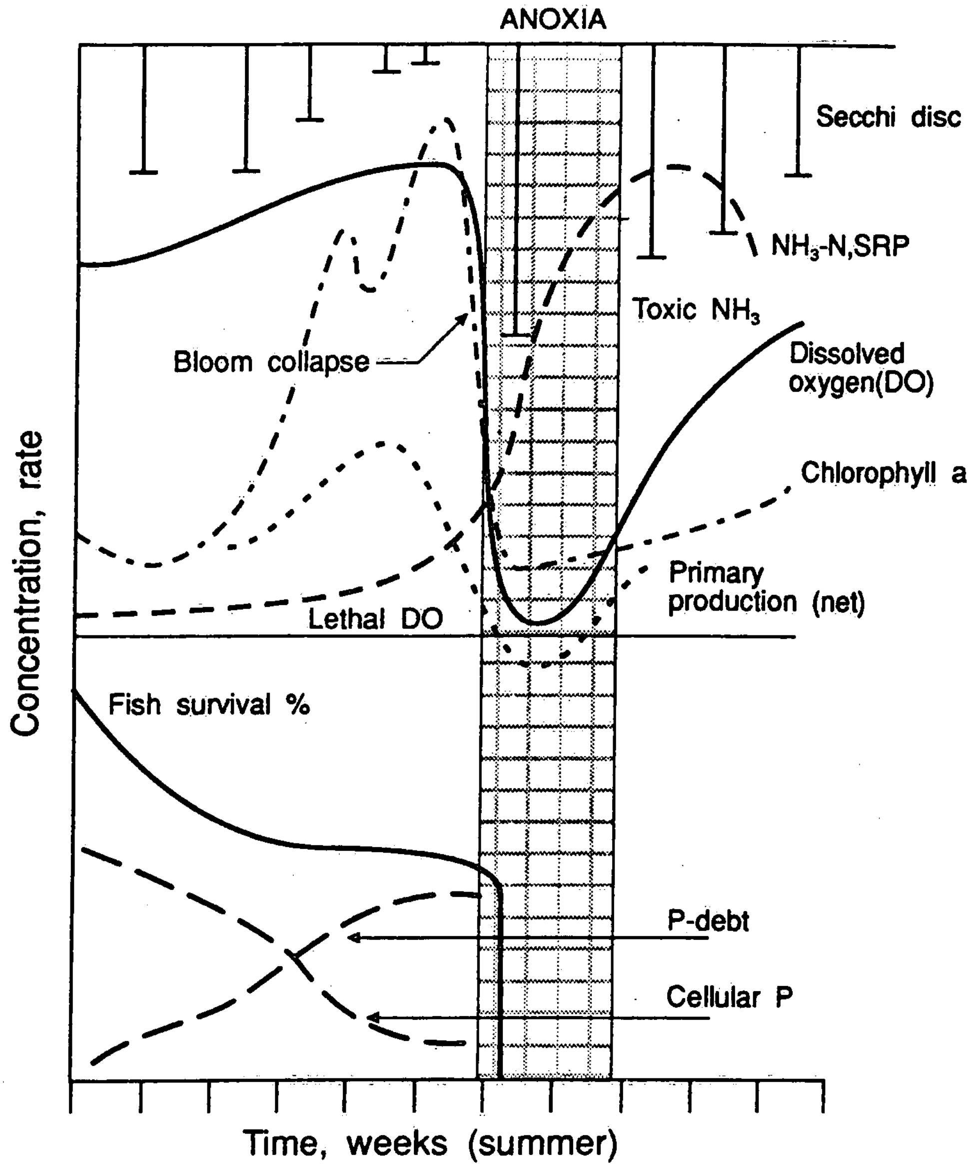

Figure 2: Mechanism of an algal bloom collapse with changes in major chemical and physiological characteristics (from Barica, 1978).

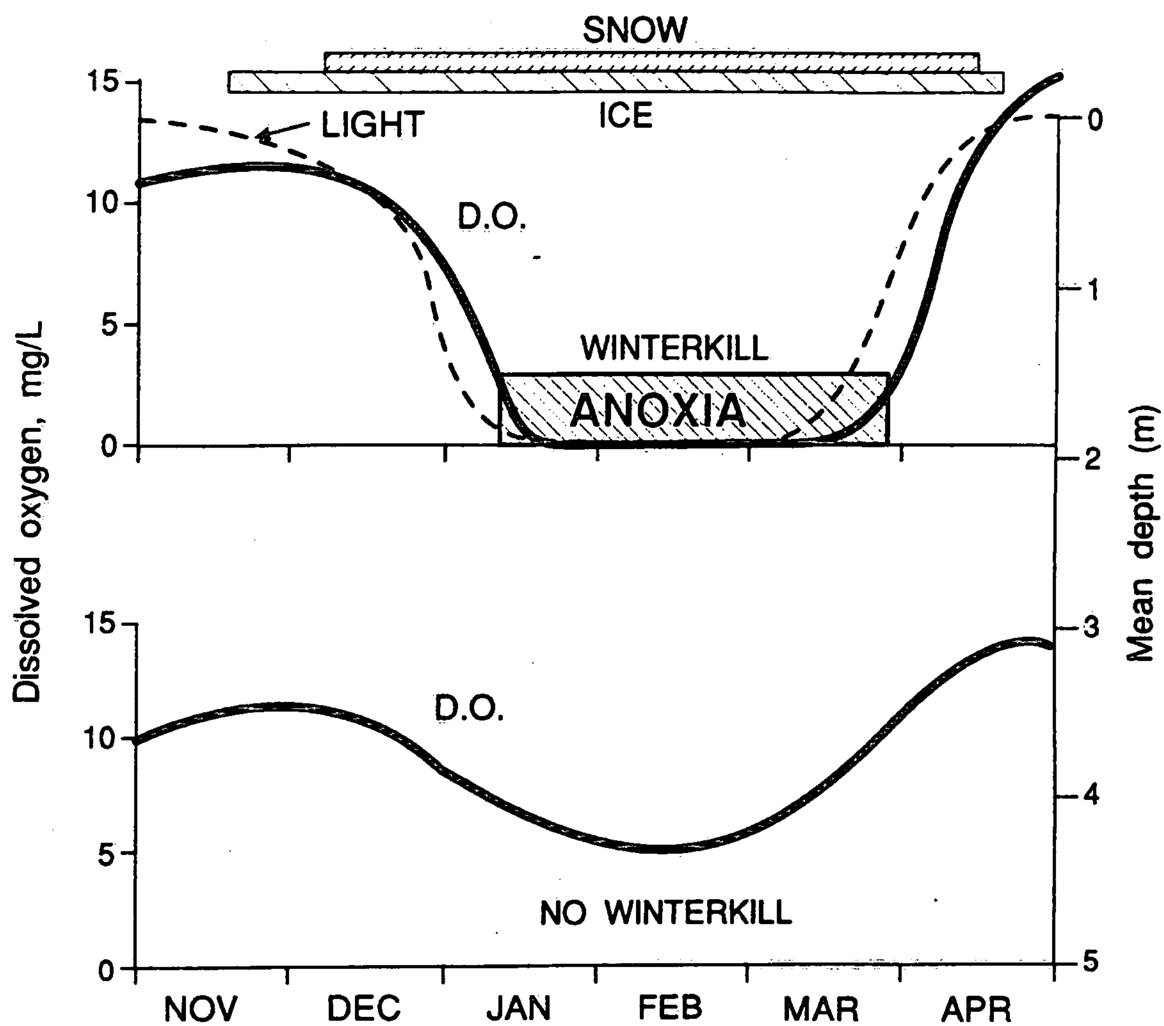

Figure 3: A schematic diagram of winter oxygen depletion in a shallow lake (mean depth 2 m) and a deeper lake (mean depth 5 m). Critical range of mean depths for winterkill conditions: <2.7 to 3.5 m.

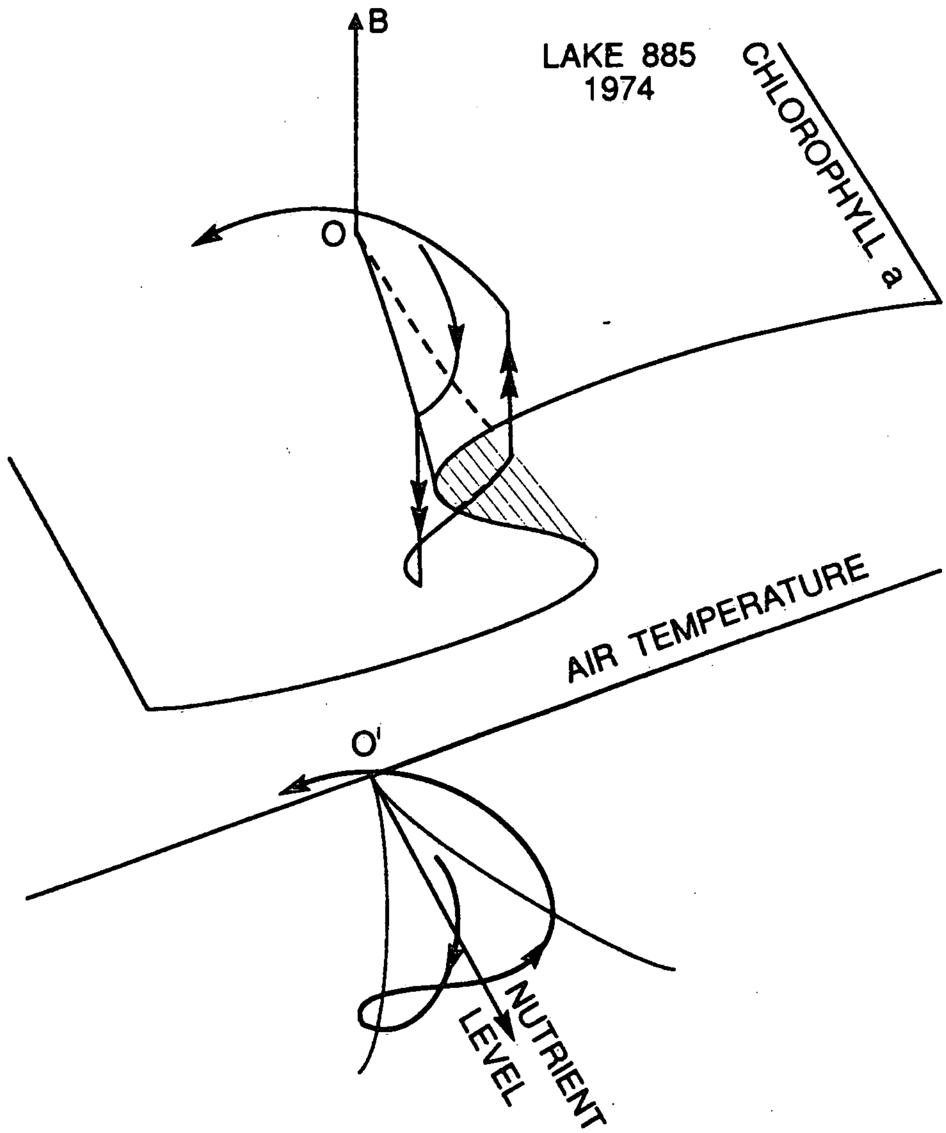

Figure 4: Application of the catastrophe theory to an algal collapse: morphological representation of the state of phytoplankton biomass (B) on a cusp catastrophe (from Van Nguyen and Wood, 1979; date from Barica, 1978).

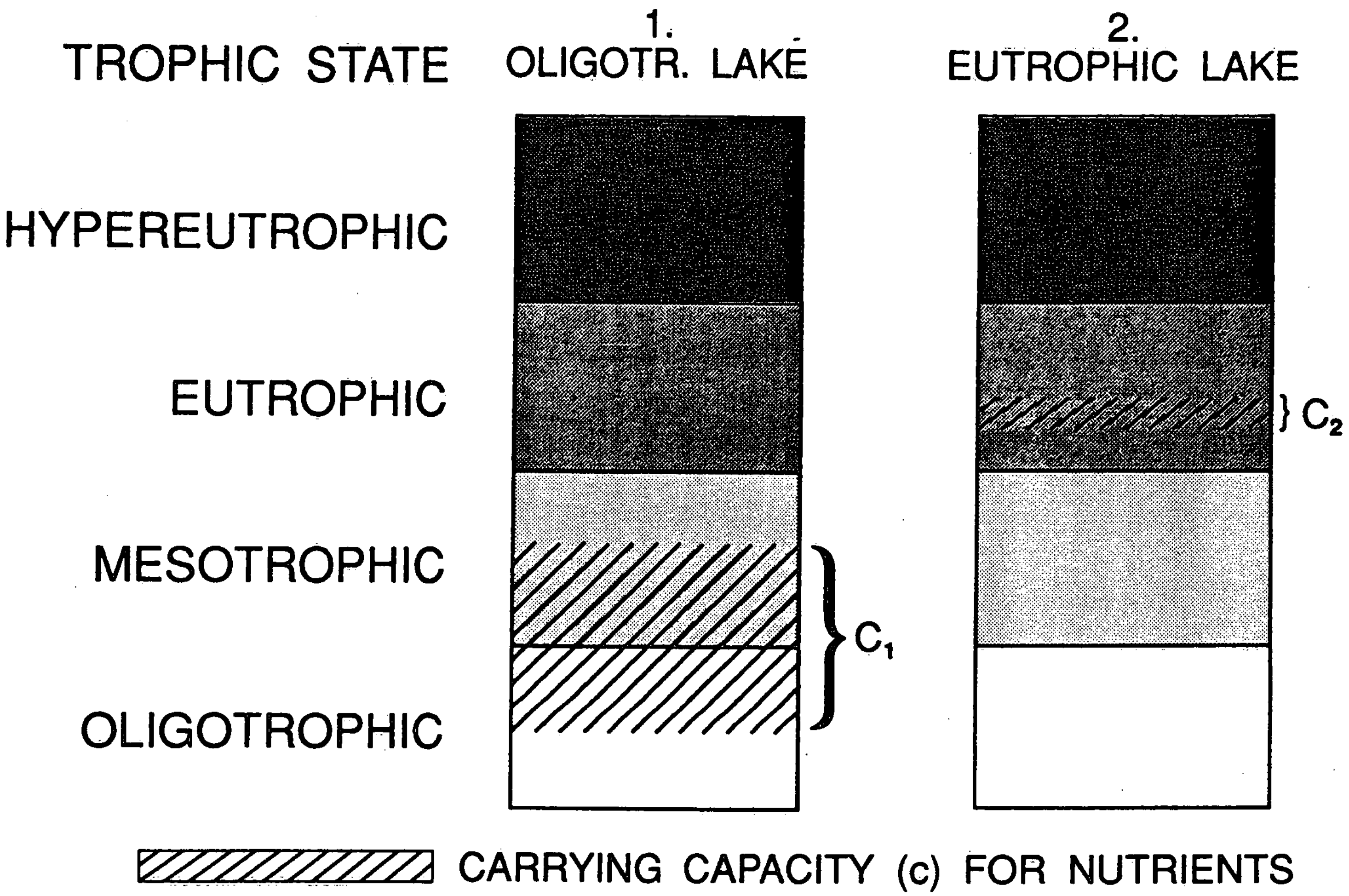

Figure 5: Carrying capacity for additional nutrient loadings in an oligotrophic (1) and eutrophic (2) lake (generalized). Arrows indicate present trophic levels. Room for additional loadings in (2) is minimal.

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