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Item 12 of the provisional agenda*

ECONOMIC COMMISSION FOR AFRICA

Twenty-second session of the Commission/ thirteenth meeting of the Conference of Ministers

Addis Ababa, Ethiopia
23-27 April 1987

Item 6 of the provisional agenda**

REPORT ON THE INTERNATIONAL SCIENTIFIC CONFERENCE ON THE CAUSES OF THE LAKE NYOS DISASTER

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* E/ECA/TPCW.8/1.

** E/ECA/CM.13/1.

I. INTRODUCTION

1. The International Scientific Conference on the causes of the Lake Nyos disaster in Cameroon was held in Yaounde, Cameroon, from 16 to 20 March 1987. The Conference was held at the initiative of the President and Government of the Republic of Cameroon. In response to that initiative, the Conference of Ministers of the Economic Commission for Africa (ECA) at its second extraordinary session held in Addis Ababa, in October 1986, adopted resolution ES.2/3 requesting the Executive Secretary of the Commission and the Administrator of the United Nations Development Programme (UNDP) and other concerned agencies of the United Nations system to provide additional resources in order to assist the Government of Cameroon in the organization of this Conference. Pursuant to that resolution, UNDP in consultation with the Government of Cameroon selected UNESCO to administer the project resources provided by UNDP, in collaboration with ECA.

2. The objectives of the Conference were to:

(a) Present and discuss the results of the investigations carried out in the field after the disaster;

(b) Determine the cause(s) and evaluate the consequences of the catastrophe;

(c) Mobilize the international scientific community to undertake research aimed at understanding such phenomena;

(d) Define measures to be taken in order to prevent the recurrence of this type of disaster in the short, medium and long term;

(e) Advise on problems of land use and resettlement;

(f) Promote the transfer of technology related to the prevention of such disasters;

(g) Make workable recommendations to the Government of Cameroon.

II. ATTENDANCE AND ORGANIZATION

3. The Conference was attended by over 120 scientists from 25 countries in Africa and overseas, including those countries that sent missions to the scene after the incident. Also attending were 76 Cameroonian scientists and other professionals in medicine, social studies, economics and anthropology.

4. The countries represented were Algeria, Austria, Burkina Faso, Canada, Chad, China, Côte d'Ivoire, Ethiopia, Federal Republic of Germany, Democratic Republic of Germany, France, Ghana, Guinea, Iceland, India, Israel, Italy, Japan, Kenya, Morocco, New Zealand, Nigeria, Senegal, Switzerland, Uganda, United Kingdom, United Republic of Tanzania, United States of America, Zaire, Zambia and Zimbabwe. The following international and intergovernmental organizations were also represented: Organization of African Unity (OAU), United Nations Development Programme (UNDP), United Nations Educational, Scientific and Cultural Organization (UNESCO), World Health Organization (WHO), Economic Commission for Africa (ECA), United Nations Disaster Relief

Organization (UNDRO), World Meteorological Organization (WMO) and United Nations Centre for Human Settlements (UNCHS).

Official opening ceremony

5. The Conference was opened by the Minister of Higher Education and Scientific Research of Cameroon.

6. In his opening address, the Minister requested participants to rise and observe a minute of silence in memory of those who had died during the Lake Nyos disaster.

7. On behalf of H.E. Paul Biya, President of Cameroon and his Government, he paid great tribute and expressed gratitude to all those who, as individuals, corporate bodies, States or international organizations, had been kind enough to rush to the aid of his country when it was facing very trying times. The preparation and holding of the Conference had been decided upon by the President of the Republic himself. The help of three agencies of the United Nations system (UNDP, ECA and UNESCO) had greatly facilitated matters and deserved to be commended.

8. In his statement, the representative of the United Nations Economic Commission for Africa praised the Head of State, Government and people of Cameroon for the presence of mind they had demonstrated during the incident, the self-help procedures they had instituted for rehabilitating the survivors and the initiative they had taken in convening the international scientific conference on the causes of the Lake Nyos disaster. He hoped that the discussions would come up with practical programme-oriented recommendations for the prevention and/or containment of like incidents in the future. He lauded the assistance and collaboration given by the United Nations system and other international and bilateral agencies and hoped that they would help to implement the recommendations of the Conference.

9. The representatives of UNESCO and UNDP said that their agencies were particularly honoured to have been called upon to assist in the preparation of the Conference and hoped that in the implementation of its recommendations the same spirit of collaboration would prevail.

Election of officers

10. The Minister of Higher Education and Scientific Research supervised the election of the officers of the Conference.

11. At the proposal of the representative of Côte d'Ivoire the Conference unanimously elected the following officers:

Chairman:	Professor Marc Bopelet (Cameroon)
First Vice-Chairman	Dr. John P. Lockwood (USA)
Second Vice-Chairman:	Prof. Haroun Tazieff (France)
Third Vice-Chairman:	Prof. Georgio Marinnelle (Italy)
Rapporteur General:	Prof. Sigvaldason (Iceland)
Assistant Rapporteurs-General	Dr. Amamoo-Otchere (Nigeria)
	Prof. Paul Nchoji Nkwi (Cameroon)
	Prof. Thomas Njine (Cameroon)

Plenary sessions	Geological and geophysical aspects
Co-Chairmen:	Prof. Gupta (India) Prof. Felix Tchoua (Cameroon)
Rapporteur:	Dr. Peter Bankwitz (RDA)
	Biomedical and physio-chemical aspects
Co-Chairmen:	Prof. Lazare Kaptue (Cameroon) Prof. P.J. Baxter (United Kingdom)
Rapporteur:	Dr. Y. Yamamoto (Japan)
	Ecological and agro-pastoral aspects
Co-Chairmen:	Prof. Akpati (Nigeria) Dr. Garban (Ghana)
Rapporteur:	Dr. [illegible] (Canada)
	Socio-cultural and economic aspects
Co-Chairmen:	Prof. Shanklin (USA) Prof. Zitoun (Algeria)
Rapporteur:	Samuel Ndoumbe-Manga (Cameroon)
	Case studies of catastrophes
Co-Chairmen:	Dr. Hassan Ahmed Hassan (Kenya) Dr. Aramari (Japan)
Rapporteur:	Dr. D. Westercamp (France)
Working groups:	
Group A:	Causes and mechanisms of the Lake Nyos phenomenon
Convenor:	Prof. L. Sigvaldason (Iceland) Prof. P. Bankwitz (GDR)
Rapporteur:	(France)
Group B:	Hazard evaluation and zoning
Convenor:	Prof. H.K. Gupta (India)
Rapporteurs:	Mr. J. Tomblin (UNDRO) Dr. R.D. Adams (UK)

12. After the election of the officers, the Minister of Higher Education and Scientific Research suspended the meeting to allow those who were invited only to the opening session, to withdraw.

13. On resumption, at 11.55 a.m., the Chairman, Prof. Marc Bopelet, recalled the objectives of the Conference as stated above and the expectations of the Government of Cameroon. The Conference called for very technical discussions on the papers to be presented so as to determine the causes of the disaster, define the measures to be taken to prevent similar tragedies in future, and suggest measures to be taken with a view to rehabilitating the victims.

14. Prof. Fèlix Tchoua gave a brief presentation of the findings of the Cameroon scientific team which visited the site a few days after the disaster, and had been carrying out studies on the site since then. Prof. Tchoua informed the group that the multidisciplinary team of geomorphologists, geophysicists, geochemists, medical doctors, ecologists, agriculturists, economists, sociologists, was formed by the Ministry of Higher Education and Scientific Research after the disaster and that this team provided very useful background information to the other 11 scientific teams from overseas that had also been studying the causes of the Lake Nyos disaster. Finally, he reviewed various hypotheses on the causes of the disaster based on the first-hand information the team was able to collect and on the subsequent findings of the other overseas teams.

III. AGENDA AND PROGRAMME OF WORK

15. The following agenda and programme of work were adopted:

(a) Agenda

1. Official opening ceremony
2. Election of officers
3. Presentation of scientific reports
4. Closing ceremony.

(b) Programme of work

Monday, 16 March 1987

Morning : 8 a.m.	Opening ceremonies Arrival of participants Arrival of invited guests
9.25 a.m.	Arrival of the Minister of Higher Education and Scientific Research
9.30 a. m.	Opening of the Conference
	Opening speech by the Minister of Higher Education and Scientific Research
	Statement by the Deputy Executive Secretary of the Economic Commission for Africa
	Statement by the Resident Representative of the United Nations Development Programme
	Statement by the representative of the Director General of

10.30 a.m.	Election of officers Break
11 a.m.	General remarks on the theme of the Conference by Prof. Marc Bopelet Presentation of reports of the Cameroonian scientific team by Prof. Félix Tchoua
3 p.m.	Presentation of reports by the scientific teams from: 1. United States of America 2. France 3. Italy 4. Federal Republic of Germany
4.30 p.m.	Break
5 p.m.	Presentation of scientific reports (continued) 5. Japan 6. United Kingdom 7. Switzerland

<u>Tuesday, 17 March 1987</u>

10.30 a.m. <u>THEME 1</u>: GEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL ASPECTS

1.	Freeth, S.J.	The tectonic setting of the Lake Nyos disaster.
2.	Tchoua, F.	Origine et mode de formation du Lac Nyos.
3.	Lockwood, J.P.	Geological setting and origin of Lake Nyos.
4.	Schenker, F. et al.	A magmatological interpretation.
5.	Devine, J.P. et al.	Possible mantle metasomation beneath the Cameroon Volcanic Line.

11 a.m.-12 noon

6.	Kusakabe, M. et al.	Role of lake water in 1986 Nyos gas disaster.
7.	Kay, R. L.	Hydrogeochemistry of Lake Nyos.
8.	Chevrier, R.M.	L'explosion du mois de décembre 1986 au Lac Nyos.
9.	Zogning, A.	Eruption et diffusion du gaz de Nyos : contexte géographique.

10.	Tuttle, M.L. et al.	Geochemistry of Lake Nyos: implications for the origin and accumulation of carbon dioxide.

3-4.30 p.m.

11.	Oskarsson, N.	Carbon dioxide bursts of Lake Nyos as periodic supersaturation in a counter-current reactor: implications of chemical monitoring and future prevention.
12.	Le Guern, F. et al.	Nyos 1986: the degassing process.
13.	Giggenbach, W.	Limits on composition and amounts of gas dissolved in waters of Lake Nyos.
14.	Chévrier, R.M.	Hydrogéochimie des eaux du lac Nyos et de son environnement.
15.	Tazieff, H.	Hypothèses publiées sur les mécanismes du phénomène, et choix correspondant à celle qui répond le mieux aux faits d'observation.

5-6.30 p.m.

THEME 3: HAZARD EVALUATION

1.	Tietze, Klaus	A newly discovered stratification on Lake Nyos.
2.	Freeth, S.J. and Coulson, M.G.	Evidence for the emission of toxic gas from Lake Nyos prior to the August 1986 disaster.
3.	Faivre-Pierret, R.X. et al.	CO^2 in the soil around lakes in Cameroon, origin and implications.
4.	Sigurdsson, H.	Gas bursts from anoxic crater lakes a natural hazard.
5.	Baubron, J.C. et al.	Stratégie pour l'évaluation et la zonation des risques d'éruptions gazeuses en République du Cameroun.
6.	Obenson, ...	Geophysical monitoring in Cameroon.
7.	Sabroux, J.C.	Limnic eruption: a new geological hazard.
8.	Le Guern et al.	Establishment of models of the natural convection in Lake Nyos.

Wenesday, 18 March 1987

Plenary sessions:

THEME 2: BIOMEDICAL, ECOLOGICAL AND AGRO-PASTORAL ASPECTS

9-10.30 a.m.

1.	Kaptue, L.	Manifestations cliniques observées chez les victimes.
2.	Muna, W.	Physiopathologie des manifestations cliniques.
3.	Niat, G.	Suivi des malades.
4.	Njine, T.	Evaluation des causes de la catastrophe du lac Nyos par une analyse des composantes physico-chimiques des lacs Nyos, Wum et Monoun.
5.	Yamamoto, Y.	Clinical and pathological study of Lake Nyos disaster victims and nature of poisonous gas.

11 a.m.-12 noon

6.	Baxter, P.J.	Health effects of natural and volcanic gases.
7.	Monzali, C.H. et al.	Effects of CO^2 at high temperatures on skin.
8.	Mesfin D.	Some health aspects of the Lake Nyos disaster.
9.	Sallah, J.	Effects of the Lake Nyos disaster on animals.
10.	Epoh, J.T.	Les effets de la catastrophe du lac Nyos sur les éléveurs et sur l'environnement.
11.	Tutuwan, H.	Ecological aspects of the Lake Nyos disaster.

3-4.30 p.m.

THEME 4: EVALUATION OF RISKS

1.	Viewing, K.A.	CO^2 levels in volcanic rocks of Archaen age in the Craton area, Zimbabwe.
2.	Asfaw, L.M.	Recent experience in Ethiopia on volcano-associated hazards.
3.	Nanyaro, J.T.	Meru and Kilimanjaro volcanic region in Northern Tanzania: need for surveillance of volcanic hazards.
4.	Fairhead, J.D. and Djallo, S.	Seismicity of the volcanic province of South-West Cameroon.

6.	Wendorff, M.	Oxic and anoxic conditions of sedimentation in a geosynclinal basin.

5 p.m.-6.30 p.m.

Plenary sessions: SOCIO-CULTURAL AND ECONOMIC ASPECTS

1.	Nkwi, P.N. and Ngu N.	General assessment of the socio-economic consequences of the disaster.
2.	Hinge, Paul (MINPAT/CER)	Guidelines for the resettlement of the survivors of the Lake Nyos disaster.
3.	Ms Lacroux (UNCHS/HABITAT)	Rapport succinct sur la problèmatique et les perspectives de la ré-installation des sinistrés.

Thursday, 19 March 1987

Plenary session: PROBLEM OF SURVEILLANCE PREDICTION AND PREPAREDNESS

9 a.m.-10.30 a.m.

1.	Tazieff, H.	Prévention d'événements similaires à ceux de Nyos 1986.
2.	Tchoua, F.	Les catastrophes de Nyos et de Njijon, sont-elles prévisibles ?
3.	Tomblin, J.F.	The management of volcanic prediction, warning and evacuation.
4.	Degrances, P.H. et al.	Etude géochimique du lac Nyos.
5.	El-Etr, H.S.	Physical - Chemical processes of gas explosions: the case of Lake Nyos

11 a.m.-12 noon

6.	Amamoo and Otchere	Remote-sensing aspects of relief management of volcanic hazards.
7.	Hassan, H.A.	Satellite remote-sensing forewarning of active volcanies.
8.	Browitt, C.W.	Seismic data acquisition and telemetry.
9.	Baxter, P.	Disaster planning: Prevension health measures in volcanic eruptions.
10.	MESFIN D.	Rapid assessment of an emergency situation.
11.	SCHENKER, F. et al.	Prevention of gas eruptions by drilling operations: A proposal

3-6.30 p.m.

WORKING GROUPS:

Working Group A
Working Group B

Friday, 20 March 1987

9-12.30 p.m.	Working Groups continued
3-4.30 p.m.	Working Groups continued
5.30 p.m.	Closing Ceremony

Saturday, 21 March 1987

Sunday, 22 March 1987:	Field trip to Lakes Nyos and Monoun (selected 35 participants only).

16. During the plenary sessions which lasted from Monday, 16 to Thursday morning, 19 March, discussions were made on the themes presented above in the agenda and programme of work.

17. After the presentation of all the papers at plenary sessions, the Conference then spilt into two working groups. Group A was to attempt to determine the causes and mechanisms of the Lake Nyos phenomenon as inferred from physical, chemical and bio-medical observations and examine the prospects for monitoring, prediction and public warning for emergency preparedeness. Group B dealt with hazard evaluation and zoning and their implications for long-term preventive measures and land-use planning.

IV. CONCLUSIONS AND RECOMMENDATIONS OF THE CONFERENCE

PART I: THE LAKE NYOS DISASTER AND ITS CONSEQUENCES

A. The Geological environment

18. The basic reason for the catastrophic gas release from Lake Nyos on 21 August 1986 is ultimately related to the fact that Cameroon is dissected by a linear zone of crustal weakness that has served to localize volcanic activity. This zone, the so-called "Cameroon volcanic line" has been active for several million years, producing lavas and pyroclastic material. Lake Nyos was formed as a result of this volcanic activity. The deep-seated heat reservoir of volcanism is magma which, besides silicate constituents, contains differing amounts of volatile compounds in solution. These compounds are carbon dioxide, water, several sulphur species, hydrogen, hydrogen chloride and hydrogen fluoride. Carbon dioxide is by far the most abundant of these. Upon pressure release or slow in-situ cooling of the magma body, the volatile components exsolve from the magma as a gas phase. In the process of exsolution, the least soluble of these components leave the magma first. Carbon dioxide has a low solubility in magma and is therefore released from the magma in relatively larger amounts than the other components during the early stages of degassing.

19. After leaving the magma, the magmatic gas rises towards the surface, through permeable rock formations which are partly or wholly saturated with steam or liquid water. The gas, together with water and solid rock, constitute a highly reactive system which will consume all of the chemically active components of the magmatic gas phase, provided that the path of travel is long enough to complete the process. Due to its larger quantity and lower reactivity, carbon dioxide is the major component most likely to reach the surface. Being soluble in water, all or part of it may dissolve in the ground water along its path.

20. The mode of release of carbon dioxide of deep magmatic origin to the atmosphere is therefore generally via a water solution, as in the case of carbonated springs which discharge water that has been saturated with carbon dioxide at higher than atmospheric pressure. It is also possible that the carbon dioxide may accumulate in subsurface zones or voids and be released explosively to the atmosphere. Occasionally, the final part of the path of ascent may be a lake. As demonstrated by the catastrophic Lake Nyos event in August 1986, this can become a major natural hazard. Other recent catastrophes involving carbon dioxide where the gas burst from Lake Monoun in Cameroon in 1984 and the massive release of carbon dioxide to the atmosphere in a phreatic eruption at Dieng (Java) in 1979.

21. The Conference discussed at great length the wealth of scientific data that have accumulated as a result of the efforts made by a number of researchers since the Nyos event. These data can be grouped into a few partially overlapping categories:

(a) Geological observations which, with minor differences in emphasis, lead to the conclusion that Lake Nyos was formed at some time within the past millenium by a volcanic eruption. The chemical and mineralogical composition of the products indicate a deep origin, of the order of 90 kilometres below the surface. At the surface, the eruption products interacted with water and formed fragmental deposits. In the immediate vicinity of Lake Nyos, there are carbonated springs, which in addition to the presence of solid volcanic products, indicate recent volcanic activity in the area;

(b) Detailed analysis of water samples taken at various depths and at various locations in Lake Nyos, and at various times after the 21 August event, indicate that the Lake contains high amounts of dissolved carbon dioxide, which at present correspond to about 20 per cent of saturation of the water with respect to that component. Several lines of argument indicate strongly that the lake contained higher amounts of carbon dioxide before the event. The carbon dioxide dissolved in the lake is of deep magmatic origin, possibly expelled from the same magmatic reservoir that fed the volcanism that originally formed Lake Nyos. Due to the great depth of the source, all the reactive gases that left the magma at the same time as the carbon dioxide were consumed in reactions with water and wall rock on the way to the surface. The solubility of carbon dioxide and other gases in water increases with increasing pressure so that, although water itself is incomprehensible, a higher amount of dissolved gases in the deep waters of the lake increases the density of the solution. A stable density gradient was therefore established in the lake, creating a meromictic condition. This stability can be disturbed by several processes, but, once it is disturbed, a spontaneous degassing of the lake water can result in the release of a large amount of carbon dioxide in a very short time. Calculations based on the chemical equilibria and thermodynamics involved in such a spontaneous degassing indicate that the amount of gas that could be released in this way from the waters of the lake is of the same order of magnitude as that of the fatal gas cloud which caused the Nyos catastrophe;

(c) Medical examination of victims and survivors of the catastrophe has shown that the cause of sudden death was suffocation (asphyxia) in a carbon dioxide atmosphere. The ailments of the survivors can also be generally attributed to inhalation of excess amounts of carbon dioxide gas. However, the presence of other gases cannot be excluded. Skin lesions were observed on a few corpses and in about a quarter of hospitalized survivors coming from all parts of the disaster area, nearly all of whom were reported also to have suffered from unconsciousness immediately after the gas release.

B. The cause and mechanism of the gas eruption in Lake Nyos

22. In spite of fairly comprehensive information that is now available on the present state of the lake, little is known about the lake as it was before the gas eruption. It is known however, that carbon dioxide-rich springs have been active in the Lake Nyos area at least since 1975. Any model constructed to explain the Nyos gas eruption will have to lean on some assumptions supported only by indirect evidence. Such arguments may assume different degrees of importance in the minds of different scientists. At the present state of knowledge, complete agreement on every detail of such a complicated natural phenomenon would be most unusual and even unnatural, since scientific progress depends on argument and counterargument. However, the Conference reached agreement on most of the essential aspects of the problem and was able to draw important conclusions that will help define what scientific work needs to be done in order to provide maximum safety to the people living in hazardous areas around Lake Nyos and other similar lakes in Cameroon.

23. Brief summary of evidence

(a) Lake Nyos is roughly circular, with an irregular shore line. Its surface area is about 1.5 square kilometre. It fills an elliptical, near-cylindrical depression, whose long axis is about 1,800 metres in a north-south direction. This has a flat bottom at a depth of 208 metres. The lake volume is about 0.17 cubic kilometres. The maximum lake level is controlled by a natural spillway at its north-western end;

(b) During the evening hours of 21 August 1986, a large volume of gas heavier than air was released from Lake Nyos. It swept over nearby villages killing more than 1,700 people and a large number of livestock;

(c) As inferred from the distribution of dead animals, a lethal concentration of gas reached a height of 120 metres above the lake surface. It spread subsequently to a distance of up to 25 kilometres from the lake, following the downhill topography;

(d) The distribution of animal and human casualties makes possible an estimate of the volume of potentially lethal gas mixture. The amount of carbon dioxide which degassed has been estimated at about 1 cubic kilometre. A 10 to 20 per cent mixture of carbon dioxide with air is potentially lethal, so that the total volume of the gas cloud responsible for death and injury is estimated to have been about 0.15 cubic kilometres.

(e) As inferred from the damage to vegetation (mainly in a nearby village) the moving gas travelled at a speed sufficient to flatten, anything in its path in some places;

(f) The lake turned dull red, due to the formation of a surface layer containing iron hydroxide and floating plant debris;

(g) Soil damage, apparently caused by splashing water, was most intense on the southern parts of the lake shore, and an 80 metres high promontory was partly stripped of vegetation and soil;

(h) About 5 per cent of 845 survivors who attended Wum and Nkambe Hospitals (including those hospitalized) in the six weeks after the disaster had weakness (palsies) of one or occasionally more limbs: swelling (oedema) of the affected limbs was often observed. Pressure on, or stretching of, nerves during coma was the most likely cause, but other aetiologies in some victims could not be ruled out;

(i) Eye inflammation (conjuctivitis) was present in numerous survivors but its precise significance (e.g. congestion from asphyxia or irritation by noxious gases) is not clear. These problems were soon resolved;

(j) After the event, the lake level fell approximately 1 metre lower;

(k) Vegetation was mechanically damaged by the event, but no thermal or chemical damage could be identified with certainty.

Two alternative scenarios to explain the above evidence are envisaged:

(i) Rapid degassing of carbon dioxide gas dissolved in the lake water;

(ii) Eruption of gases from beneath the lake floor in conjunction with volcanic activity.

24. The scientific data available so far tend to favour the first alternative, although it is possible that elements of both scenarios contributed to the Lake Nyos disaster. Extensive research is needed to clarify this.

Alternative A: Rapid degassing of carbon dioxide from the lake water

The principal arguments for this scenario are based on the following observations:

(a) The present content of dissolved chemicals can best be explained as resulting from interaction between carbonated water and wall rock. The reaction rates leading eventually to the observed composition are slow, and the observed level of salinity could not have been reached in the short time between the gas eruption and the first sampling after the eruption;

(b) The temperature of the lake as a whole has risen since the event. Exsolution and expansion of a gas causes fall in temperature. The observed temperature rise is therefore consistent with degassing of the lake water;

(c) The deep water close to the bottom of the lake was essentially free from suspended solids at the time of sampling 12 days after the event;

(d) The amount of carbon dioxide required to form a lethal gas cloud of 1 cubic kilometre is only 0.15 cubic kilometre of pure carbon dioxide. This is a minimum value, but is significant, since the mechanical impact is less than if the amount of gas was several times the volume of the water body.

<u>The triggering mechanism</u>

25. If Lake Nyos was meromictic (i.e. with permanent density stratification), it could be described as a stable water body. However, the stability can be upset by several forces, which can be classified into two general groups: (a) forces which are released due to the internal physico-chemical properties of the lake as a dynamic system; and (b) external, mechanical forces which disturb the physico-chemical equilibrium. Several such triggering mechanisms have been suggested, but the available information does not allow a clear distinction between the alternatives to be drawn. It may nevertheless be concluded that, whatever the triggering mechanism, the lake must be charged with high levels of carbon dioxide in order to become a serious hazard.

<u>The future according to the first scenario</u>

26. The basic assumption of the first scenario is that the lake water contained all the carbon dioxide released during the tragic event of 21 August 1986. This carbon dioxide must have accumulated over a considerable but unknown period of time. The degassing event would not affect the carbon dioxide input and therefore accumulation continues, probably at the same, or a similar rate as before the event. Accordingly, the first scenario points to well defined monitoring methods.

<u>Alternative B: Injection of gases from levels beneath the lake floor in conjunction with volcanic activity</u>

27. The principal arguments in favour of this scenario are based on the following observations:

(a) Carbon dioxide is the major component of volcanic exhalations throughout the world. By analogy, and by considering the recent volcanic origin of Lake Nyos, it is natural to associate the gas eruptive event with active volcanism;

(b) The volume of the lethal gas mixture was estimated to be several times the volume of the lake water. Spontaneous exsolution of such a large volume of gas would result in a mechanical disturbance which is unaccounted for;

(c) The surface temperature of the lake was considerably above the mean temperature immediately after the event, and decreased gradually towards the mean over a period of several days. This observation is considered to indicate surficial heating by contact with warm volcanic gas, which penetrated the lake water but did not otherwise interact with the water, either thermally or chemically;

(d) Recent seismic monitoring in the area has recorded some local events;

(e) The medical findings could be explained by asphyxia caused by a gas such as carbon dioxide but this cannot be confirmed. The presence of other volcanic gases, e.g. hydrogen sulphide, cannot be ruled out;

(f) Several months after the main gas eruption on 21 August 1986, renewed activity was observed. This was probably of similar nature but smaller in scale than the main event. A red spot on the lake surface like the ones seen after the catastrophe was observed on 31 December 1986. Such a phenomenon has, however, been reported at other times.

The future according to the second scenario

28. A volcanic eruption is a stochastic event which is difficult to forecast, let alone predict. The pattern of a catastrophic event followed by smaller events is characteristic of many well-known eruptions and earthquakes. A volcano which awakens after an unknown, possibly long, repose period may go through several activity episodes closely spaced in time. The Nyos event may be a part of episodic activity which could be either: (a) a natural phreatic activity starting with the major event of August 21 and followed by decreasingly strong events; or (b) a precursor to a possible reactivated volcanism in that part of the volcanic area. Both alternatives suggest the application of commonly used monitoring methods.

C. MONITORING AND RESEARCH ON LAKE NYOS

29. It is recommended that the following parameters should be monitored during a period of at least one year:

Essential parameters, easy to monitor:

30. Thermal profiles, by means of thermistors or platinum resistance thermometers. Lake Nyos is a typical meromictic lake with a chemocline under normal conditions. However, observations of its thermal regime are essential because (a) heavy cooling of the mixolimnion may weaken the density stratification produced by solubles; (b) there have been statements, not yet firmly proven, that heating took place near the bottom of the lake. Both these possible processes can induce mixing of the lake and the release of carbon dioxide.

Transparency, using a Secci disk

31. None of the investigations undertaken so far have considered the importance of transparency. Changes in transparency, induced not only by the dynamics of the phytoplankton and turbid material brought in by surface runoff and by diffuse sources during the rainy season, but also by the upwelling of water from the monimolimnion, which is rich in iron and manganese. On entering the mixolimnion zone with high oxygen content, iron and manganese will flocculate and thus influence transparency. Additional colorimetric analysis is highly desirable but not essential if colour changes are observed carefully (by simple methods such as the Forel-Ule scale).

Conductivity in-situ

32. The essential characteristic of every meromictic lake is its chemical gradient (chemocline). Any change in this gradient caused for example by oversaturation at any depth affects the lake's stability. Frequent conductivity measurements along vertical profiles would yield information not only about the transfer of solubles through the lake bottom but also on the dynamics of the process.

Carbon dioxide profiles measuring gas volume concentrations

Gas and matter release from the bottom

33. Measurement of this would contribute to the essential knowlege of the transfer mentioned under in paragraph 32 above, and result in the discovery of any "hot spots" that may exist in the flat bottom area.

pH in-situ and alkalinity:

34. In combination with the conductivity measurements, they would contribute to a better understanding of both biogenic and inorganic chemical processes.

Oxygen and redox potential

35. Its distribution is confined to mixolimnia and may be an important parameter of the biogenic dynamics of the mixolimnion. Fluctuations of the oxygen-zero depth are of critical interest.

Material budget

36. Monitoring of the water budget (inflow and outflow) and of effluents, including dissolved and particulate matter such as iron, manganese, phosphorus and the oxides of nitrogen. Knowledge of fluctuations of the inflow is essential to explain any changes within the mixolimnia.

Meteorological parameters (wind, rain, barometric pressure, etc.)

Desirable parameters, needing more sophisticated equipment

3.2.1 Density measurements in-situ.

3.2.2 Careful echosounding and continuous seismic profiles of the lake bottom (direct observation by a bathyscaph), in order to detect possible sources of massive gas and/or water release.

3.2.3 Turbidity measurements. Data on turbidity are needed not only to evaluate the density, but to detect possible sudden upwelling water from deep layers or from the bottom layers containing sedimentary material.

3.2.4 Phytoplankton and zooplankton, as indicators of: (a) changes due parameters such as pH, etc.; and (b) paleoclimatic regimes and trends.

3.2.5 Sediment cores for evaluating the age of the lake and for obtaining evidence of any former catastrophic events (indicated by concentrations of plankton kill) or other chemical events.

3.2.6 Stable and radioactive isotopes of water and dissolved species:

(a) Regular monitoring of oxygen, hydrogen and carbon isotopes;

(b) Baseline-levels of radon and inert gases;

(c) Radon levels after any future event, in order to discriminate between alternative hypotheses (enhanched radon contents would indicate a release of parent radioelements from surrounding or underlying rock within the preceding 30 days;)

(d) Uranium isotopes, for better understanding of the hydrolic system.

3.2.7 Rate of erosion of the outlet, as an indicator of the age of the lake.

3.3 Other scientific studies and research in the Lake Nyos area

Geological mapping

37. A detailed geologic map of the area immediately surrounding Lake Nyos (ca. 25 square kilometres) should be made, in order to determine the distribution of all volcanic products, including pyroclastic ash deposits, scoria cones and lava flows. The mapping should also indicate the distribution of regional faults and lineaments. Attempts should be made to determine the relative and absolute ages of the features.

Remote sensing

38. Regional structures which may have contributed to the localization of volcanic features in the Lake Nyos area should be mapped, using the most detailed available remote sensing imagery.

Seismology

39. The present seismological network around Lake Nyos should be maintained, both as a local monitor and to give general information about possible seismic activity in the neighbourhood of lakes.

Co-ordination of data acquisition

40. In view of the number of scientific teams from different countries and institutions that have undertaken field studies of Lake Nyos since the catastrophe, and the fact that these and other teams are likely to pursue such studies further, as recommended by the present Conference, an appropriate mechanism should be established for liaison between the teams, for co-ordination of their data-collecting programmes and for the cataloguing and eventual exchange of the data obtained.

D. ACTION AIMED AT REDUCING THE HAZARDS AT LAKE NYOS

41. On the basis of the available scientific evidence, it is impossible to exclude the possibility that further potentially disastrous events may occur at the lake in the future. These may be: (a) further degassing of the lake water due to either of the two possible causes described in Section 2 above, or to other possible causes such as a strong earthquake; and (b) sudden failure of the volcanic material which is at present damming the outflow at the northern end of the lake, due to water infiltration, a strong earthquake or some other cause.

42. The Conference therefore examined various possibilities of reducing the probability of such events by technical means.

Controlled degassing of the lake water

43. Two possible methods were discussed by the Conference:

CO_2 rich bottom water of the lake could be progressively pumped out by the natural gas-lift method. To prevent underground conditions beneath the lake being disturbed, the rate of removal of bottom water should be about equal to the original rate of surface water outflow. Thus, without any significant change in the water level of the lake, the existing stratification would gradually sink and disappear. The result would be a lake consisting of rainwater with a relatively low content of minerals, and in which large quantities of gas could no longer accumulate. Care would have to be taken to control the rate of pumping in order to avoid the risk of inducing an uncontrolled distabilization of a non-convective layer of the lake. The second method would consist in drilling from the outside of the lake into the hydro-thermal system beneath the lake. Bore holes reaching the hydro-thermal system underneath the lake could diminish the gas migration from underground into the lake, and thus tend to reduce the amount of carbon dioxide accumulating in the lake water.

Stabilization of the dam

44. Although there is no indication that a failure of the material damming the lake at its northern end is likely to occur in the near future, this risk should not be ignored entirely. It is therefore recommended that the stability of the dam be investigated as soon as technically possible.

There are two means by which the risk of dam failure could be reduced:

(a) Grouting of the dam, in order to reduce its permeability to water and to consolidate and strengthen the material;

(b) Progressive removal of material from the upper part of the dam, thus lowering the water level of the lake. Care would have to be taken in this case to avoid uncontrolled degassing of the lake due to a too rapid reduction in hydrostatic pressure.

Cost-benefit analysis

45. Since some of the actions envisaged above would be costly to implement, they should not be undertaken until detailed cost-benefit analysis have been

made, weighing the costs against the reductions in risk to life and property that would be achieved if they are successful.

E. RESETTLEMENT AND OCCUPATION OF THE LAND AROUND LAKE NYOS AND OTHER LAKES

46. The resettlement of disaster victims is a delicate human problem which always brings about profound changes in the way of life of the populations concerned. The close involvement of these populations in the operation is vital for its success. Their participation presupposes taking into consideration the socio-cultural and socio-economic factors that characterize their way of life. It also presupposes that ample information is collected and discussions are held between technicians of the local and national administration and the populations themselves.

47. These should focus on the wishes of the populations in relation to the scope for the development in the resettlement area. A resettlement operation can become an ideal occasion to rethink the development of the area that has been affected and launch, at the initiative of the populations, a pilot development project that will receive the support of the public authorities. In this way, the living conditions of both the resettled populations and the host populations will be improved. A co-ordinated effort carried out in the area itself by government authorities and the local population should be facilitated by the establishment of specific operational mechanisms.

48. The alternative of resettling the victims of the disaster in their place of origin or on other sites depends on the assessment of risks of danger and the preventive measures that can be taken. The recommendations relating to these two factors of decision concerning resettlement show that some studies are under way and others will be carried out before an effective prevention system becomes operational.

49. Together with actions recommended for the assessment and reduction of hazards in the area concerned, a quick permanent solution should be sought for the resettlement of the disaster victims who cannot stay any longer in the temporary situation represented by camps.

50. It is proposed that alternative solutions should be sought to resettle them first near the disaster area, then within the region (division or province). In order to determine the area, the following activities are recommended:

(a) A preliminary zoning map should be carried out in the light of the risks that we know in the lake region (see also section D). Zonation should include the identification of:

(i) Valley bottoms, where settlements and permanent activities are not allowed;

(ii) Zones where temporary activities could be carried out;

(iii) High ground (except in the immediate vicinity of a lake) where settlement is allowed.

It must be considered that in the future it would be difficult to prevent people from going back to settle on the fertile lands of the disaster area as and when the memories and fear of disaster fade, whether or not detection facilities are installed. In any case, the resettlement of the disaster area should be planned by the public authorities so that permanent houses are built on high ground.

(b) The occupation of farm and grazing lands should be analyzed, their potential assessed, and their ownership or tenancy regulated. Potential areas for farming or grazing will be determined on the basis of the rural development programme being implemented in the area;

(c) Considering the relatively high population density in the area, it would be desirable that the resettlement go hand in hand with an intensification of agricultural and stock-farming activities which will lead to an increase in productivity. In particular, cattle pest-control programmes will be necessary;

(d) Infrastructures and collective facilities for the villages should be provided in order to attract the people. Access roads will be a priority. The facilities should meet the needs of the victims and those of the people receiving them. Resettlement will thus be integrated into the development of any given area;

(e) The participation of the people concerned should be supported by public bodies. They should be given a sufficient measure of initiative in the building of houses, farming, grazing, etc. and at the same time they should be given the necessary help to permit them restart life, like providing them with building materials, tools, seed, livestock as well as means of information and training to enable them improve their production methods.

51. In addition, the feasibility and need for an epidemiological study of survivors should be considered, focusing on the possible long-term respiratory and neuro-psychiatric consequences of exposure to the gases.

F. PREDICTION AND WARNING OF FUTURE POTENTIALLY DISASTROUS EVENTS

52. The possibility of making predictions and issuing warnings of future potentially disastrous events, such as those that occurred at Lake Monoun and Lake Nyos, was examined by the Conference and it was made clear that no method of reliable prediction could be envisaged, at least until the recommendations given in section C above have been fully implemented. Until then, the authorities responsible for public safety should assume that any such events, if they occur, may occur without warning.

PART II: NATURAL HAZARDS IN OTHER AREAS OF NORTH-WEST CAMEROON

A. TYPES OF HAZARD

53. Two types of hazard must be considered: The possible occurrence of events similar to those at Lakes Nyos and Monoun (Type 1), or the renewal of magmatic activity along the active volcanic line of Cameroon (Type 2).

Type 1: The main hazard here is considered to be the emission of carbon dioxide, possibly mixed with some other gases such as hydrogen sulphide, from lakes in this region. An accompanying hazard is flooding through over-topping of a lake rim following lake disturbance. Collapse of part of a lake rim would cause flooding, mud or debris flows, or landslides. An additional hazard consequent on lake disturbance is pollution or loss of water supply.

Type 2: Hazards arising from a renewal of magmatic activity, such as ash falls, pyroclastic flows, mud and lava flows have to be considered. Hazards from volcanic and tectonic earthquakes originating in the area have also to be considered.

B. IDENTIFICATION OF HAZARDOUS LAKES

54. In order to make best use of the resources available, it is necessary to determine some priorities for the investigation of lakes. A preliminary survey may show which lakes are likely to be hazardous, and which may be quickly shown to be safe. Criteria for selecting lakes for further investigation include: (a) the density of surrounding population; (b) their physical characteristics such as the nature of the lake (whether or not a crater lake), its size and depths, the potential of the rim for failure, evidence of nearby recent or present-day hydro-thermal or seismic activity, local legends referring to past events, etc.

55. Selected lakes should be further examined to determine the level of potential hazard. This should be done initially by simple surveys of bathymetry, chemical and thermal stratification, carbon dioxide content in the water and carbon dioxide flux in soil around the lake.

56. Lakes which, by their depths, stratification and CO_2 content are judged to be significantly hazardous should be monitored regularly and in a more detailed fashion.

C. LONG-TERM MONITORING OF HAZARDOUS LAKES

57. Those lakes found to be potentially hazardous should be subjected to routine monitoring in order to establish a long-term data base which will make it possible to judge the significance of any unusual change in one of the parameters, and eventually lead to a more intensive study of the lake and its surroundings for the purpose of surveillance and eventual warning. In particular, measurements should be made of the following parameters, either continuously or at regular intervals: Water level; profiles of temperature, density and CO_2 content in the lake; CO_2 content in the surrounding soil; meteorological parameters, particularly rainfall; seismic activity (one seismometer near each such lake).

58. It would also be helpful to obtain some sample cores of sediments from lakes thought to be hazardous and to seek evidence of past disturbances.

D. ZONATION OF LAKE HAZARDS

59. The main purpose of hazard zonation is to identify and map the areas liable to be affected in the event of one or more of the phenomena mentioned in section C above.

60. A preliminary zonation of the hazard associated with gas bursts from lakes would be based on a study of the topography of the surrounding areas

and on the experience of the spread of lethal gas from Lakes Monoun and Nyos during the recent disasters there. More precise zonation may be based on mathematical modelling of the propagation of a gas cloud, taking into account its volume and density, the main features of the local topography and various possible meteorological conditions. Parameterization of such models might be based to some extent on the results of research into the dispersal of industrial effluents into the atmosphere.

61. Zoning for flood hazards associated with the possibility of large volumes of water from lakes may be based on the results of the many studies already made throughout the world of flooding resulting from the failure of man-made dams.

E. GENERAL VOLCANIC AND SEISMIC HAZARD ZONING

62. In addition to hazards particularly associated with lakes and their water throughout the area, there is an overall hazard and volcanic activity and earthquakes. In addition to contributing to hazard on their own account, such events may also contribute to the triggering of lake overturning leading to gas emission and overspill.

63. Eruptions of Mount Cameroon are well known, the most recent being in 1982, and magmatic and phreatic activity could occur elsewhere along the Cameroon Volcanic Line as indicated by radiometric data and the recent history of monogenic basaltic volcanism. Similarly, earthquakes are known to occur along this line, but up to now have not been adequately monitored. As recently as January 1987, an earthquake of magnitude 5 occured near Tibati and was felt over a wide area.

64. To evaluate these hazards more precisely and to improve understanding of the processes causing them, additional regional surveys should be carried out, including geological mapping of rock type and structure and surveys of geophysical parameters such as gravity, magnetism, conductivity and geothermal heat flux. Remote sensing techniques and satellite imagery appear to be useful in carrying out this work. Regional structures which have controlled the distribution of volcanic eruptive centres should be carefully evaluated from available and future remote sensing imagery. Particular attention should be paid to intersecting zones of weakness that could control the location of the future volcanic activity. Maps of these features should be used to evaluate anomalous seismic or geochemical activity which may be identified in the future.

65. Reconnaissance geological maps should be made of the areas immediately surrounding in North-West Cameroon. Such generalized maps should show the distribution of pyroclastic ash deposits and other volcanic products. Special care should be taken to evaluate the age of such deposits by careful observations of the degree of erosion.

66. It is further recommended that regional mapping of the abundance of elements and isotopic compositions of soil gases be undertaken, including carbon dioxide, helium, radon, etc., taking into account seasonal variations and contributions from respiration and fermentation processes within the soil. Stations that record data continuously should be set up near lakes containing high amounts of carbon dioxide at control locations, enabling correlations to be made of variations of gas flux with seismic data and water chemistry

67. The zoning of hazards associated with possible volcanic eruptions may be based on the methods described in the "Manual on Volcanic Hazard Zonation" published by UNESCO (Unesco, 1985).

68. Methods of seismic hazard zoning have been the subject of intensive study in many parts of the world, and abundant information of this subject is available in the scientific literature. Concurrently with seismic zoning, steps may be taken to formulate appropriate earthquake-resistant building codes.

69. For earthquake monitoring, the present network around Lake Nyos should be extended to link with the existing network in Cameroon, for which there are already plans for expansion. There should also be provision for the operation of mobile recording networks to study areas of particular interest or to investigate earthquake sequences and swamps. All institutions concerned with seismic monitoring should co-operate in network planning and sharing of data, and additional co-operation with institutes outside Cameroon is invited.

F. INTEGRATION OF HAZARD INFORMATION INTO REGIONAL DEVELOPMENT PLANNING

70. It is vital that emphasis be placed on disaster preparedness and planning at local community level both in the long-term and in the short-term. More specifically:

(a) In the short-term, the local communities are the critical operative (and analytic) units for the distribution of information in emergencies and for contingency plans for leadership and the rapid and appropriate distribution of resources;

(b) In the long-term, it is at the local, and specifically at the family and kinship level, that most rehabilitation occurs.

71. Towards this end, the requisite analyses of indigenous land tenure and settlement patterns, as well as agricultural and pastoral practices, should be available to the planning commissions, and suggestions should be solicited from the community.

72. The Conference therefore suggests:

(i) That requests for relevant information be sent as soon as possible to every social scientist who has worked in the Bamenda Grassfields and to the resident members of voluntary organizations, in order to assemble a reservoir of information for planning;

(ii) That emergency preparedness training be initiated for all resident relief mission personnel, for all educational staff, and for local community leaders.

73. In order to strengthen local involvement, it is suggested that local education authorities assist in preparing and organizing disaster preparedness training and programmes, aimed at stimulating awareness of the nature of the hazards and of the steps that can be taken to protect individuals and communities against them.

V. CLOSING OF THE CONFERENCE

74. In closing the Conference the Minister of Higher Education and Scientific Research, on behalf of the Head of State, the Government and people of Cameroon, thanked all the scientists and all those who took part in the Conference. He pointed out that he was particularly happy that, despite the divergence in opinion as to the causes of the Lake Nyos disaster, there was consensus as to the recommendations for developing an infrastructure to monitor the behaviour of Cameroonian lakes and their immediate environments and to develop capabilities for coping with such emergency situations in the future.

75. The Conference was then declared closed at 7.30 p.m. on 20 March 1987.