Modeling a Release Scenario of Carbon Dioxide – Lake Nyos Disaster

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***Abstract*— On August 21, 1986, Lake Nyos in Cameroon released a large cloud of Carbon dioxide and suffocated people and livestock up to 25 km from the lake. To model the scenario - Complex Hazardous Air Release Model (CHARM) - a sophisticated tool has been used to simulate hazardous accidental release. This study covers process of data acquisition and its utilization in CHARM to see the impact in both 2-D and 3-D. Simulation was performed to demonstrate an example of a software tool that can be used to analyze a real-world scenario of chemical release. Real-world release modeling requires actual terrain data, meteorological information, and impact levels and the study describes bringing all that information together to compare the simulation results with the real-world reported impacts. Model was set to run to visualize impact and it was found that upto 10 km area affected from released location in 3 minutes duration contrary to 23 km as mentioned in research [1]. Affected area reported in literature up to 23 km or 25 km implies that the distances given are travel distances following the terrain and not distances following a bee-line (Straight line).**

***Index Terms* — CHARM; accidental release; remote sensing; Digital Elevation Model (DEM); surface roughness; Lake Nyos.**

I. Introduction

An event of excess gas release occurred naturally in 1986. It was happened in Lake Nyos which is Crater Lake situated in Cameroon, Africa. It was found by Researchers that a pocket of magma lies beneath the lake and leaks carbon dioxide (CO_2) into the water, changing it into carbonic acid. Unlike usual normal leakage; on August 21, 1986 Lake Nyos suddenly emitted a large cloud of CO_2 which suffocated 1,700 people and 3,500 livestock in nearby town and villages within 25 km. Though not completely unprecedented, it was the first known large-scale asphyxiation caused by a natural source mentioned in researches [1]-[3].

Human bodies were found at Fang, 23 km from the emission spot and animals were found dead 120 m above the lake level, on its southern side. Cliff on the southwest shore of the lake had been stripped of its surface cover up to 80m above the lake [1].

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To explain how the CO_2 was given off two hypotheses have been considered. The limnic hypothesis puts forward a spontaneous inversion of the lake triggered by a local variation in density, causing the movement of deep layers saturated in CO_2 towards the upper most CO_2 unsaturated layer. Furthermore, the volcanic hypothesis puts forwards a sudden emission of a large volume of CO_2 of volcanic origin from far underneath the lake [1].

Reference [1] concluded that the event as a volcanic origin based on sudden emission of CO_2 from the lake bottom. Contrary to the volcanic origin consideration; limnic hypothesis is discussed in this paper to explain the release of CO_2 due to inversion of the lake triggered by a local variation in density, causing the movement of deep layers saturated in CO_2 towards the upper most CO_2 unsaturated layer.

Complex Hazardous Air Release Model (CHARM ®) is used as modeling tool to visualize the release scenario [4], [5]. CHARM can calculate such type of releases in an atmosphere using different sets of data like release type, release parameters, meteorological parameters, digital elevation etc. as per model requirements. Several parameters such as Effected area, effected height on different sides of cliff, volume of estimated release of pure CO_2 related to release in Lake Nyos in 1986 are available in research [1]. CHARM has built in chemical properties of more than 200 chemicals and other properties which are related to release and propagation in environment and produces results in 2-D and 3-D.

II. Material

A. Satellite Base Map

CHARMInetMap software utility was used to download background satellite images. CHARMInetMap is the free mapping software utility [6]. It gives freedom to download and save image of your study area from Google®, MapQuest® or Bing®. The main advantage is that the maps are not required to geo-referenced. Downloaded maps are saved with projection information and are used in CHARM without any preprocessing.

B. Digital Elevation Model

To model scenario terrain information is always required as actual terrain provides obstacles and channels. 30 M DEM is available free at WEBGIS website [7]. The DEM was downloaded from WEBGIS website to provide terrain information to the model.

C. Meteorological Parameters

Meteorological parameters play a major role for transport of atmospheric pollutants. Ambient temperature, pressure, Humidity, wind direction and wind speed are necessary to be incorporated addition to the stability class.

The information may be collected from different ways. National Weather Service (NWS), USA provides real time weather information of several stations around the world [8]. This meteorological information can be incorporated directly into CHARM using meteorological interface MetInter which updated automatically and update generated plume. On the other hand, Meteorological information can be entered manually considering mean values of study area. To get real time meteorological parameter portable met station such as WeatherPak® MTR can be used [9]. Such types of met stations are capable to send date remotely to its receiving unit. The receiver data has an interface with the computer and CHARM can receive data through the same meteorological interface MetInter and updates the plume.

In case of Lake Nyos event on August 21, 1986 the literature survey was conducted to acquire observed facts and figures for the model input [1]. As per local meteorology of the event day near Lake Nyos; day averages were noted. Ambient Temperature 22° C, Relative Humidity 50%, Wind Speed 1.5 m/s, Wind Direction Southward and stability class D were incorporated in the model.

D. Surface Roughness Data

Surface roughness is a measure of the interaction between the wind and the surface [10]. Surface roughness of 1km resolution for entire world is available at USGS website [11]. This is called Global Land Cover Characterization (GLCC) data. Some examples of surface roughness are mentioned in Table I [10]. Surface Roughness Data was acquired from USGS website for the study area.

TABLE I. SURFACE ROUGHNESS EXAMPLES

Surface	*Roughness (cm)*
Smooth mud flats; ice	0.001
Smooth snow	0.005
Smooth sea	0.02
Level desert	0.03
Snow surface; Lawn to 1cm high	0.1
Lawn, grass to 5 cm	1-2
Lawn, grass to 60 cm	4-9
Fully grown roof crops	14
Parkland, bushes	50
Large obstacle; suburb, forest	50-100

E. Chemical Parameters

Chemical and Physico-Chemical properties determine the behavior of released particles in an environment. For example in case of gas if it is lighter than air it behaves differently compare to the gas which is heavier than air. In Lake Nyos incident the released gas is CO_2 which is heavier than air. Fortunately CHARM has a built in database and contains most of the properties of CO_2 which are required for modeling like Triple point Temperature and Pressure, Critical Temperature, Critical Pressure, Critical Volume, Heat of Vaporization, Surface Tension of Liquid Phase, Liquid Density and Vapor Heat Capacity [12].

F. Data related to catastrophic event

Data related to release of CO_2in Lake Nyos was collected through ground survey by researchers and other reporting agencies which is available in literature and was used for manipulating boundary conditions and for other estimations [1]. Effected area= 25 km, effected height= 120 m on southern side and 80 m on cliff on southwest shore, volume of estimated release of pure CO_2 =0.6 km^3.

G. Acute Exposure Guideline Levels

In Lake Nyos event CO_2 was released for few minutes and suffocated people and livestock within 25 km of radius due to its toxic effect. There are different levels of threat poses by toxic substances and several standards have been formed to explain them. One of them is Acute Exposure Guideline Levels (AEGL) for high priority toxic chemicals. Other guidelines are Threshold limit values (TLVs) and Occupational Exposure Limits (OELs). Threshold Toxicity Values of CO_2 are mentioned in Table II [13] below.

TABLE II. THRESHOLD TOXICITY VALUES

Exposed via inhalation		
ppm	***mg m^{-3}***	***Symptoms***
20,000	36,000	Headache and dyspnoea (several hour exposure)
30,000	54,000	Weakly narcotics, reduced hearing, hypertension, tachycardia
50,000	90,000	Headache, shortness of breath, dizziness, confusion, respiratory distress
80,000 – 100, 000	108,800 – 180,000	Severe headache, sweating, dimness of vision, tremors and loss of consciousness in 5-10 minutes
120,000	216,000	Unconsciousness may occur
200,000 – 300,000	360,000 – 540, 000	Exposure can cause convulsions and coma within one minutes

III. METHODS

A. Base Map, Digital Elevation Model & Surface Roughness

Base Map, Digital Elevation Model & Surface Roughness which were downloaded from their respective sites now shown as Fig. 1, Fig. 2 and Fig. 3 respectively in CHARM Editor (CharmEd). This editor is an application to work with maps, DEM, Surface Roughness and other utilities. It is noted that Digital Elevation (Fig. 2) and Surface Roughness (Fig. 3) have a representing value of each square in a Grid. Presently each square representing 200 x 200 m^2 while Fig. 4 representing

3-D version so that one can visualize the terrain of study area without map and Fig. 5 representing DEM along with Base Map.

Fig. 1. Geo referenced Base Map of Lake Nyos viewed in Charm Ed.

Fig. 2. Grid over Base Map projecting elevation on each square of grid.

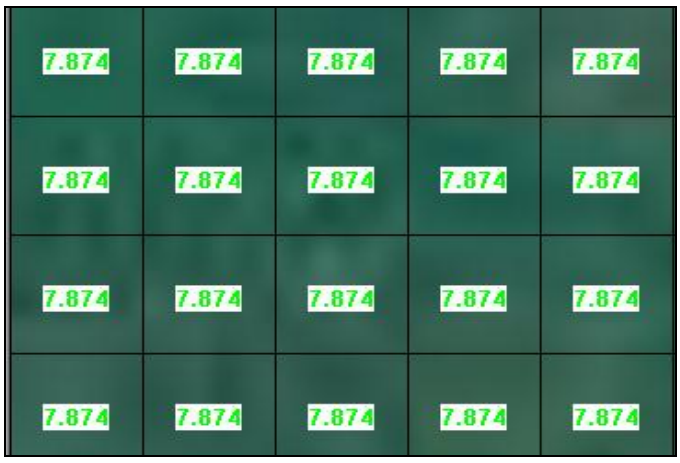

Fig. 3. Grid over Base Map projecting Surface Roughness over grid.

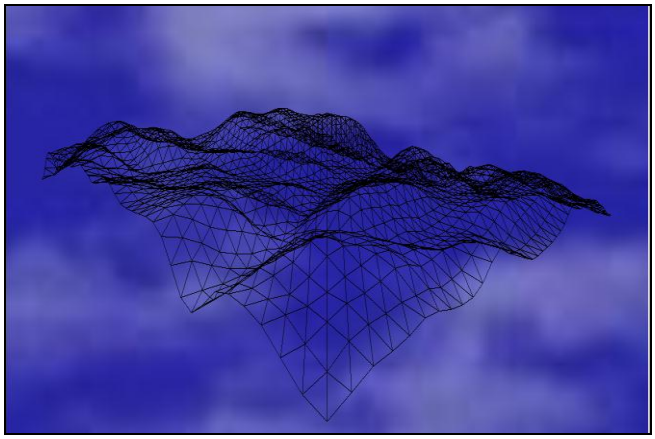

Fig. 4. 3D Mesh showing terrain formation of Lake Nyos and surroundings.

Fig. 5. 3D view of Lake Nyos and surroundings with DEM and Base Map.

B. CHARM® input screen

Fig. 6 representing main CHARM® input screen. It has three main sections. In first section data related to Lake Nyos release scenario which has been noted earlier has to be incorporated. Second section is showing Grid data and third section is showing meteorological data. Input data is given below:

Version 11.42.0.3
Title: Release over three minutes at Lake Nyos. Exit speed calculated - August 21, 1986
Species: Carbon Dioxide
No radionuclide selected
Species Surface Deposition Efficiency: 0
Release type: User Specified After-Release Conditions
Emergency response output: Plume
Location: 6° 26.1353' N, 10° 17.7833' E
Isopleth Concentrations (ppm): 5000 , 5e+004 , 5e+005
Release delay time: 0 sec

Release Height Above Ground	0 ft
Continuous Emission Rate is constant	
Initial Emission Rate:	3.333e+006 cms
Release Duration:	3 min
No particle distribution defined	
Exit Temperature:	22 °C
Source Diameter:	1000 m
Emission moving opposite of wind direction	
Vertical Angle of Release:	90°
Exit Speed (Calculated):	4.244 m/s
Exit state assumed vapor	
Droplet Mass Fraction:	0
Molar Water Vapor Fraction:	0
Molar Air Fraction:	0
Grid Data	
Title: Area around Lake Nyos extending northward toward highway	
Min Altitude: 722 m, Max Altitude: 1.44 km	
Min Roughness: 0.03 cm, Max Roughness: 50 cm	
Nx = 43, Ny = 43, Nz = 50	
Dx = 200 m, Dy = 200 m, Dz = 20 m	
SW Corner at 6° 25.3179' N, 10° 15.0173' E	
Met Data	
Title: 1.5 m/s wind speed, 22C, D	
Location: 6° 26.7249' N, 10° 17.9521' E	
No particle distribution defined	
Relative Humidity:	50 %
Ambient Temperature:	22 °C
Ambient Pressure:	1 atms
Cloud Cover (tenths)	10
Stability Class: D (User supplied)	
Solar Radiation	0 kW/m²
No inversion present	
Wind measurement height	10 m
Winds Time Direction Speed	
00:00 180° 1.5 m/s	

Fig. 6. CHARM ® main input screen.

C. Simulated output

Model was run to see the impact of the release with all necessary parameters. The vertical angle of release was set to 90 ° and release diameter 1000 m to get reasonable result. Release duration was set to 3 min. Exit Temperature and Ambient Temperature were set to 22 °C while exit speed was calculated by CHARM itself which was 4.244 m/s instead of 28 m/s as described in [1]. Wind speed is low and it was assumed 1.5 m/s and Southward. Stability Class was taken as 'D' which is denoted as "Neutral". To identify different threat zone the data related to Threshold Toxicity values were also assimilated. Three zones were considered 5,000 ppm, 50,000 ppm and 500,000 ppm for output display whereas 200,000 ppm is life threatening zone as mentioned in Table II which lie well in given range. Fig.7 representing color codes of the output display for three set zones.

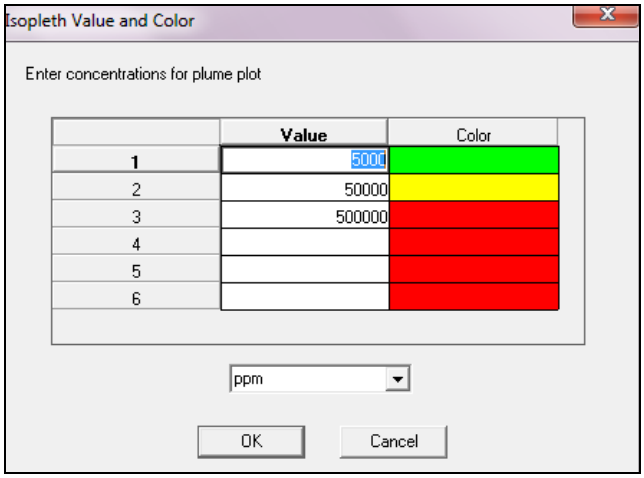

Fig. 7. CHARM ® main input screen.

IV. RESULTS

Model was set to run for 1 hour to visualize impact in both 2-D and 3-D. Fig. 8 and Fig. 9 showing 2-D and 3-D visuals for 1 hour of CO_2 release respectively. Fig. 10, Fig. 11 and Fig. 12 are the cross-sectional views. Fig. 10 is representing West-East view over lake. Released gas is moving northward extend of the lake as well as East and West sides over the hill. Fig. 11 is showing extension of the plume along the length of the lake moving towards North West direction. In Fig. 12 Released gas partially moving along the North East direction following terrain and moving along the highway. From Fig. 13 it is clear through graph plot that more than 600,000 ppm of CO_2 is still present up to 3.75 km which is almost 3.0 times greater than the 200,000 ppm – 300,000 ppm limit mentioned in Table II. which can cause convulsions and coma within a minute. Release impact at any point on map with in impact of foot print can be obtained by clicking on desired location. Fig. 13 also shows 3.75 km away in Northward direction (4° NE from release location) the concentration of CO_2 reached at 50,000 ppm or more after 18 minutes of release and within an hour the concentration reached at around 800,000 ppm. Fig. 14 is a dose table representing actual dose at selected location for model runs for 1 hour duration.

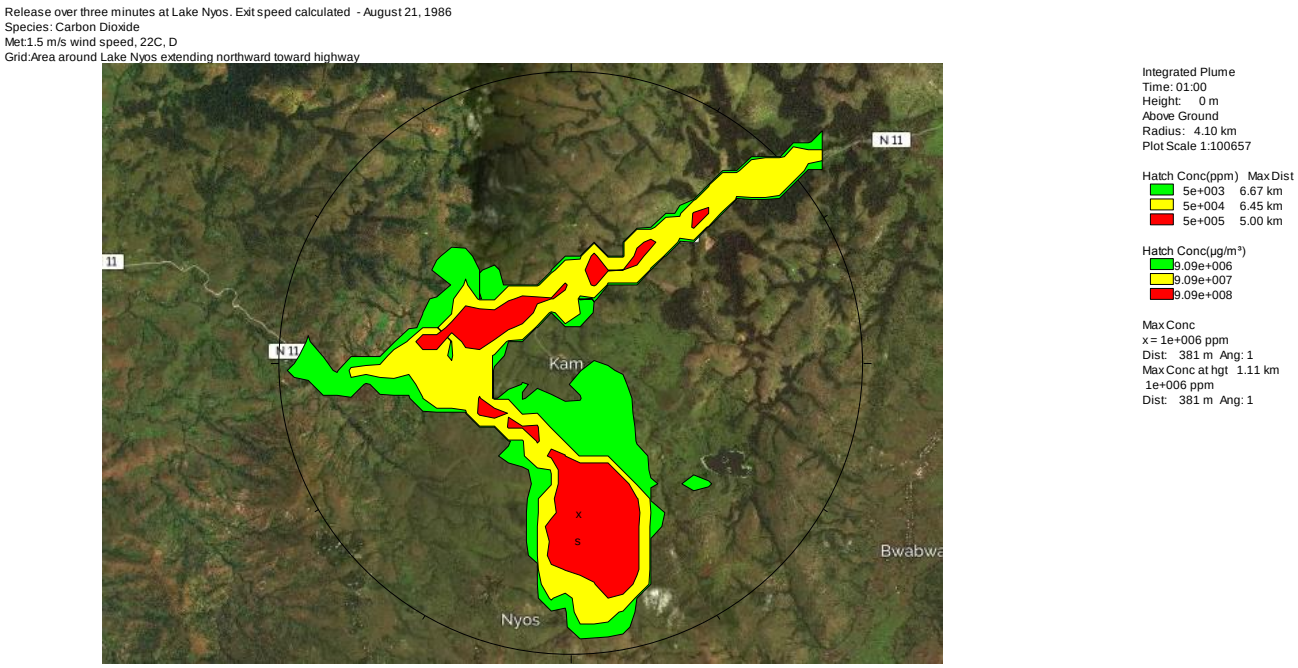

Fig. 8. CHARM ® model run for 1 hour in 2 - dimensional display

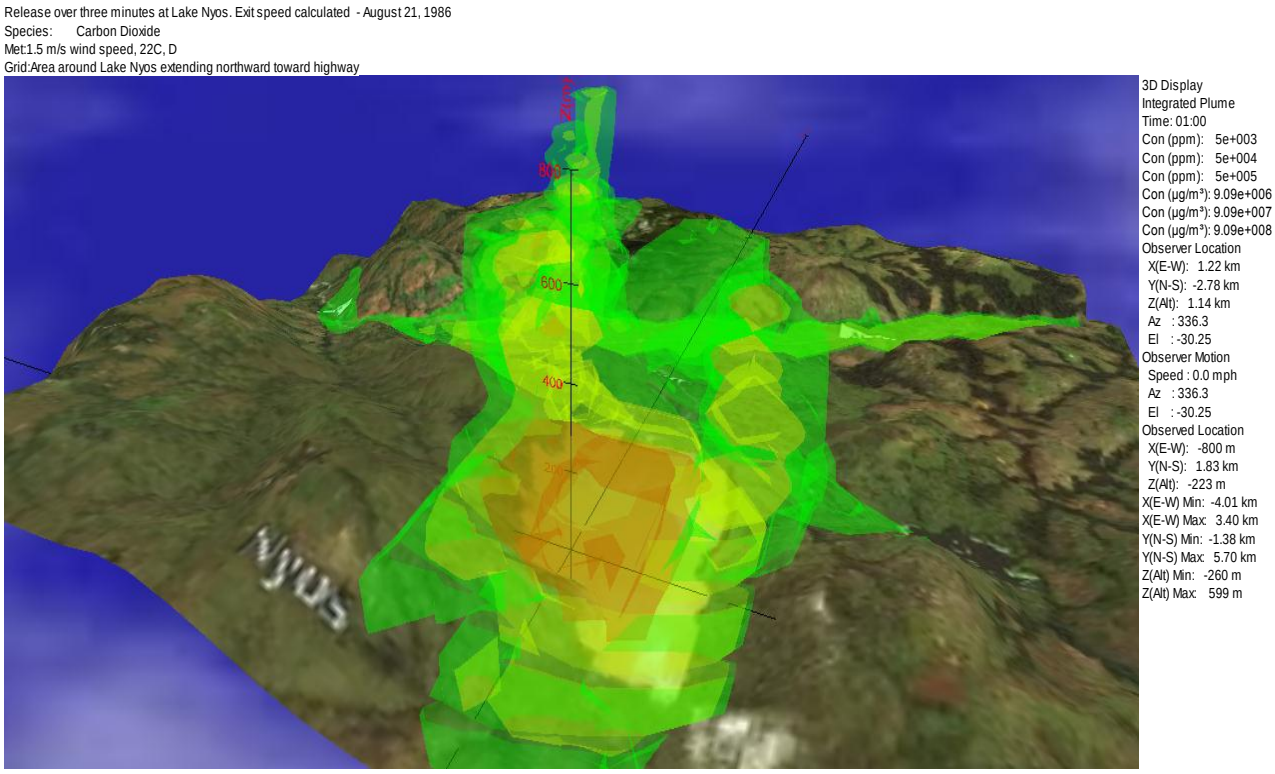

Fig. 9. CHARM ® model run for 1 hour in 3 - dimensional display

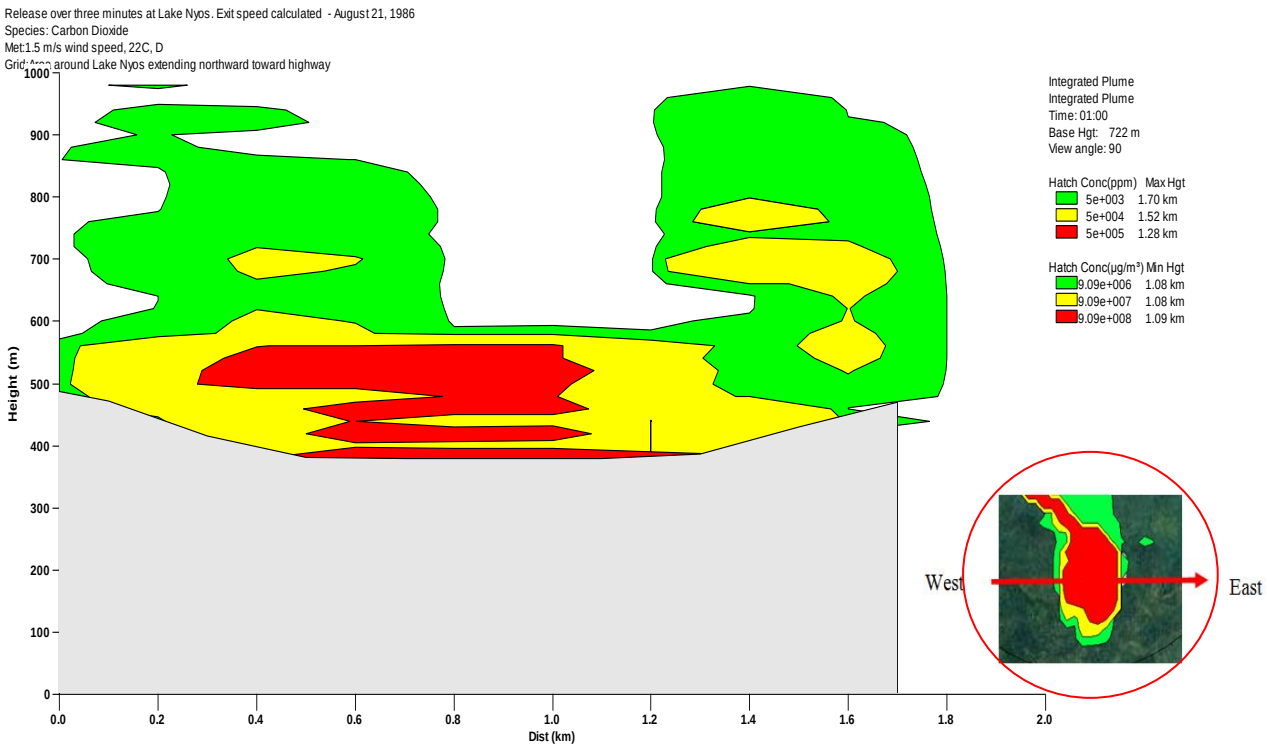

Fig. 10. Cross sectional view over lake (West-East) for entire 1 hour model run. Released gas is moving over hills present at both western and eastern side of Lake. Location of crossectional view showing in figure inset.

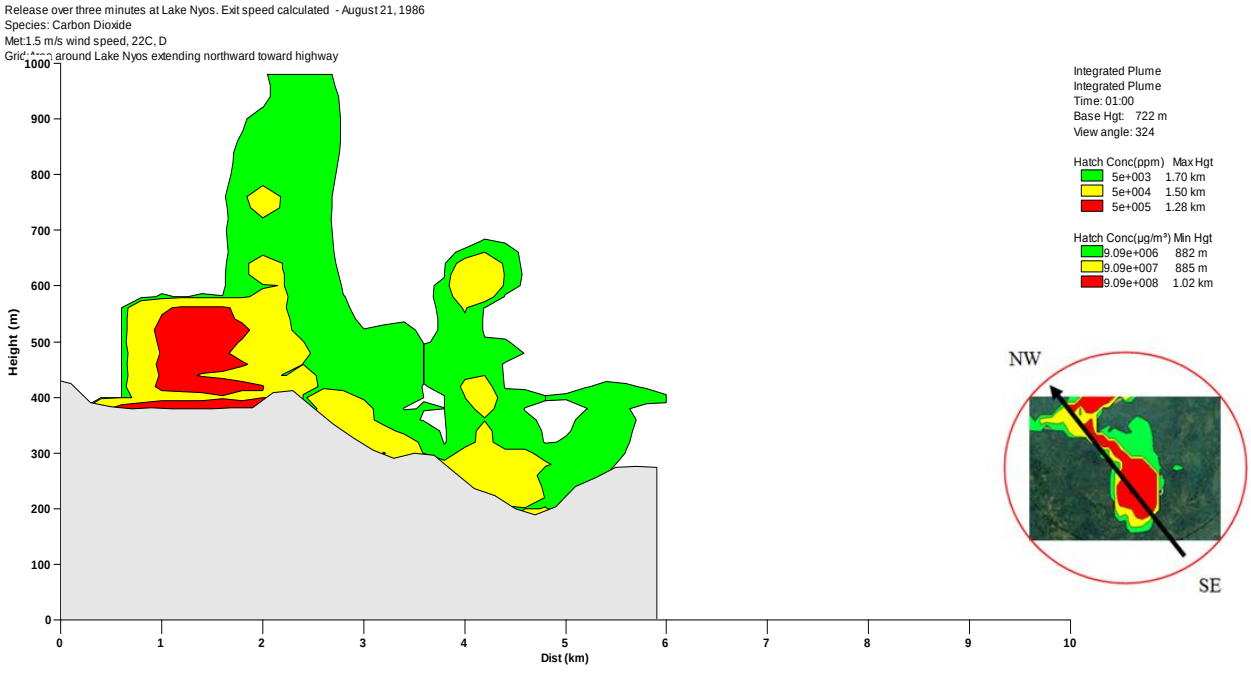

Fig. 11. Cross sectional view over lake (SE-NW) for entire 1 hour model run. Released gas is moving towards NW following Terrain. Location of crossectional view showing in figure inset.

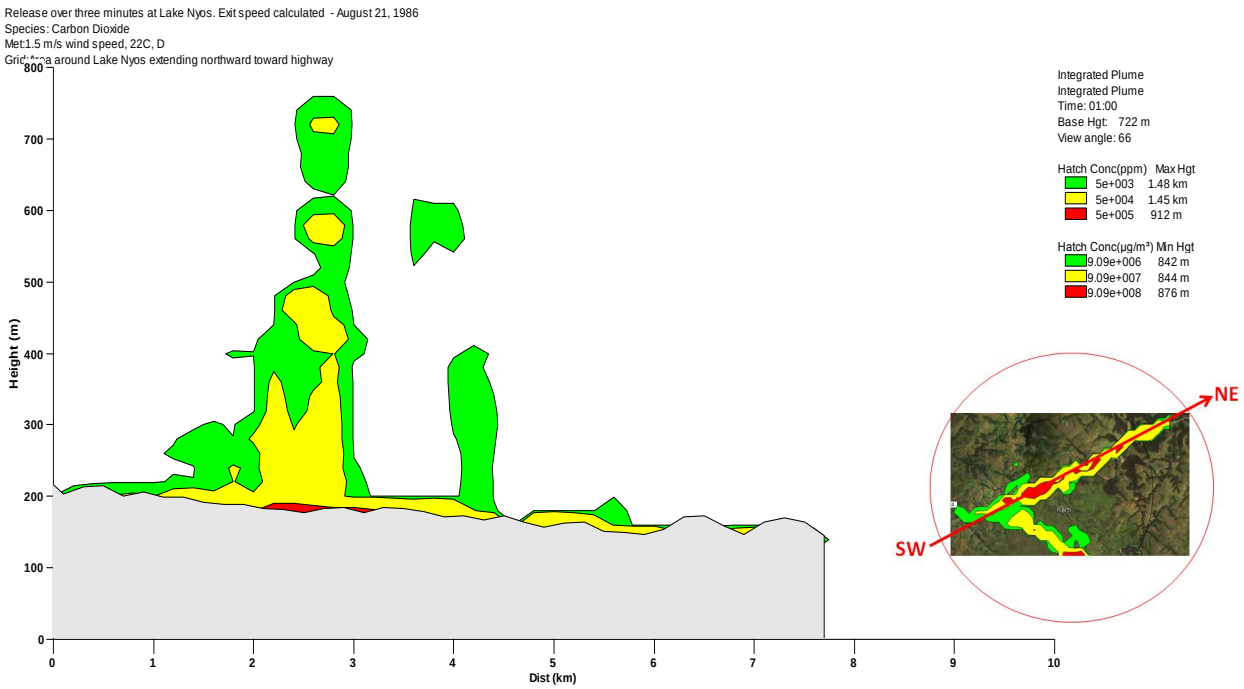

Fig. 12. Cross sectional view over lake (SW-NE) for entire 1 hour model run. Released gas is moving towards NE from SW direction following Terrain and moving paralllel to the highway. Location of crossectional view showing in figure inset.

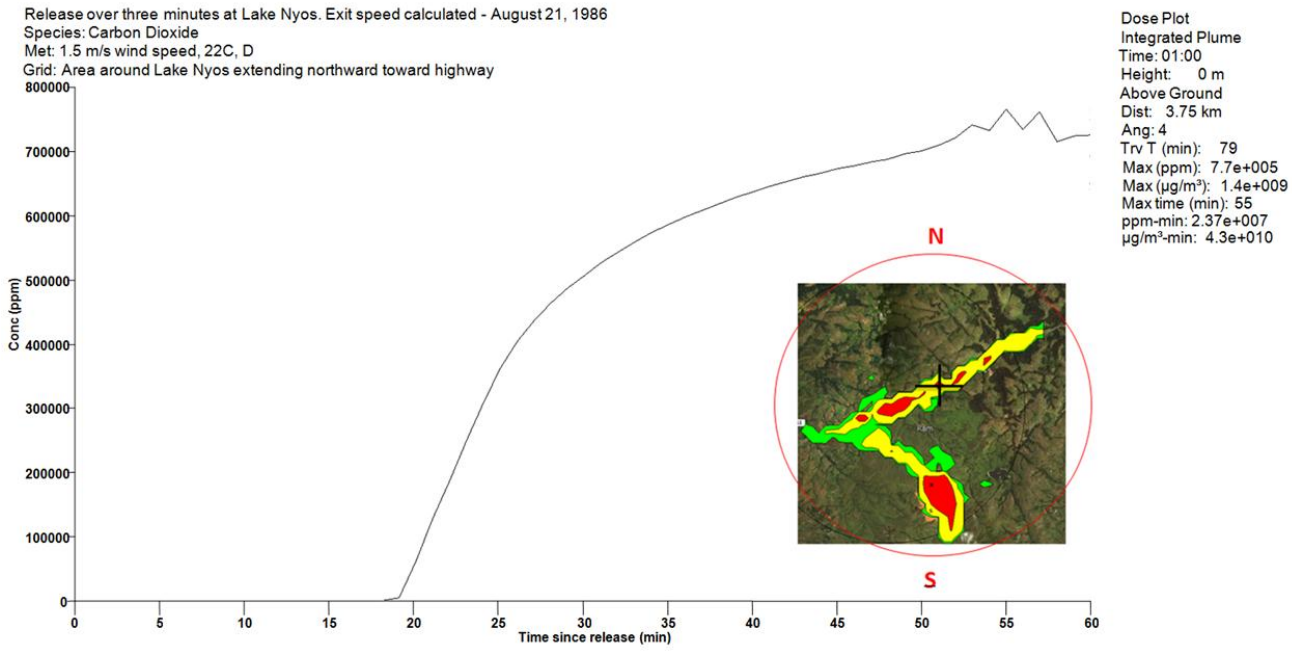

Fig. 13. Concentration in ppm versus Time in minute plot showing impact after release and reached at value around 800,000 ppm within 20 minutes. Location of selected location showing by "plus" in figure inset

Release over three minutes at Lake Nyos. Exit speed calculated - August 21, 1986
Species: Carbon Dioxide
Met: 1.5 m/s wind speed, 22C, D
Grid: Area around Lake Nyos extending northward toward highway
Dose Table
Snapshot Plume
Time: 01:00 Height: 0 m Distance: 3.79 km
Angle: 4
Above Ground
Travel Time (min): 80 Averaging Time (min): 0
Dosage: 2.63e+007 (ppm-min), 4.78e+010 (µg/m³-min)

Time (min)	*Conc (ppm)*	*Conc (µg/m³)*
1.	0	1
2.	1.82e-038	3.32e-035
3.	2.57e-034	4.67e-031
4.	4.88e-028	8.87e-025
5.	5.05e-024	9.17e-021
6.	4.8e-021	8.72e-018
7.	1.11e-018	2.01e-015
8.	9.83e-017	1.79e-013
9.	4.4e-015	8e-012
10.	1.18e-013	2.14e-010
11.	2.25e-012	4.09e-009
12.	1.71e-010	3.11e-007
13.	1.2e-007	0.000217
14.	2.71e-005	0.0493
15.	0.00145	2.64
16.	0.197	358
17.	6.46	1.17e+004
18.	219	3.99e+005
19.	3.3e+003	6e+006
20.	6.15e+004	1.12e+008
21.	1.44e+005	2.62e+008
22.	2.09e+005	3.79e+008
23.	2.79e+005	5.07e+008
24.	3.46e+005	6.28e+008
25.	4.06e+005	7.37e+008
26.	4.55e+005	8.26e+008
27.	4.91e+005	8.93e+008
28.	5.22e+005	9.49e+008
29.	5.49e+005	9.97e+008
30.	5.73e+005	1.04e+009
31.	5.95e+005	1.08e+009
32.	6.14e+005	1.12e+009
33.	6.32e+005	1.15e+009
34.	6.48e+005	1.18e+009
35.	6.63e+005	1.2e+009
36.	6.76e+005	1.23e+009
37.	6.88e+005	1.25e+009
38.	7e+005	1.27e+009
39.	7.11e+005	1.29e+009
40.	7.21e+005	1.31e+009
41.	7.3e+005	1.33e+009
42.	7.38e+005	1.34e+009
43.	7.46e+005	1.36e+009
44.	7.54e+005	1.37e+009
45.	7.6e+005	1.38e+009
46.	7.67e+005	1.39e+009
47.	7.72e+005	1.4e+009
48.	7.78e+005	1.41e+009
49.	7.82e+005	1.42e+009
50.	7.87e+005	1.43e+009
51.	7.9e+005	1.44e+009
52.	7.93e+005	1.44e+009
53.	7.93e+005	1.44e+009
54.	8e+005	1.45e+009
55.	7.95e+005	1.44e+009
56.	7.99e+005	1.45e+009
57.	8.02e+005	1.46e+009
58.	8.13e+005	1.48e+009
59.	8.17e+005	1.48e+009
60.	8.19e+005	1.49e+009
60.	8.19e+005	60 1.49e+009 [MAX]

Fig. 14. Dose table of the Concentration of CO_2 for selected location for the entire release time of 1 hour.

V. Conclusion

The released volume 0.6 km^3 was set to account for asphyxiation of people 23 km away from the lake [14]. Release duration was considered 3 min which is enough to effect surrounding area up to the Fang which appears at 10 km in Google contrary to 23 km as mentioned in [1]. This has been mentioned in literature that affected area up to 23 km or 25 km implies to me that the distances given are travel distances following the terrain and not distances following a bee-line (Straight line). This showed that the grid used in the CHARM should be sufficient for covering most of the area of interest. Reference [1] mentioned that the release was *volcanic origin* resulting in a vertical jet of CO_2 somewhere between 75 and 100 meters in width. It has been argued that such jet is needed to get a 20% CO_2 concentration up to 120 meters above the lake surface. On the other hand the cross section of an Integrated Plume calculated by CHARM shows that a 20% may go much higher than 120 meters above the lake surface. The concentration was above 20% for only about few minutes but the maximum concentration was noted more than 80%. The dose may have then been sufficient for death. The path breaking east-west after traveling north some distance indicated it was operating in agreement with observation and that CHARM appeared to be correctly predicting the general behavior of the released cloud both in trajectory and in concentration and explained the *limnic origin* of release in which a spontaneous inversion of the lake triggered by a local variation in density, causing the movement of deep layers saturated in CO_2 towards the upper most CO_2 unsaturated

layer. The exact meteorology as well as released duration & temperature of gas at the time of release were unknown due to non-availability of related data in literature. There is a possibility that the release was much colder than the assumed 22 °C and it would go -6 °C when the release would be assumed to be simply due to depressurization.

The concentrations at the location to the southwest at 120 m above the lake and the 80 m high to the south were high enough to cause the effects noted. Simulated results support actual findings related to the event shows that CHARM appeared to be giving reasonable results in the near field.

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