



DID GLOBAL WARMING AND CLIMATE CHANGE CAUSE THE DEGRADATION OF LAKE CHAD, AFRICA'S MOST IMPORTANT 'ECOLOGICAL CATASTROPHE'?

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ABSTRACT

This paper explores six hypotheses/theories on Lake Chad's degradation: i) natural climate variation; ii) anthropogenic climate change compounded the effects of the Sahel drought; iii) unregulated exploitation of Lake Chad's hydrologic system overwrote the regenerative potential of the lake system; iv) high rates of deforestation in the tropical rain forest belt of West-Central Africa shifted the rain belt Southwards; v) pressure from rapidly expanding human and livestock populations exceeded the carrying potential of the Lake Chad ecosystem; and vi) anthropogenic aerosol emissions in the northern hemisphere shifted the tropical rain-belt southwards. The evidence shows that there is no single-cause explanation for Lake Chad's degradation; rather the influence of global warming and climate change compounded those from pre-existing drought conditions and non-climate factors e.g unregulated exploitation of Lake Chad's hydrologic system to degrade the lake.

Contribution/Originality: The paper contributes to the existing literature by exploring six hypotheses/theories to show that the influence of global warming and climate change on ecosystems can be compounded by non-climate variables. The degradation of Lake Chad illustrates vividly the interaction between the climate factors and non-factors in eco-system degradation.

1. INTRODUCTION

1.1. Background and Purpose of Study

Global warming and climate change¹ constitute the major environmental degradation challenge facing human societies currently. Its symptoms in Earth's ecosystems have been intensely studied and extensively documented in the climate literature. This paper explores the literature in order to identify and analyse the symptoms of global warming and climate change in ecosystems. Specifically, it examines how climate change degrades ecosystems, with particular focus on the response of inland freshwater ecosystems to climate change, drawing empirical illustration from the degradation of Lake Chad, an inland freshwater lake ecosystem embedded in the West African Sahel. Lake Chad's degradation clearly illustrates the interaction between the climate factor and non-climate factors in the degradation of ecosystems. The paper explores six theories/hypotheses to attempt to explain Lake Chad's experience: (i) natural climate variation; (ii) anthropogenic climate change compounded the effects of the Sahel drought to undermine the regenerative capability of Lake Chad's hydrologic cycle; (iii) unregulated exploitation of Lake Chad's hydrologic system overwrote the regenerative potential of the hydrologic cycle; (iv) high rates of deforestation in the tropical rainforest belt of West-Central Africa shifted the rainbelt southwards; (v) pressure

from growing human and livestock populations exceeded the carrying capacity of Lake Chad's ecosystem; and (vi) anthropogenic aerosols emissions in the northern hemisphere caused regional climate change that shifted the tropical rain belt southwards with steady decrease in precipitation in the Sahel. A careful survey of evidence shows that: First, there is no single-cause explanation for the degradation of Lake Chad; rather, the influence of anthropogenic climate change compounded those from non-climate factors – e.g. deforestation, unregulated exploitation of Lake's resources, etc. to degrade Lake; Second, Lake Chad's experience, quite exceptional though, tallies with the experience of other freshwater inland lakes.

Africa is endowed with some 677 inland freshwater lakes holding about 30,000 km³ of freshwater and yielding 1.4 million km³ of freshwater annually. As shall be shown, all major African inland lakes – e.g. Lakes Victoria, Tanganyika, Malawi, etc. – have been affected by climate change one way or the other. However, none seems to have been so degraded as Lake Chad. The 1950s and 1960s saw record levels in the size of Lake Chad; the 1970s onwards, with the unraveling of the current climate change dynamics, saw severe contraction of the surface area of the lake “changing its character to swampy delta at the mouth of the Chari River...” (Evans, <http://www.fao.org>). It seems, then, that climate change compounded the effects of preexisting Sahel drought to speed up the degradation of Lake Chad.

Figure 1 dramatizes the shrinking of Lake Chad's surface area: within a space of five decades (1963–2013) 90% of the lake's surface area disappeared. Quite an exceptional ecological degradation experience aptly described by the UNEP as an “ecological catastrophe”², Lake Chad's experience is surpassed only by that of the Aral Sea in South-Central Russia³. However, it tallies with the experiences of inland lakes in arid regions (e.g. Bai, et al. [1]).

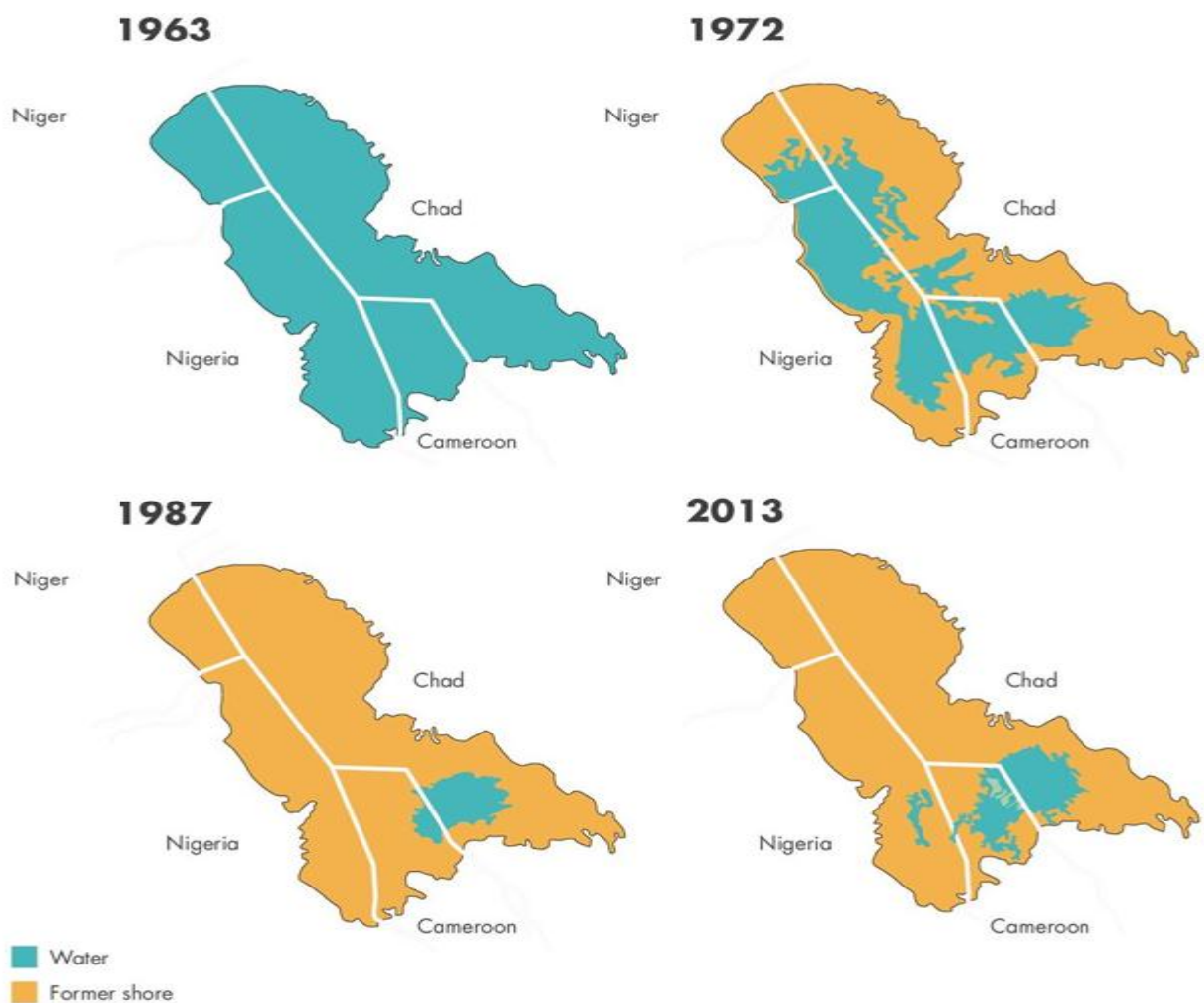


Figure-1. Changing Surface Area of Lake Chad, 1963 – 2013

Source: Nikoulima [2]

The literature, however, contains similar dramatic changes in many ecosystems: e.g., melting of mountain snow caps and ice covers;⁴ retreating polar glaciers;⁵ warming oceans leading to bleaching of coral reefs and sea level rise (SLR);⁶ destruction of the ozone layer (ozonosphere), which exposes Earth's biosphere to the harmful effects of ultraviolet (UV) solar radiation,⁷ etc. So, there is nothing particularly unique in the Lake Chad experience, if considered in the global context of current climate-change induced changes in ecosystems properties. However, there is still need to explore the following question. Is the shrinking of Lake Chad just a result of climate change or are non-climate forces involved?

1.2. Structure of the Paper

The remaining part of the paper is structured into four sections; as follows. Section 2 links climate change and ecosystems functioning, and shows how climate change influences the latter. Section 3 highlights salient features of the Sahel climate in which Lake Chad is embedded. Section 4 deals with a case study of the Lake Chad ecosystem proper, focusing on one of the Lake's key response variable to climate change, namely, long-run changes in water levels and surface area. Section 5 sketches the symptoms of climate change in top – 4 sub-Saharan African inland freshwater lakes (Lakes Victoria, Tanganyika, Malawi, and Lake Chad itself) in order to put Lake Chad's experience in a comparative perspective. Section 6 concludes the paper.

2. CLIMATE CHANGE AND ECOSYSTEMS DEGRADATION: SOME THEORETICAL ISSUES

2.1. Anthropogenic Climate Change

This, as already noted, describes observed long-term change over the centuries in the elements of climate, most important temperature and precipitation, caused by human-induced concentrations of green-house gases (GHGs) in Earth's atmosphere. This constitutes the major environmental degradation problem currently facing the global community. Two relevant facts are worth noting in current climate change. First, it is caused largely by human activities – so-called anthropogenic footprint of climate change, whereby combustion of fossil fuels (coal, petroleum products, natural gas) to drive economic development, deforestation, livestock production, etc. emit massive volumes of GHGs into the atmosphere.⁸ Specifically, huge build-ups of human-induced GHGs beyond the assimilation capacities of Earth's atmosphere as a natural 'waste sink' have transformed the chemical composition of Earth's atmosphere leading to fundamental changes in global temperatures and rainfall patterns, which, in turn, have destabilized ecosystems functioning, in some cases leading to irreversible changes in their regenerative potentials.

Table-1. Historical and Current Atmospheric GHG Concentrations

GHG	Average concentration 100 years ago (ppb) ^a	Approximate current concentration (ppb) ^a	Lifetime (residence in atmosphere) (years)	Approximate contribution of greenhouse effect (%)
Carbon dioxide	288,000	370,000-400,000	120	9-26
Methane	848	1,800	12	4-9
Nitrous oxide	285	312	120	n.a.
Chlorofluorocarbon (CFCs) and halocarbon	0	1.2	5-100	n.a.
Water vapour	n.a.	Most abundant GHG	n.a.	36-70
Aerosols ⁶ and soot (black carbon)	n.a.	n.a.	Drops out within weeks	n.a.
Ozone (O ₃)	n.a.	n.a.	n.a.	3.7

Source: Compiled from Wright and Nebel [3] Table 21-22, p. 520; see also Schmidt [4]; Russel [5].

Notes: n.a. = not available

- a ppb = parts per billion. When natural scientists analyse atmosphere GHG concentrations they use the term ppb or ppm (parts per million), which is a stock or mass phenomenon.
- b Aerosols have cooling effect in contrast to other GHGs which heat up the atmosphere.

Second, it is occurring at a pace hitherto not experienced in any part of the world. Scientific evidence shows that Earth's average surface temperatures have warmed up as much as by 6°C (42.8°F) over the past century, 60% of this occurring in the 1970s onwards, and is projected to rise further if no effective measures were taken to reduce significantly GHG atmospheric emissions.

Table 1 shows that atmospheric carbon dioxide concentrations were stable at 270-288 parts per billion (ppb),⁹ the 'natural bound', for a long time prior to the European Industrial Revolution of the 1700s and 1800s. Thereafter, they moved beyond the 'natural bound' to current levels put variously at 395 and 400 ppb. It may be relevant to note to conclude this theme, that scientists had speculated on global warming till the late 1900s, but it was not until the 1980s, when the idea of global warming evolved to become "one of the biggest arguments of our time" [6]. The 19th century Swedish physicist Svante Arrhenius pioneered the theory of the link between human combustion of carbon dioxide emitting fossil fuels and rising global surface temperatures which he described as the 'Greenhouse effect' [7]. Although Arrhenius's idea remained in circulation until the 1960s, most scientists had dismissed it as implausible, believing, instead, that the oceans and other natural 'sinks' (forests, etc.) would absorb carbon dioxide faster than human-induced sources would emit the gas. As it turned out, the opposite has happened: human-induced sources (industrial, agricultural, transportation, domestic activities, etc) emit more carbon dioxide than natural 'sinks' can effectively absorb – which is the major cause of current trends in rising global temperatures and changing precipitation patterns.

2.2. Ecosystem as Biological Community Interacting with a Physical Environment

The scientific literature defines ecosystem to refer to a biological community (of plants, animals, and microbial organisms) and the physical environment associated with that biological community (Mayhew, op. cit., p. 151; *Oxford Dictionary of Science* [8]). The ecosystem concept, thus, includes consideration of the processes by which plant and animal populations and microbial organisms interact with each other and the natural environment (air, land, and water) to reproduce and perpetuate the entire community. Thus, an inland freshwater lake, or a tropical rainforest, or a wetland, or mangrove swamp, etc. each with its plant (flora) and animal (fauna) species in a particular natural environment, constitutes an ecosystem. Nutrients pass between the different organisms (animals, plants, microbes) that constitutes a biological community such as when oxygen (O₂) is absorbed by fish in an inland freshwater lake, which are then consumed by humans and other animals, which are then consumed by other organisms; etc. Pioneered in the 1930s by ecologist Arthur Tansley [9]¹⁰ the ecosystem concept permits us to appreciate the reciprocal relationships between biological organisms (humans, animals, plants, microbes) and their physical environment and the conditions, circumstances and influences that underpin and determine their continued reproduction. This brings us to the concept of ecosystem resources.

Ecosystem resources, then, describe the whole complex of factors or items – both organic and inorganic – supplied by a particular ecological environment and consumed by members of the ecological environment to sustain and reproduce their existence. This definition of ecosystem resources suggests that the concept itself incorporates, also, spatial needs – e.g. swamps for fish to live and hide from predators; recreational facilities for humans (e.g. beaches on a lake shore), etc. Also, non-organic elements that vary across space and time, but are never used up or made available to other species (e.g. certain temperature thresholds, wind direction or pattern, salinity, etc.) might be classified as ecosystem resources. Thus, when such non-organic resources become disturbed or are no longer available in their optimal quantities and/or qualities, there will begin to occur biodiversity loss; otherwise the

biological organisms that constitute the ecosystem will begin shift their ranges, failing which they might begin to face extinction.

Table-2. Major Terrestrial Ecosystem Complexes

Ecosystem	Climate and Soil	Dominant Vegetation	Dominant Animal Life	Geographical Distribution
Deserts	Areas of very low rainfall, sometimes specified as below 250mm/yr; or where evapo-transpiration exceeds precipitation. Soils are thin and porous, as climate is too dry to permit chemical weathering and humus formation	Widely scattered thorny bushes and shrubs; cacti, etc.	Rodents, lizards, snakes, numerous insects, hawks, small birds.	North and Southwest Africa; parts of Middle East and Asia; Southwest USA, Northern Mexico.
Grasslands	Seasonal rainfall, 250-1500 mm/yr; fires frequent, soils rich and often deep.	Grass species; bushes and woodlands in some areas.	Large grazing mammals; wild horses, lions, termites.	Central North America; Central Asia; Subequatorial Africa; and South America; much of South India, Northern Australia.
Tropical rainforests	Non-seasonal, annual average temperature 28°C; rainfall frequent and heavy, averages over 2375 mm/yr; soils thin and poor in nutrients. Within this ecosystem complex are found variants such as: <ul style="list-style-type: none"> • Tropical Mangrove Swamps. Where prop-roots trap sediments from the ebb and flow of tidal currents gradually extending land seawards. The mangrove rainforests of the Niger Delta (in Nigeria) are the largest in the world, covering some 11,700km². • Tropical Montane Forests. In mountainous regions of the tropics, where rainfall can be heavy and persistent, trees are typically short and crooked, etc. • Tropical Dry Forests. Characterized by annually dry season. Soils sometimes producing pockets or tropical dry forest. 	High density of broad-leafed evergreen trees, dense canopy, abundant epiphytes and vines; little under story.	Enormous biodiversity; exotic colorful insects, amphibian, birds, snakes, etc.	Northern South America, Central America; Western, Central Africa, Southwest Asia; Islands in Indian and Pacific Ocean.
Temperate forests	Seasonal; temperature below freezing in winter; summers warm humid, rainfall from 750-200 mm/yr; soils well developed.	Coniferous trees (Spruce, fir, pine, hemlock), some deciduous trees.	Large herbivores (e.g. male deer); important nesting area for neotropical birds.	West and Central Europe, East Asia, Eastern North, America.
Tundra	Bitter cold except for an 8-to-10 week growing season with long days and moderate temperatures; precipitation low, soils thin and underlain with permafrost well developed in the barren plains of northern Canada, Alaska and Eurasia; Arctic tundra ecosystems are highly responsive to temperature changes on a relatively short time scale; highly sensitive to both environmental fluctuation and climate change, and play a significant role in biospheric feedbacks to global climate.	Low-growing mosses, lichens and seages, etc. Tundra vegetation restricted by the intense winter cold, insufficient summer heat and soils with a thick, peat layer of poorly decomposed vegetation, which is usually underlain by a frozen layer of soil. Climate change may cause tundra soil to dry, which accelerates oxygen uptake, which, in turn, would lead to increased carbon dioxide and methane emissions.	Year-round; arctic hares, arctic foxes; many migrant shorebirds, geese, and ducks, etc.	North of the coniferous forest in Northern hemisphere, extending Southwards at elevations above the coniferous forests.

Source: Compiled from Wright and Nebel (Op. Cit., Table 2.3, pp. 42-43); Mayhew (Op. Cit., p. 517).

For instance, IPCC [10] reports of marine ecosystems that a warming of 2°C above 1990 levels would result in mass mortality of coral reefs; that 4°C increase in global temperatures by 2100 (relative in 1990-2000 levels) may lead to many freshwater species becoming extinct, etc. As just noted, the degree to which each ecosystem resource is available or otherwise lacking or high or low, profoundly affects the ability of the organisms in the specific ecosystems to survive and reproduce themselves. So, which non-organic resources are available or absent, and in

what quantities determine which plant and/or animal species may or may not survive in a specific region or area; in turn, which organisms do not survive is the key determinant of the nature of a given ecosystem.

Tables 2 and 3, respectively, summarize the major categories of terrestrial and aquatic ecosystems, including their dominant parameters, animal and plant life, and geographical or spatial distribution globally. Table 4 summarizes the various ecosystem services and functions.

Table-3. Major Aquatic Ecosystems

Aquatic System	Major Environmental Parameter	Dominant Plant Life	Dominant Animal Life	Distribution
Lakes and Ponds (freshwater)	Bodies of standing water; low concentration of dissolved solids; seasonal vertical stratification of water	Rooted and floating plants, phytoplankton	Zooplankton, fish, insect, larvae, geese, herons.	Physical depressions in the landscape where precipitation and groundwater accumulate.
Streams and Rivers	Flowing water; low level of dissolved solids; high level of dissolved oxygen.	Attached algae, rooted plants.	Insect, larvae, fish, amphibians, birds, ducks, geese, etc.	Landscapes where precipitation and groundwater flow by gravity towards oceans or lake.
Inland Wetlands (freshwater)	Standing water, at times seasonally dry; thick organic sediments; high nutrients.	Marshes: grasses, reeds, etc Swamps: water-tolerant trees. Bogs: low shrubs, etc.	Amphibians, snakes, numerous invertebrates, wading birds, ducks, geese, alligators, etc.	Shallow depressions, poorly drained, often occupy sites of lakes and ponds that have filled in
Estuaries	Variable salinity; tides, create two-way currents, often rich in nutrients, turbid.	Phytoplankton in water, column, rooted grasses like salt-marsh grass, mangrove swamps-in tropics with salt-tolerant trees and shrubs.	Zooplankton, rich shellfish, worms, fish, wading birds, ducks, geese, etc.	Coastal regions where rivers meet the ocean; may form bays behind sandy barrier islands.
Coastal Ocean (saltwater)	Tidal currents provide mixing nutrients high	Phytoplankton, large benthic algae, turtle grass, symbiotic algae in corals.	Zooplankton, rich bottom fauna of worms, shellfish; coral colonies, jelly-fish, fish, turtles, ducks, sea lions, seals, dolphins, penguins, whales.	From coastline outward over continental shelf; coral reefs abundant in tropics.
Open Ocean	Great depths (to 11000 metres); all but upper 200 m dark and cold; poor in nutrients except in up-swelling regions.	Exclusively phytoplankton	Diverse zooplankton and fish adapted to different depths; sea birds, whales, tuna, sharks, squid, flying fish.	Covering 70% of Earth, from edge of continental shelf outward.

Source: Wright and Nebel (Op. Cit., Table 2.1, p. 29).

2.2.1. Ecosystem Resources: The Renewable and Nonrenewable Distinction

The literature draws a fundamental distinction between renewable and nonrenewable ecosystem resources, a distinction based on the criterion, namely, whether the resource in question can or cannot replenish its stock within a time-frame meaningful to the human mind. A time frame meaningful to the human mind may be interpreted to mean such timeframe within which some human or economic activity can be completed – such as farming cycle, within which a certain crop can be planted, grown and harvested. Human beings, as economic agents, plan their economic activities within timeframes within which their plan objectives can be meaningfully realized – e.g. days, weeks, months, decades. Thus, a renewable resource (also an infinite or perceptual resource) is one that can replenish its stock at a sufficient rate for sustainable economic extraction in a meaningful timeframe. Examples are timber, fish, wildlife – these are organic or biological resources that can reproduce themselves according to some biological laws within timeframes meaningful to the human mind, provided their rates of use or exploitation do not undermine or destroy their regenerative potentials through degradation or over exploitation (see Tietenberg [11]). Some inorganic ecological resources – e.g., underground and surface water, agricultural soils, solar energy, wind or wave energy, etc. – though nonbiological, their localized replenishment occurs within time-frames meaningful to the human mind; thus this category of resources is available for use on a continuing basis.

Table-4. Ecosystem Services and Functions

Ecosystem Service	Ecosystem Function
Gas regulation	Regulation of atmospheric chemical composition.
Climate regulation	Regulation of global temperatures, precipitation and other biologically mediated climatic processes at global or local levels – e.g. greenhouse gas regulation, etc.
Disturbance regulation	Capacitance, damping, and integrity of ecosystem response to environmental fluctuations – e.g. protection, flood, control, drought recovery, and other aspects of habitat response to environmental variability controlled by vegetation structure.
Water regulation	Regulation of hydrologic flows – e.g. provisioning of water for agriculture (e.g. irrigation) or industrial (e.g. milling) processes or transportation.
Water supply	Storage and retention of water – e.g. provisioning of water by watersheds, reservoirs and aquifers.
Erosion control and sedimentation retention	Retention of water within ecosystem e.g. prevention of loss of soil.
Soil formation and nutrient cycling	Soil function processes and storage, internal cycling, processing, and acquisition of nutrients – e.g. nitrogen fixation.
Waste treatment	Recovery of mobile nutrients and removal or breakdown of excess nutrients and compounds – e.g. waste treatment, pollution control, detoxification.
Pollination	Movement of floral gametes – e.g. provisioning of pollinates for the reproduction of plant populations.
Biological control	Trophic–dynamic regulations of populations – e.g. keystone predator control of prey species, reduction of herbivores by top predators.
Food production and raw materials production	That portion of primary production extractable as food and raw materials–e.g. fish, game, crops, fruits as food, timber, fuel, fodder, etc. as raw materials.
Genetic resources	Sources of unique biological materials and products – e.g. medicines, products for materials science, genes for resistance to plant pathogens and crop pests, etc.
Recreation and cultural	Provision of recreational activities (ecosystem, sports, fishing and other outdoor activities); provision of opportunities for non-commercial uses (cultural: aesthetic, artistic, educational, etc. values).

Source: Wright and Nebel (Op. Cit.), Table 3.3, p. 76.

The literature points our though, that there is certain difficulty in establishing, in practice, whether certain renewable ecological resources qualify as renewable in the strict definition we have posited above, namely, ability to replenish at a sufficient rate for sustainable economic extraction in meaningful timeframes. In principle, surface freshwater lakes, for example, are renewable inorganic resources replenished via the hydrologic (water) cycle. However, in practice, in the absence of good water management, short-term exploitation of a water resource can be characterized by over-drawing relative to rates of recharge, which will likely lead to unsustainable use. The Lake Chad experience serves as a good illustration, to which we return.

2.3. Ecosystems as Dynamic Entities Subject to Occasional Disturbances

Ecosystems are dynamic entities subject to occasional disturbances that destabilize their equilibrium – referring to the balance between organisms and their environment – but are, nonetheless, capable of restoring their equilibrium provided their self-reproductive capabilities are not destroyed or permanently impaired. For instance, a drought (a local or regional lack of rainfall such that the ability to engage in water-dependent crop and/or livestock production is seriously impaired), warming inland lake temperatures above a certain threshold or tolerance level, etc. could constitute a short-term variability in ecosystem processes, which could destabilize ecosystem functions. Long-term changes in ecosystem environment do, also, shape ecosystem processes: e.g. drought conditions decades (or even centuries) earlier could still leave their imprints on current ecosystem environment.

The frequency and severity of ecosystem disturbances, however, determine how ecosystem processes are affected. For instance, as suggested already, the frequency and severity of drought will affect the hydrologic cycle and, hence, the regulation of water balance. Specifically, ecological disturbances like drought could leave behind shrinking freshwater inland lakes and flood plains with disappearing animal and plant species – as in the Lake Chad experience, to which we return.

Ecosystems are controlled by external and internal processes and forces. External forces, most importantly climate (precipitation and temperature), control the overall structure of ecosystems but remain themselves

uninfluenced (at least, not directly) by the ecosystems themselves.¹¹ But the climate determines the biome (the type of plant life that dominates within an ecological zone, which, in turn, will influence animal life and soil types) in which the ecosystem is embedded. On the other hand, internal processes (e.g. plant and animal (including human and life, microbial organisms, etc.) not only control ecosystem processes, but are also controlled by them – hence, they (internal forces) are often subject to feedback referring to the effect that a change in one part of an ecosystem has on another part (of the same ecosystem) and how this effect then feeds back to influence the source of the change, inducing more or less of it. Ecosystem feedback may be negative or positive; it forms the basic dynamics for regulating the state of the ecosystem.

Negative feedback causes the ecosystem to revert to its original equilibrium state, and, thereby, regaining or restoring stability. Citing Nunally [12] Mayhew (op. cit., p. 176) gives an example of negative feedback from a river system, when erosion, as a negative feedback mechanism, restores stream stability by lowering channel gradient or slope and increasing bed material size. Positive feedback, in contrast, causes transition to a new ecosystem trajectory, when, for instance, human activities (e.g. overdrawing the regenerative potential of a lake system) causes transition to a completely new lake surface level with different fauna and flora composition.

2.3.1. Over-Exploitation and Degradation of Ecosystems

The most important internal element controlling ecosystems is the human element and its activities – so-called anthropogenic influences on ecosystems. Unlike other internal controlling factors, the cumulative effects of the human influence on ecosystem performance are large enough to influence external processes like climate, and even create new ecosystem trajectories, as just suggested.

The proposition that ecosystems are dynamic entities with feedback mechanisms that restore their stability or equilibrium, assumes, however, that the regenerative capabilities of ecosystems are not undermined or overburdened by human-induced activities such as when fishing activities, water withdrawals, etc. overburden the natural potential of an inland freshwater lake to naturally replenish or maintain itself via the hydrologic cycle. An important consideration here is the carrying capacity (CC) of an inland freshwater lake or any ecosystem for that matter.

As suggested above, inland freshwater lakes as aquatic ecosystems can sustain a certain amount of use or exploitation and still retain their viability. However, a point could be reached at which increasing exploitation of an inland freshwater lake begins to undermine its natural potential to replenish or replace its water level. At that point over-use or degradation has set in, with the possibility of evolution of a lake system completely different from the original state.

The problem of exceeding the CC of inland freshwater lakes does, indeed, occur because in most developing countries inland freshwater lakes represent a kind of common property resource (CPR) – an ecosystem resource or good with open access to all and sundry at zero charge (free). Because there is zero user fee to exploit CPRs, there is a tendency to abuse them or exploit them beyond their CC or natural capacity to replenish, which, in turn, could result in their degradation – a problem known in the academic literature as the tragedy of the commons theory propounded by ecologist [13].

As noted in the literature, CPRs – e.g. an open lake – raise problems similar to those of global public goods¹² (e.g. Earth's atmosphere)¹³: they ultimately get degraded through overexploitation, because there is no 'exclusion' principles; consequently their CC ultimately gets exceeded.

Hardin's tragedy of the commons theory suggests that increasing human activities will inexorably result in environmental degradation. There is a certain neo-Malthusian flavour to this hypothesis, invoking, as it does, the ideas of the 18th century classical economist Thomas Malthus, who argued that rapidly expanding human population (in 18th century England) was bound to exhaust available land for feeding the population, because, according to Malthus, the human population expands at a geometric proportion relative to the means of subsistence

(agriculture) that grows at an arithmetic proportion – so-called Malthusian population trap. Versions of the Malthusian trap thesis can be traced in neo-Malthusian development theory, though current focus has shifted from emphasis on land and agriculture to all natural capital and the global environment.

Critics counter that the neo-Malthusian argument remains tenable only if technology, tastes, and investments to improve environmental quality remain static. Development experience has shown, however, that the overall impacts of human activities on ecosystems are continuously changing, influenced by the dynamic interactions of diverse economic, social, demographic and technological influences and processes (e.g. World Bank [14]). This literature emphasizes that efficiency gains resulting from economic policies will reduce pressure on Earth's natural environment as a source of inputs to derive economic growth; that environmental policies can reinforce efficiency in resource exploitation and produce incentives for adopting eco-friendly technologies. The extent environmental policies have succeeded in relieving pressure on Lake Chad's ecosystem resources is not pursued in the present paper due to space constraints.

3. SALIENT FEATURES OF LAKE CHAD'S CLIMATIC AND HYDROLOGIC ENVIRONMENTS

“As you approach the Lake Chad basin from Maiduguri, in northeastern Nigeria, the atmosphere of despair is telling. The air is dusty, the wind is fierce and unrelenting, the plants are wilting and the earth is turning into sand dunes. The sparse vegetation is occasionally broken by withered trees and shrubs. The lives of herders, fisher folk and farmers are teetering on the edge as the lake dries up before our eyes. Vegetation and water ... are vanishing. Vultures feast on dead cows as drought and desertification take their toll ... the lake could disappear this century” [15].

Lake Chad is situated between latitude 12° and $14^{\circ} 30'$ N and longitude 13° and $15^{\circ} 30'$ E. [Figures 2 and 3]. It is located, as already posited, in the Sahel climatic zone, perched on the southern edge of the African Sahara Desert and straddling four countries in West-Central Africa: Niger, Chad, Cameroon, and Nigeria.

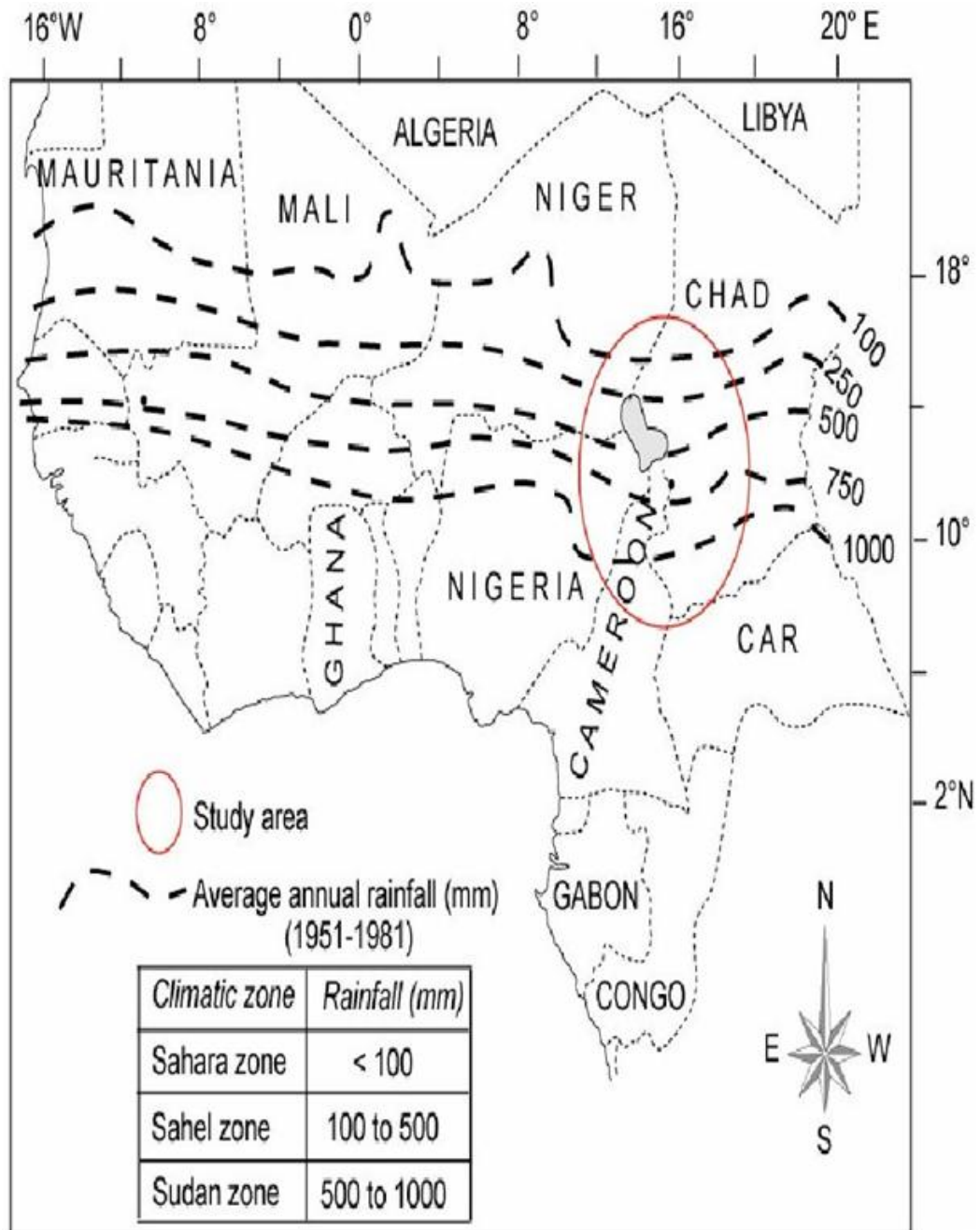


Figure-2. Rainfall and Climatic Zones of Lake Basins

Source: Ngatcha [16]

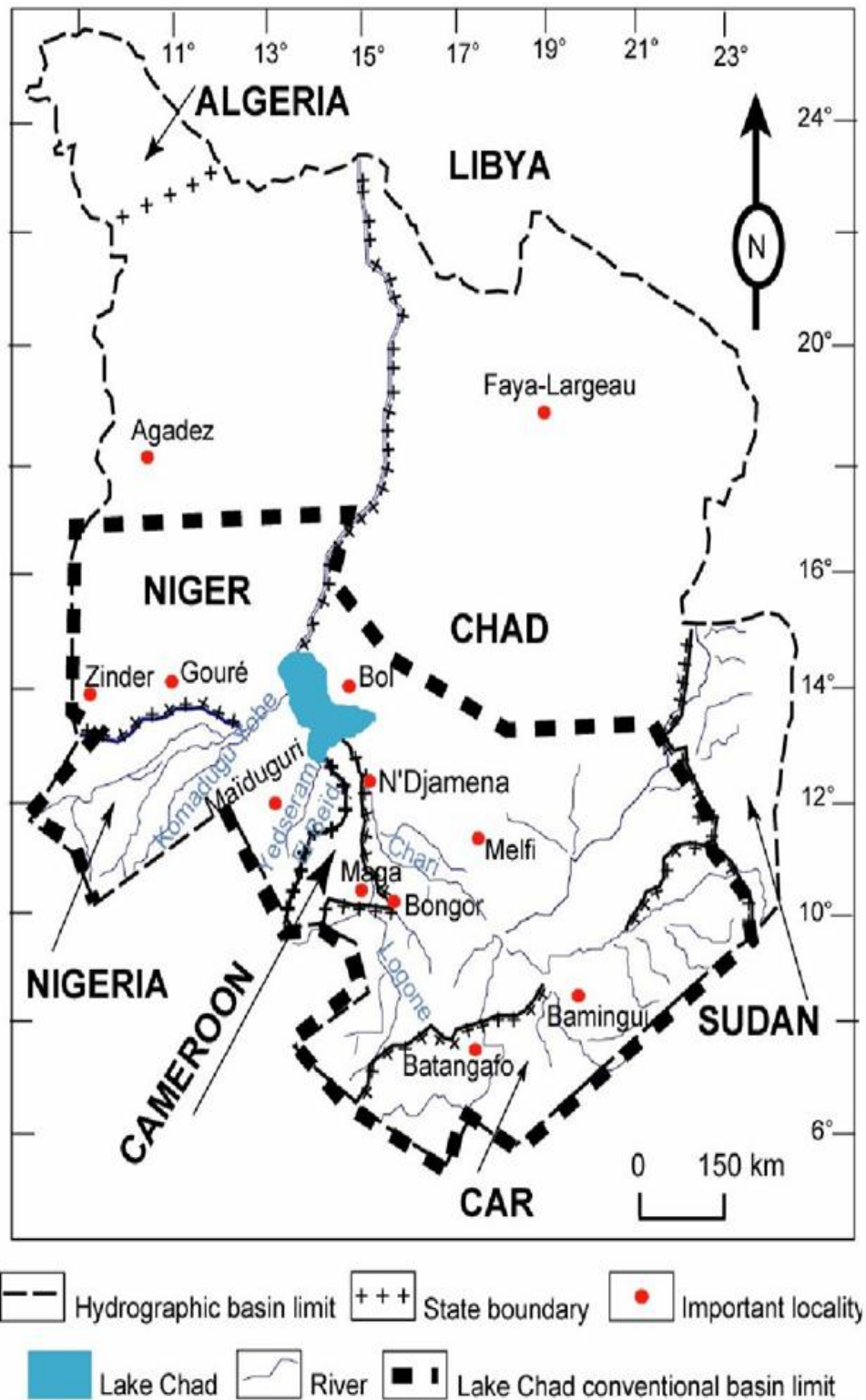


Figure-3. Hydrology of the Lake Chad Basin

Source: Ngatcha [16]

The Lake Chad drainage basin covers three distinct climatic regimes: Sahara, Sahel, and Sudan. The annual rainfall varies, of course, across the three climatic zones, averaging 500–1000 mm in the Sudan, 100–500 mm in the Sahel, and less than 100 mm in the Sahara (Figure 2). As already posited, the Sahel ecology, compounded by global warming and climate changes, remains the most important external factor shaping the shrinking of Lake Chad's surface area. The Sahel climate is characterized by a short rainy (wet) season (June-September) and a long dry and hot season (October-May). The average annual temperature in the Chad basin varies between 35°C and 40°C; the

zone has low relative air humidity, and thus high atmospheric evapo-transpiration. The Sahel climate has been compounded by global warming and climate change characterized by rising surface temperatures and extreme heat to induce high rates of evapo-transpiration in the Lake Chad basin.

Finally, the unique, closed nature of the Lake Chad basin has an impact on the behaviour of the lake in response to climate change. Generally, a lake basin may be subdivided into two major subsystems for analytical purposes: first, the drainage basin or watershed system which is dominated by the processes of overland flow and flow through the soil; and, second, the lake system itself, which is composed of the lake itself and all its permanent and ephemeral tributaries in which open channel flow occurs. Given that drainage basin processes control the amount and rates water, sediment, and dissolved load supplied to the lake system, it would be insightful to briefly highlight this feature of Lake Chad. The drainage system of Lake Chad is dominated by the Logone-Chari rivers, the Kemadugu-Yobe, the Yedseram and the EL Beid [figure 3]. The Logone-Chari river account for well over 90% of water flowing into Lake Chad; input from the Komadugu-Yobe is ephemeral, coming only during the peak flood period in the brief rainy season (June-September). Besides, water can also reach the lake through smaller tributaries and groundwater discharge, whose regenerative potentials have been seriously undermined by drought compounded by climate change.

Finally, Lake Chad's drainage basin, as already pointed out, is a closed one with no outlet to an outside sea or the ocean. Much more importantly, the Sahel climate characterized by high temperature and extreme heat and associated high evaporation mean that the Lake system loses water considerably through high rates of evaporation.

4. SIX THEORIES/HYPOTHESES ON LAKE CHAD'S OVER-EXPLOITATION AND DEGRADATION

Records show that the overexploitation and degradation of Lake Chad leading to the dramatic shrinking of its surface area has occurred in more recent decades – precisely, in the post-1960s decades. Before its current dramatic shrinking, Lake Chad was ranked the 4th largest of Africa's inland freshwater lakes, spanning 25,000 km². It might be relevant to state, however, that different data sources give different sizes on the lake's surface area. What is, perhaps, agreed is that the level, volume and surface area of the lake all have fluctuated over the post-1960s decades. A Lake Chad Basin Commission Report (LCBC, no date) observes that:

“The level, volume and surface area ... fluctuate as a function of climate variation. During the humid years of the first half of the 20th century, around 70% of the lake's area comprised open water. The remainder was a marshy archipelago. During the prolonged dry periods, and in the dry season, there is almost no vegetation in the lake. With the arrival of the rainy season ... the seeds in the soil germinate and the plants grow back ... since becoming the small Lake Chad, the lake has a very limited area of open water and resembles a swamp dominated by grasses, papyrus, common reeds and bulrushes. New small Islands have appeared which have become quickly settled and exploited by the population” (p. 42).

At its deepest, the lake measures no more than 7 meters, and is dotted by islands and mudbanks in areas once (by the 1960s) covered by freshwater.

What can account for the Lake Chad 'catastrophe'? The literature contains, at least, six theories and hypotheses to explain this problem.

- 4.1. Lake Chad had experienced 'wet' and 'dry' phases for 1000s of years caused by natural climate variation.
- 4.2. The influence of anthropogenic climate change compounded the effect of the Sahel drought to undermine the regenerative potential of the hydrologic cycle in the Lake Chad basin.

- 4.3. Unregulated exploitation of the waters of the Lake Chad system for dam construction and irrigation purposes overdrew the regenerative potential of the Lake Chad hydrologic cycle.
- 4.4. High rates of deforestation in the tropical rainforests of West-Central Africa shifted the rainbelt southwards, which resulted in the Sahel droughts.
- 4.5. Pressure from rapidly growing human and livestock populations exceeded the carrying capacity of the Lake Chad ecosystem resources.
- 4.6. Anthropogenic sulphate aerosols emissions in the northern hemisphere created a cooling effect (regional climate change) that shifted the equatorial tropical rainbelt southwards resulting in a steady decrease in Sahel rainfall.

We argue that there is no single-cause explanation for the degradation of Lake Chad; rather, the influence of anthropogenic climate change compounded those of non-climate factors – e.g. deforestation, unregulated exploitation of lake resources, etc – to degrade Lake Chad.

4.1. Natural Climate Variation

This theory is advanced by palaeoclimatologists who study climate of earlier geological era before historical records or instrumental observation began.¹⁴ They derive their explanation from examination of data gleaned from study of sediments that were deposited million of years ago, and from fossils (the remains or traces of biological organism, namely plants, animals, microbes). They explore lake sediments cores and use them to reconstruct past hydrologic variations, and then use them to show how variations affected ecosystem processes. Although relying on paleoclimatic analogue could prove an extremely unreliable approach, studies based on this hypothesis have produced useful insights by expanding the temporal framework to times prior to those recorded in the instrumental climate studies.

Palaeoclimatic scientists premise their studies on the theory that there are two major drivers of climate in the Lake Chad region: the seasonal migration of the ITCZ (Intertropical Convergence Zone), referring to a belt of low pressure which circles Earth generally near the equator, where the trade winds of the northern and southern hemispheres converge; and the contrast between sea surface temperature and continental temperature in the Gulf of Guinea. They assume that the differences in the path of the ITCZ are the major cause for the formation of pre-historic humid climate in an ecosystem, which today is arid.

Palaeoclimatologists explain that in North Africa an enhanced monsoon prevailed some 1500 to 5000 years ago than what obtains now, which created wetlands and lakes in the African Sahara [17]. The lake history of Lake Mega Chad, from which modern Lake Chad is hypothesized to have evolved (e.g. Gritzner [18]) shows that Lake Mega Chad was Africa's largest lake. On the other hand, Lake Chad though evolved some 20,000 years ago – which is quite young in the context of geological time-scale involving millions of years.

Recent interpretation of data from the Shuttle Radar Topographic Mission (SRTM), supported by sedimentological evidence, and geomorphic analyses clearly support the interpretation of extended sand-ridges as lake deposits (e.g [19, 20]) rather than being result of plate tectonics (the theory that Earth's surface is made of lithospheric plates, which have moved throughout geological time resulting in the present-day position of the continent and which explains the location of mountain building, etc.).

During its maximum extension Lake Mega Chad had covered an area approximately 350,000 km² with its deepest point in the Bodelo Depression (about 210 meters) and linked modern Lake Chad through the Bahr Al Ghazal. Its maximum level of about 325 meters was controlled by the Mayo Kebbi Spill point, from where water would discharge through the Benue River into the Atlantic Ocean. Geomorphological studies suggest several Lake Mega Chad episodes (since at least 3 to 3.5 million years) with the latest lasting until approximately 5,300 years to 4,400 years before now and coinciding with the mid-Holocene¹⁵ wet period of northern and cultural Africa.

Modern General Circulation Models (GCMs)¹⁶ used by climate scientists now supply convincing evidence that attribute the wetter condition during the Holocene to differences in sun orbital parameters. During the Lake Mega Chad time, the sun reached further to the north (today's Tropic of Cancer of Latitude 23° 5' N) causing a northward shift of the ITCZ – that is, the rainbelt shifted northwards into the Sahara.

The integration of the ITCZ affects seasonal precipitation patterns, bringing Monsoon¹⁷ (rain-bearing air) from the Gulf of Guinea during the summer (May-September), but hot and dry air from the Sahara (harmattan) as the sun moves south (winter) to the Tropic of Capricorn. With a northward shift of the ITCZ, rain-bearing air sucked in from the Gulf of Guinea could move further inland into the Sahel and provide the necessary rainfall. This modification of the ITCZ during the Holocene is hypothesized to be responsible for the existence of the 'wet' Sahara, of which Lake Mega-Chad and Lake Chad are remnants.

4.2. Anthropogenic Climatic Change Compounded the Influence of Drought-Prone Sahel Climate to Degrade the Regenerative Potential of the Hydrologic Cycle in the Lake Chad Basin

Anthropogenic climate change beginning in the 1970s onwards dominates the discourse on the degradation of the Lake Chad ecosystems. It is argued that anthropogenic climate change reinforced the influence of a drought-prone Sahel climate to degrade Lake Chad. Contrary to popular belief current anthropogenic climate change is posited not to be the cause of the Sahel drought; on the contrary, this theory claims, drought has been a regular feature of the Sahel, and anthropogenic climate change has only exacerbated the drought conditions in the Sahel. The gist of this argument is that global warming and climate change destabilized the hydrologic (water) cycle in the Lake Chad basin, thereby compounding the preexisting drought condition in the basin.

Specifically, global warming and climate has the direct effect of speeding up the hydrologic cycle which, in turn, destabilizes the equilibrium of Earth's aquatic ecosystems. Climate scientists have established that the hydrologic cycle is very sensitive to global warming and climate change (e.g. Held and Soden [21]); that, indeed, much of the effect of climate change on Earth's environment tends to be registered in its effect on precipitation (rainfall, snow, hail, etc.) [22, 23]. On the other hand, the circulation of water between the atmosphere, land, and ocean is enhanced through the warming of global atmospheric temperatures, with immense implications for the frequency, intensity, and duration of hydrologic events: precipitation, floods, drought, etc [24].

There is a certain confusion in the debate on the roles of anthropogenic climate change and non-climate change factors in the Sahel drought, which should be cleared before we can proceed. The popular view is that the Sahel drought is climate change driven. This view is not quite correct. The correct position is that anthropogenic climate change unravelling in the 1970s onwards has merely compounded the effects of long-standing drought events in the West African Sahel on the ecosystems of the ecological zone, by increasing the impacts of drought as well as possibly increasing its likelihood.

Studies on the experiences of other regions (e.g. the drought-prone West Coast of the United States) find that rising average air temperatures and extreme heat are key variables in the equation of drought (e.g. Shukla, et al. [25]) that extreme temperatures, even more importantly than decreased rainfall, influence the impact of drought on ecosystems. This suggests that the shrinking surface area of Lake Chad is not a result of the low abnormal rainfall witnessed in the West African Sahel alone, but also of very high temperatures and extreme heat due to global warming. Other researchers find that not every dry period results in severe drought; that a low-precipitation period is more likely to produce a water supply crisis when temperatures are high, due to the compounding effects of higher evaporative loss, increased water demand, etc. Diffenbaugh, et al. [26] find that enhanced GHG emissions have increased the probability that dry precipitation years (as have obtained in the Sahel beginning since the 1970s through the 1990s) are also warm, leading to an increased frequency of drought events.

Ly, et al. [27] have studied the evolution of extreme temperature and precipitation indices in West Africa spanning latitudes 10-25° N and longitudes 17° W – 15° E; these results show a general warming trend throughout

the region during the period 1960–2010. Nights were found to be warmer rather than cooler, apart from more frequent warmer days and warmer spells; this included, also, the coastal zones. The general tendency of decreased annual total rainfall reinforced the rising surface temperature trends. For sub-Saharan Africa, the mean average temperatures have risen, beginning since the 1970s, by as much as 1–3°C, the highest increase registering in the inland regions (e.g. Darfur region of Sudan, South Sudan, West African Sahel, etc) where average increases are reported to exceed 3°C [28]. Increased temperatures have led to greater evaporation (the Clausius-Clapeyron relationship) whereby saturation vapour pressure increases exponentially with temperature; in turn, the increase in water vapour affects precipitation events and risk of flooding.

The climate change influence on the Sahel drought only came to attract global attention in the aftermath of the 1972–1974 Sahel droughts in West Africa, which led to a debate in the United Nations resulting in the 1977 United Nations Conference on Desertification (UNCOD) in Nairobi, Kenya organized by the United Nations Environment Programme (UNEP) (Adams, op. cit.). Global support became further enhanced by continued drought in later part of the 1970s through the 1980s in the West African Sahel and Horn of Africa (Ethiopia, Somalia, Northern Kenya); also, in Southern Africa in the early 1990s, and, yet, again the West African Sahel in 2005 and Horn of Africa in 2006. All these did, indeed, reinforce the hypothesis that anthropogenic climate change compounds the drought effect particularly drought-prone arid and semi-arid ecology.

4.3. Unregulated Exploitation of the Waters of the Lake Chad Basin for Dam Construction and Irrigation Purposes Overdrew the Regenerative Potential of the Hydrologic Cycle

If natural climate variability and anthropogenic climate change and associated high atmospheric temperatures and extreme heat have negatively affected the water balance in Lake Chad, diversion of the waters of the rivers draining into Lake Chad for dam construction and irrigation purposes further compounded the shrinking of the lake's surface area. Large and unsustainable irrigation projects and impoundments undertaken by the riparian countries, Chad, Cameroon, Nigeria and Niger, which diverted substantial volumes of water from Lake Chad itself and its two major input flows, Chari-Logone and Kamaduga-Yobe rivers, constitute significant factors contributing to the shrinking of Lake Chad. The major facilities which have contributed to the shrinking of Lake Chad are:

- the construction of both the Yaguou-Tekele dyke (on the Chari-Logone) and the Maga dam by Cameroon. The Maga dam has reduced the flow of the Logone River into Lake Chad.
- a series of dams by Nigeria – e.g. the Tiga dam on Yobe River, Alau dam on Ngadda River, the Yedseram dam by Yedseram River and the South Chad Irrigation Project (SCIP). The SCIP was aimed at developing wheat production in Nigeria's 'Far North'. Developed to irrigate 67,000 ha, a special technological feature of the SCIP is the cutting and dredging of a 38-km long intake canal from Lake Chad; the water flows into a 21-km long canal, from where it is carried to another pumping station from which it can be released into the irrigation system. Due to the shrinking surface area of the lake the water has largely been unable to reach the intake canal designed to transport water to the irrigation system even in peak flood periods [29]. The shortage of irrigation water is cited as a key factor underlying the failure of wheat development in Nigeria [30, 31].
- the MAMDI Polder Project in Chad Republic.

The above dam and irrigation facilities combined account for upwards of 30% of the observed shrinking of the surface area of Lake Chad since 1960 (e.g. Coe and Foley [32]). By the end of the 1970s, irrigation development was observed to have had a modest impact on the hydrology of the Lake Chad basin; in the 1980s onwards, in contrast, large-scale irrigation systems began to withdraw water 4-fold relative to the amount extracted in the previous quarter century, accounting for 50% of the additional decrease in Lake Chad's surface area.

Water represents a perfect example of a renewable ecosystem resource that is showing signs of exhaustion due to over-exploitation and degradation of the natural potential of the hydrologic cycle to replenish the natural water

flow in many parts of the world. Globally, freshwater is abundant though; each year an average of more than 700 m³ per capita of freshwater is known to enter rivers and aquifers (deposits of rocks, such as chalk, that yield economic supplies of water to wells or springs as a result of their porosity or permeability). However, such water has been found to not always arrive where and when it is needed, due partly to diversions.

In several parts of the world surface freshwater reservoirs – e.g., rivers, lakes, etc. – have been overdrawn to develop dams and irrigation facilities; while such projects have provided livelihoods for millions, they have simultaneously generated considerable negative environmental spillovers. As pointed out earlier, the world's most dramatic example of an aquatic ecosystem that has been over exploited and degraded to extinction is the Aral Sea.¹⁸

4.4. High Rates of Deforestation in West-Central Africa shifted the Rainbelt Southwards

This was the first hypothesis to be advanced to explain the declining rainfall in the Sahel and was popular in research circles in the 1900s up until the 1990s (e.g. [33-36]). This perspective hypothesized that the upper limits of the carrying capacity of the Sahel grazing pastures have been exceeded by the numbers of herds grazing on Sahel pastures. Variations in annual rainfall amounts and vegetation cover were cited as a evidence, that the African Sahara desert was shifting southwards caused by human activities. Lamprey [37] for instance, was among the early empirical adherents of this hypothesis; he claimed that the Sahara Desert had shifted some 90-100 km southwards in the north Kordofan region of Sudan between 1958 and 1975. The so-called Charney's hypothesis [38] argued, also, that reduction in Sahel rainfall were a result of human activities: the systematic and irreversible degradation and desertification of the zone through overgrazing and deforestation and inefficient land-use practices. More technically, decreases in the region's vegetation cover and deforestation resulted in an increase in the reflectivity or albedo,¹⁹ as dense vegetation yields to bare sand, and light-coloured soils; that this increase in reflectivity results in reduction in the heating of the ground, which, in turn, reduces the heating of the atmosphere by the ground surface, resulting in a reduction in the convection that is essential for the formation of rain-bearing clouds.

Generally, environmental degradation in the form of deforestation can – and does, indeed – lead to a reshaping of the biosphere in a significant way, adversely affecting the functioning of the hydrologic cycle (Wright and Nebel, op. cit., p. 221). Specifically, with existence of forests and other ecosystems, there is little runoff; rather, precipitation is intercepted by vegetation and infiltrates into porous topsoil – a process that “provides the life-blood” of the natural ecosystems that constitute the biosphere (ibid). But the evaporation taking place in these ecosystems not only sustains the latter, but also recycles the water to local rainfall; some of the water percolates down to recharge the groundwater reservoirs, which, in turn, release water through springs, streams, rivers, etc. As forests become lost to deforestation – as has happened in several parts of West-Central Africa (see Dike and Dike [39]) or land is overgrazed, the natural pathway of the hydrologic cycle is destabilized: it shifts from infiltration and groundwater recharge to runoff, as the water runs into streams or rivers almost immediately – a major cause of flooding, as happened in Nigeria's Niger-Benue confluence around Lokoja in 2013 [40].²⁰

Climate scientists find that sub-Saharan Africa's tropical rainforest ecosystems affect rainfall in the North Atlantic and West Africa (e.g. Conway [41]). Several studies hypothesize, that in the 1970s onwards extensive deforestation of the West African tropical rainforest and grassland ecosystems has been a cause of drought in the West African Sahel. As shown earlier, Africa's Sahel zone is perched on the southern edge of the Sahara Desert or the northern edge of the savanna grasslands flanking both sides of Africa's equatorial tropical rainforests noted as one of the 'hot spots' of tropical rainforest deforestation (Dike and Dike, op. cit.).

It was argued that the prolonged mismanagement of the savanna ecosystem, coupled with the fragile nature of the natural capital of the zone, has stripped open large areas of vegetation thereby making “the soil susceptible to wind/water erosion” [42]. Earlier in the 1970s, the United Nations Food and Agriculture Organization [43] cited in LCBC, op. cit.) noted that soil degradation in the Chad Basin has substantially increased the risk of desertification because of mutually reinforcing factors, including loss of organic matter and nutrients, soil structure deterioration

and surface crusting, which, in turn, decrease water infiltration and retention, etc. The environmental degradation has been both a cause and outcome of poverty, with the Sahel belt comprising some of the most impoverished countries of the world. The FAO concluded that the Sahelian societies face a formidable challenge making the entire belt an “environmental hot spot”. There is, as a result, likely high pressure on the resources of the river valleys and major wetlands – e.g. the flood plains of the Hadejia – Nguru plains.

The deforestation hypothesis seems to have been accepted by a team of researchers at the Massachusetts Institute of Technology (MIT) (cited in Smith [44]) who located the cause of incessant droughts in the West African Sahel in heavy deforestation in the coastal rainforest belt; they concluded that further deforestation in that zone “could cause the complete collapse of the West African monsoon.” The MIT researchers used a statistical computer model to demonstrate that as deforestation proceeded in West Africa’s coastal rainforests coastal rainfall will no longer be recycled to create inland precipitation, premising their explanation on drought developments in the 1970s, when, according to them, three decades of heavy deforestation had resulted in the collapse of rainfall in the region by shifting the ITCZ further southwards.

In West-Central Africa the ITCZ describes the convergence of the rain bearing Guinea monsoon winds from the Southern Atlantic Ocean and the dry dusty harmattan winds blowing across the Sahara Desert. Meteorologists inform us though, that the movement of the ITCZ is quite unpredictable as its position is influenced by the apparent movement of the overhead sun, the relative strength of the trade winds, and the changing locations of maximum sea-surface temperatures. Citing studies by other researchers, Mayhew (op. cit., p. 271) inform us that in May 2005 (the rainy season begins about June-July in the African Sahel) the African portion of the ITCZ was 1° South of the average (the tropical rainbelt shifted further north), which explains the heavy rains in Ethiopia, and flooding in Khartoum (Sudan).

The deforestation hypothesis began, however, to be relaxed in the 1990s onwards, as evidence on the effect of global warming and climate change on ecosystems began to accumulate. More importantly, remote-sensing-based research on the Sahel began to reveal evidence that the Sahel had not, after all, experienced systematic degradation and irreversible desertification at the regional scale due to deforestation. For example: [45-47] employing satellite technology to study vegetation cover produced evidence that vegetation has capacity to recolonize areas that had apparently suffered desertification and land degradation when rainfall permits; that the desert boundary, defined in terms of vegetation cover, changes, with rainfall. So, changes in land surface seem to be driven by climate factors (precipitation, temperature, etc.) rather than by human activities [48].

If desertification describes “the transition of a region into dry barren land with little or no capacity to sustain life without an artificial source of water” [49] then we could conclude that parts of the Sahel have experienced only transient desertification caused by drought and climate desiccation, which differs from desertification of the Sahel leading to an irreversible loss of cultivability.

4.5. Pressure on Lake Chad’s Ecosystem Resources from Rapidly Growing Human and Livestock Population Degraded the Lake

Beyond the adverse impacts of natural climate variation, drought, and overdrawn of the regenerative potential of the Lake Chad hydrological system to develop dams and irrigation facilities, pressure on the lake’s water resources by a rapidly growing human population has been theorized to be a key factor behind the over-exploitation and degradation of Lake Chad. Even though the Lake Chad Basin Commission (LCBC) was formed way back in 1964 to regulate the exploitation of the water resources of Lake Chad, the status of the lake as a free-access natural resource, accessible to all at no fees has resulted in the over-exploitation and ultimate degradation of the lake’s regenerative potential.

For much of Lake Chad’s estimated 20,000 years of existence (e.g. Coe and Foley, op. cit.) human population growth and pressure from economic activities were never considered a significant factor in the ecological balance of

the lake. However, as from the 1970s, the impact of these forces began to register themselves. Various estimates on the human population size that exploit the lake's resources exist – e.g. Table 5, gives 27.94 million as the population of the lake's basin in 2001, and this is projected to double by the year 2050.

Table-5. Population and Surface Area of Lake Chad

	Cameroon	Chad	Central African Republic (CAR)	Niger	Nigeria	Total
Population (2001)	2,671,200	6,428,056	890,400	305,280	17,648,832	27,943,768
Population (2050)	5,288,976	12,727,550	1,762,992	604,454	34,940,687	55,328,659
Surface Area (km ²)	56,800	361,098	197,800	231,325	205,500	1,052,523

Source: Ngatcha [16] table 1

Citing UNESCO sources, Onuoha [50] put the growth rates of the human population at 2-3% per annum and the human population of the Lake Chad basin at over 37 million by the beginning of the 2000s, more than 50% of this originating in the Nigerian side of the basin. The conflicting data on the human population of Lake Chad basin should not detain us here. What seems relevant is that unregulated human population migration in the Lake Chad basin and economic activities – e.g. livestock grazing, fishing, etc. – have intensified ecological degradation in the basin (see also LCBC, no date). Indeed, the Lake Chad basin has for centuries served as the “traditional convergence point” for herdsman and pastoralists of the Western Sudan: Tuareg, Toubou, Feda, Kaemba, Shuwa Arab, Fulani and Waidai from Niger, Chad, Northern Cameroon, and Northern Nigeria [51].

Lake Chad has served as a vital source of freshwater and other vital ecosystem resources for the human, livestock and wildlife communities of the basin. The flood plains support a rich terrestrial and aquatic fauna; more than 150,000 fishermen of the artisanal category live on the lake's shores and its islands. But the artisanal nature of most economic activities on the lake as well as the common-pool property characteristics of the lake's resources pose difficulty in terms of regulation and control, which, in turn, have posed actual and potential danger to over-exploitation and, hence, degradation of the lake's ecosystems.

4.6. Anthropogenic Sulphate Aerosols Emissions in the Northern Hemisphere Created a Cooling Effect (Regional Climate Change) that Shifted the Equatorial Tropical Rainbelt Southwards Resulting in a Steady Decrease in Sahel Rainfall

This is the latest addition to the list of hypothesis attempting to explain the Sahel drought: air pollution caused by anthropogenic aerosols pumped from the factories and automobiles of a highly industrialized northern hemisphere caused a cooling effect (regional climate change) that shifted the equatorial tropical rainbelt southwards with a steady decrease in precipitation in the Sahel as from the 1950s. The lowest ever recorded rainfall in the West African Sahel was during the 1980s, “perhaps the most striking precipitation change in the 20th century observational record” (see Hwang, et al. [52]). Figure 4 shows declining rainfall over the decades (1920-2000).

Authors and adherents of this theory (e.g. [53, 54]) admit though, that this is a partial explanation for the Sahel drought, as other ‘culprits’ have been identified such as global warming and climate change, pressure from human population growth, etc. Also, the West African Sahel was not exceptional in the regional climate change caused by aerosols pollution: Northern India, and parts of South America experienced drier decades, while places at the southern edge of the equatorial tropical rainbelt – e.g. northeast Brazil and the Great Lakes Region of East Africa are known to have experienced water-than-normal conditions.

Climate scientists posit that tropical rainfall is rather sensitive to the temperature difference between the two hemispheres, with the equatorial tropical rainbelt swiftly shifting to the warmer hemisphere. Generally, the tropical rainbelt falls into bands at specific latitudes such as the equatorial tropics; a warmer northern hemisphere, for instance, causes the ITCZ to shift northwards, which shifts the tropical rainbelt northwards. The regions most affected by this shift of the ITCZ are likely to be the bands' north and south edges.

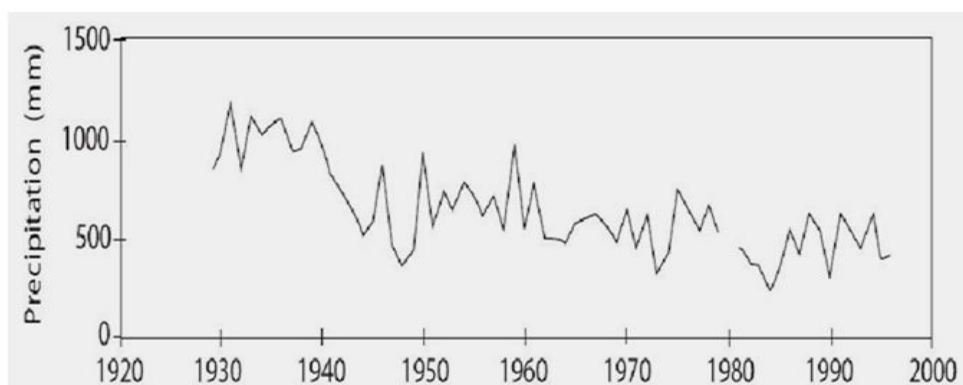


Figure-4. Precipitation in the Chad Basin, 1920-2000

Source: Ngatcha [16]

In Africa these edges most affected by shifts in the ITCZ include the West African Sahel. Abrupt changes in rainfall patterns in the last century or the 1900s in the Sahel coincide with rainfall disruptions in the equatorial tropics caused by shifts in the ITCZ. The largest temperature drop in the atmospheric temperature difference was a drop of about 0.25°C (about 0.50°F) in temperature difference in the late 1960s, which coincided with the beginning of a 30-year drought in the African Sahel that caused famine and increased desertification (e.g. Mortimore [33]).

The northern hemisphere has a greater land mass than the ocean-dominated southern hemisphere, which has implication for the movement of the ITCZs. To understand regional climate change we should not focus so much on the global mean temperature, but the regional pattern of global warming. The cooling effect of anthropogenic aerosols emissions on the northern hemisphere is an example of this regional climate change.

There exist in Earth's atmosphere natural factors and processes that lead to global cooling effects: e.g., on average, clouds cover 50% of Earth's surface and reflect some 21% of solar radiation away to space—a so-called planetary albedo – and it prevents warming from occurring; volcanic eruptions, such as the mount Pinatubo Volcano in the Philippines in 1991 that spewed some 20 million tons of particles and aerosols into the atmosphere and contributed to a significant drop in average global temperatures “as radiation was reflected and scattered away” (Wright and Nebel, op. cit., p. 517; see also Verheggen and Weijers [55]).

As already posited, heavy concentration of anthropogenic GHGs cause the warming in global temperatures known to affect regional precipitation patterns – e.g. the sudden wet season within the equatorial tropics, but, more explicitly, seasonal shift of air flows, cloud and precipitation systems known as monsoons in the equatorial tropics of South and Southeast Asia, Western Africa, etc.

On the other hand, in contrast the warming effect of GHGs, anthropogenic sulphate aerosols (from ground level pollution) have significant cooling effect by canceling out some of the GHG warming effect. Most climate models reckon that aerosols – such as those from sulphates – cool the atmosphere by about $0.3 - 0.5^{\circ}\text{C}$ (e.g. Hwang et al., op. cit.; Polson et al., op. cit.). The apparent underestimation of sulphate aerosols' cooling effect in conventional climate science models until recently might help to settle one of the major controversies in climate science: the lack of a more direct correlation between atmospheric GHG concentrations and global atmospheric temperature increases over the last several decades, which has permitted climate change skeptics to argue that global warming is all but “hot air” (Wright and Nebel, op. cit., p. 524; see also *The Economist* [56]).

Our survey of the six hypothesis posited to explain Lake Chad's shrinking reveals that none, singly, offers an adequate explanation. Collectively though they provide useful insights into the processes and mechanisms which caused this ‘ecological catastrophe’.

5. COMPARATIVE PERSPECTIVE: SYMPTOMS OF GLOBAL WARMING AND CLIMATE CHANGE IN TOP-4 AFRICAN INLAND FRESHWATER LAKES

In this section we highlight the symptoms of global warming and climate change in the top-4 African inland freshwater lakes, including Lake Chad itself, in order to provide a comparative perspective to the Lake Chad experience. Table 7 schematizes the relevant features of the four inland freshwater lakes: Lakes Victoria, Tanganyika, Malawi, and Chad.

Table-7. Comparative Features of Top-4 African Inland Freshwater Lakes

Lake	Location	Size	Response to Climate Change
1) <u>Lake Victoria</u> (also known as Victoria Nyanza)	Situated in East-central Africa along with the equator. Bordered on the north by Uganda (46%), Kenya on the east (6%) and Tanzania on the south (49%). It is the chief reservoir of the sources of the Nile River. Receives 80% of its water directly from rainfall (precipitation) and its location astride the equatorial tropical zone guarantees all-year round supply of rain fall.	Second largest freshwater lake in the world, with a total length of 344 km and 240 km wide (from east to west) and is 1,134 meters above sea level. Surface area measures 69,485 km ² , with maximum depth of 84 metres (average depth only 40 meters). It is not only Africa's largest inland freshwater lake but also the second largest globally in terms of surface area. The water volume is 2,720 km ³ .	Violent thunderstorms caused by local upsurge of warm air. Daytime breezes flow outward from the cool water towards the warm land; at night, the opposite tends to obtain [57] and storms concentrate over the lake. Climate change and associated GHG emissions will cause the extreme amounts of rainfall over the lake to increase by twice by as much as the rainfall over surrounding land [58].
2) <u>Lake Tanganyika</u>	Divided between four East-central African countries, Tanzania, DR Congo, Burundi and Zambia. Long and narrow, the lake forms the entirety of border between Tanzania and DR Congo. Formed slowly over 1 million years as the East Africa plate separated from the main African plate, creating a massive rift valley that continues to form today, if slowly. Sits at the headwaters of the Congo River which transports water from the west side some 4700 km across the African continent to the Atlantic Ocean. Links with the Congo basin provides a unique opportunity for all kinds of river animals to diversify into 100s and 1000s of species endemic to Lake Tanganyika.	Surface area measures 32,900 km ² . It is the world's 2 nd largest freshwater inland lake (by volume) and 2 nd deepest (1,470 meters), after Russia's Lake Baikal. Contains 17% of world's surface freshwater, almost as much as all 5 of north America's Great Lakes combined. Because of its great depth, the lake is among the special type of lakes that remain permanently stratified, in the sense that the warm surface waters never mix completely with the cooler waters at the depth.	Surface water temperatures have warmed 0.1°C (1.8°F) over past 100 years, resulting in reduction in biological productivity [59]. Lake's incredible biodiversity created by links with Congo basin, and this could be undermined by reduction in the magnitude and frequency of upswelling events caused by climate change.
3) <u>Lake Malawi</u> (also known as Lake Nyasa)	Divided between three East African countries, Tanzania, Mozambique, and Malawi, it is part of East Africa's Great Lakes System. Reputed to harbour more fish species than any freshwater lake in the world.	Surface area measures 30,044 km ² . It is Africa's 2 nd deepest lake.	Estimated 1000 fish species rely on freshwaters of the lake for survival. Fish stocks have dwindled 90% over since the 1990s from about 30,000 mt/year to 2000mt/year because of drop in water levels, over fishing and rapid population growth [60]. Climate change, and deforestation threaten its flora and fauna species with extinction. Drop in water level since 1980s to continue, given signs that there will be less rainfall and increased evaporation.
4) <u>Lake Chad</u>	Located in West-central Africa between Chad (60% of surface area), Cameroon, Niger, and Nigeria. Situated, in contrast to other major Africa lakes, in the Sahel climatic zone on the edge of the Sahara Desert between 12° and 14° N latitude, and 13° and 15° E longitude. Has a closed catchment basin with no outflow to external rivers or seas, which contrasts with other lakes.	Largest lake in West-central Africa in terms of surface area, but strikingly shallow measuring only 476 meters at its deepest due to the fact that the lake is embedded within the arid and semi-arid Sahel climate. Exact size of the lake has never been known though, varying widely from year to year influenced by local drought conditions. Its current surface area is put at 1200-1500 km ² . Between 85-95% of water input comes from Chari-Logone River System. Lake losses water uniquely through infiltration into underground aquifers and, more commonly, evaporation (around 4,995 km ³ annually).	Lake level, volume and surface area fluctuating as a function of climate variation. During the humid (wet) years, 1950-1970) around 70% of lake's surface area comprised open water; with the prolonged drought of the 1970s onwards, there involved the 'Small Lake Chad' with very limited area of open water resembling a swamp. During 1998-2012 lake experienced some improvement on water level; however, given Lake's history, this improvement may prove yet unsustainable.

Source: Authors

5.1. Two Distinct Features of Lake Chad vis-à-vis Other Major African Inland Lakes

Two distinct features distinguish the Lake Chad environment, which might help to understand its unique response to climate change vis-à-vis other major African inland freshwater ecosystems. **First**, it is embedded in a drought-prone Sahel climate. The latter has had significant influence on the net water balance in Lake Chad, which has decreased over the decades (beginning since the 1970s) as a result of incessant drought. Climate change has tended to compound the drought condition: global warming has led to rising surface temperatures and extreme heat, even more importantly than decreased rainfall in the African Sahel, induce high rates of evaporation of lake waters, leading to shrinking lake levels.

Agronomic models (e.g. GIZ [61]) forecast the highest projected increase of mean annual temperature for the central and eastern Lake Chad basin reaching in some areas up to 3–6°C by the end of the 21st century (the 2000s). Rising temperatures will increase evapo-transpiration, thus reducing the available water resources by up to 4-10% until 2099.

Other major African inland lakes – e.g. Lakes Victoria, Tanganyika, Malawi, etc. – are situated in a tropical ecology where regular rainfall has a moderating influence on the rising temperatures and extreme heat associated with current global warming and climate change. Lake Victoria, for instance, sits astride the equatorial tropical zone, which guarantees all-year round rainfall.

Second, Lake Chad has a drainage basin or watershed with no outlet to an outside sea or ocean. Lake Chad's only source of water input is via natural rainfall, which, however is subject to seasonal and long-term fluctuations due to climate change (see Figure 4). The water levels of Lake Chad as calculated by NASA scientists using data provided by Okonkwo, et al. [62] show that since 1900 bumps and dips characterize the lake level, mirroring fluctuations in rainfall. Between the early 1960s and end of the 1980s Lake Chad's water levels sank 3 meters below the mean level between 1900 and 2010. By the 1980s the lake surface area had reached a low of just 1500 km² – down from 25000 km² in the early 1960s.

5.2. Is Lake Chad Surface Area Recovery Sustainable?

However, by the first two decades of the 2000s the lake levels were reported to be stable and rainfall increasing somewhat (see Dong and Sutton [63]). Scientists warn, however, that the stabilization of Lake Chad's water levels observed as from 2010 should not be taken to mean that the shrinking of the lake is now a phenomenon of the past, given the history of the lake's evolution and the bumps and dips that have featured in this evolution. So, there is reason to predict a possible long-run decline in Lake Chad's surface area; even some researchers predict the Lake Chad could possibly disappear completely in the next 50 years or so.

Available evidence shows that Lake Chad's experience, though quite exceptional when viewed in the context of other major African inland freshwater lakes, does tally with the response of inland lakes in arid regions of the world to climate change. Bai, et al. [1] studied changes in the area of nine (9) inland lakes in arid regions of Central Asia during a space of 30 years, 1975-2007 and found similar results. The area changes in these lakes have been proved to be the results of regional climate changes and recent human activities. The results indicated that the total surface areas of these nine lakes decreased from 91,402.06 km² to 46,042.23 km², accounting for 49.62% of the original area of 1975.

Finally, IPCC *Assessment Reports* show that global warming and climate change has had adverse outcomes for Africa. The IPCC *Assessment Report* for 2014 predicts the following climate change induced scenarios for Africa:

- 75-250 million of Africa's population will be made vulnerable to water stress and more than 1.8 billion by the 2080s. Already inland freshwater bodies are being degraded by climate change; some are even disappearing – e.g. Lake Chad.

- Rainfed agriculture could decline by 50% in some African countries by the year 2020; wheat production will be hardest hit and may disappear from African agriculture by the 2080s, and maize (a key grain staple) will fall significantly in Southern Africa (e.g. [64, 65]).
- Arid and semi-arid land will increase by up to 8% with severe socioeconomic implication – specifically, it will exacerbate the food security problem and undermine efforts towards poverty eradication. Currently, almost 1 billion people live in arid lands; in Africa alone there are 180 million (1.8% of the global total).
- Sub-Saharan Africa and South Asia are two world regions with the highest levels of chronic malnourishment (hunger); those are regions that are most likely to be exposed to the highest degree of instability in food production.

6. SUMMARY AND CONCLUSIONS

Global warming and climate change constitutes the major environmental degradation challenge currently facing human societies. Its symptoms in Earth's ecosystems have been intensely studied and extensively documented in the climate science literature. The broad objective of this paper was to explore the scientific literature in order to identify and examine the effect of global warming and climate change on ecosystems; in particular, it examined the mechanisms and process through which global warming and climate change degrades ecosystems. The latter describes biological communities (of plants, animals, and microbial organisms) in their interaction with the natural or physical environment (land, water, air, etc.) in which they are embedded; thus, the ecosystem category includes consideration of the processes by plant and animal population and associated microbial organisms interact with each other and the natural environment to reproduce and perpetuate the entire biological community.

The specific objective of the paper was to analyse the response of inland freshwater ecosystems to global warming and climate change, drawing empirical illustration from the degradation of Lake Chad, an inland freshwater lake ecosystem embedded in the Sahel climatic zone of West-Central Africa.

The study is premised on the argument, that ecosystems are dynamic entities whose functioning is controlled by both internal and external processes and forces. The most important internal processes controlling ecosystems are human beings and their activities; specifically, human beings exploit ecosystem resources to sustain their existence. On the other hand, the most important external processes shaping ecosystem functioning originate in the climate factor (temperature and precipitation). However, the influence of the climate variables on ecosystems can be compounded by non-climate variables – specifically, over-exploitation of ecosystem resources by humans, which can – and, indeed, does – lead to degradation of the regenerative capabilities of ecosystems and even, total collapse.

The degradation of Lake Chad clearly illustrates this interaction between the climate factor and non-climate factors in the degradation of ecosystems. The paper explores six theories / hypotheses to attempt to explain the Lake Chad and experience: (i) natural climate variation; (ii) anthropogenic climate change compounding the effect of the Sahel drought to undermine the regenerative potential of the Lake Chad hydrologic cycle; (iii) unregulated exploitation of the Lake Chad hydrologic system overdrew the regenerative potential of the hydrologic cycle; (iv) high rates of deforestation in the tropical rainforest basin of West-Central Africa shifted the rainbelt southwards; (v) pressure from rapidly growing human and livestock population exceeded the carrying capacity of Lake Chad's ecosystem; and, (vi) anthropogenic aerosols emissions in the northern hemisphere caused air pollution (regional climate change) that shifted the tropical rainbelt southwards with a steady decrease in precipitation in the West African Sahel from the 1950s onwards.

A survey of evidence finds that, there is no single-cause explanation for the degradation of Lake Chad; rather, the influence of anthropogenic climate change compounded those of non-climate factors – e.g. deforestation, unregulated exploitation of lake's resources by the riparian states, human pressure on lake's aquatic resources, etc. – to degrade Lake Chad; and, second, Lake Chad's experience, though quite exceptional when viewed in the context of

the experiences of other major African inland freshwater lakes, does tally with the responses of inland lakes in arid region of the world to climate change.

End Notes

- ¹ The terms ‘global warming’ and ‘climate change’ are often used synonymously in the literature even though they describe quite different processes, the one referring to an increase over time in Earth’s average surface temperatures, the other to a long-term change in the elements of the Earth’s climate system, such as temperature, rainfall, wind, and pressure measured over time of at least 30 years. In this paper we use the term global warming and climate change to describe a single process: the exceptional changes observed in Earth’s climate system beginning since the Industrial Revolution Centuries (the 1700s and 1800s).
- ² Cited in [Nikoulima \[2\]](#) p. 83 (figure 5.4).
- ³ One of the four largest lakes in the world before its degradation, with an area of 68,000 km², the Aral Sea steadily began to shrink in the 1960s as the rivers (Ama Darya and Syr Darya) flowing into the inland Aral Sea were diverted into irrigation development for cotton production in Soviet Kazakhstan and Uzbekistan. By 2007 the Aral Sea had already lost some 90% of its original size; by 2014 satellite images revealed that parts of the original Aral Sea have, in fact, completely dried up for the first time in modern history turning into what is now called Aral Kam desert [\[66\]](#).
- ⁴ See [Adams \[67\]](#) plate 1.2, p. 18, on Mount Kenya.
- ⁵ Glacier retreat, along with melting ice caps and mountain snow loss, provides, one of the most visible and sensitive evidence of global warming climate change. Given current trends, nearly all glaciers have lost their mass balance (Gardner and 16 Others, 2013); see also [The Economist \[68\]](#) and [IPCC \[69\]](#).
- ⁶ Most of the warming due to climate change (93.4%) is going into the oceans, where a lot of ecosystem changes are transpiring. Rapidly rising GHG concentrations are driving ocean systems towards conditions not observed in millions of years, with an associated risk of fundamental and irreversible ecological changes (see [\[3, 70, 71\]](#)).
- ⁷ In the 1980s scientists had discovered that anthropogenic GHG concentrations in Earth’s atmosphere have been transforming the chemical properties of the ozone layer (ozonosphere), thus allowing more UV radiation to penetrate the biosphere, with adverse health and environmental outcomes – e.g. skin cancer which causes mutation of DNA and suppressing certain activities of the human immune system. See [Oxford Dictionary of Science, 2005, p. 594](#).
- ⁸ Previous changes in Earth’s average surface temperatures were caused by volcanic eruptions, changes in ocean currents, variations in the angle of Earth’s rotation in its distance from the sun; etc.
- ⁹ When scientists analyse atmospheric carbon dioxide concentrations they employ the term parts per billion (ppb) or parts per million (ppm), but when analyzing carbon dioxide being released into the atmosphere they use the term gigatonnes of carbon (Gt.C). Whereas ppm and ppb are mass or stock phenomena, Gt.C is a flow concept: carbon dioxide, as it cycles through Earth’s various spheres (atmosphere, land, water) often changes from one form to another, rather than remaining carbon dioxide: it is stored as carbohydrates, oils, carbonates, and various other organic materials – so-called carbon fluxes in the scientific literature.
- ¹⁰ See Adams (op. cit.,) especially pp. 37-58.
- ¹¹ A large aquatic ecosystem can influence local climate – see [Thiery, et al. \[58\]](#) on Lake Victoria in East Africa.
- ¹² [Samuelson \[72\]](#) is credited with pioneering the concept of ‘public goods’ in modern economics, defining them as “collective consumption goods” – i.e. goods which everyone enjoys in common, in the sense that each individual’s consumption of such goods does not subtract from any other individual’s consumption of these goods – the *non-rivalness* principles. In addition, a public good has a second property, namely, non-excludability meaning that it is impossible to barr or prevent others from consuming public goods. Some

goods may be rivalrous but non-excludable, and are called common-pool resources – e.g. open sea fisheries, water in an open lake, village grazing pasture, etc. Common-pool resources raise similar problems to public goods – the tragedy of the commons.

- ¹³ Earth-atmosphere's 'carrying capacity' in the present context is the maximum amount of GHGs or gaseous pollutants the atmosphere as a natural waste 'sink' can effectively assimilate without its chemical composition or properties changing to a vastly different state.
- ¹⁴ Scientists employ different approaches to attempt to discover the symptoms of climate change in Earth's natural systems, including ecosystems, namely, use of instrumental records, Palaeoclimatic analogues, and coupled general circulation models (CGCMs). See [Dike and Dike \[39\]](#) chapter 3, subsection 3.9.
- ¹⁵ The Holocene epoch was preceded by the Pleistocene epoch (or Ice Age) when most of Earth's species began to evolve. The Pleistocene epoch began since 1.8 million years ago. All known human civilizations began during the Holocene epoch. Historians put the first evidence of human civilization in 9,500 BC, only 100 years before the beginning of the Holocene epoch.
- ¹⁶ Numerical models upresenting physical processes in the atmosphere, hyerosphea, cryusphea, (solid foam of water e.g sea ice, lake ice, river ice, snow cover, glaciers, ice caps, ice sheels and frozen land) and land surface.
- ¹⁷ Monsoon involves large-scale sea breezes occurring when temperatures on land is significantly warmer than that of the oceans, causing temperature imbalance. Usually, the latter occurs because land and ocean exhibit significant differences in capacity to absorb heat, with the oceans absorbing heat faster than land can, which makes the land environment significantly warmer than ocean environment (which explains, also, why coastal regions are cooler than continental region). As the lower atmosphere (troposphere) over land gets warmer, evaporation will intensify resulting in an increase in moisture circulating in the lower atmosphere, which, in turn, leads to increased frequency over precipitation events mainly over land. As the latter warms up faster than the ocean it creates low pressure into which moisture-laden winds flow.
- ¹⁸ See End Note no. 5 above.
- ¹⁹ The proportion of solar radiation reflected from a surface, such as clouds or bare rock, which is found to be higher for lighter, white bodies than for darker, black bodies (e.g. forest canopy).
- ²⁰ Dukiya and Galhot explain that the floods in the Niger-Benue confluence come as a result of the monsoon rains occurring in July through September in West Africa. The monsoon rains produce "a surge" that expands the flood plains of the Niger River to as high as 25000 km² but which shrink to as low as 4000 km² in dry periods. Complementing the monsoon factor is a "conflict between man and environment": specifically, land-use (especially urbanization) and land-cover have been poorly managed in the drainage basin and river courses of the Niger River, which gives rise to silt-laden floodwater cascading down the Niger River and overflowing its banks.

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