

## Water resources around Lakes Nyos and Monoun along the Cameroon Volcanic Line, Central Africa; Hydrological and hydrogeological framework.

カメルーン火山帯沿いのニオス湖及びマヌーン湖周辺の水資源；地下水の水理・水質に関する研究)

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Integrated approach has been used to investigate the hydrological and hydrogeological framework of complex fractured volcanic aquifers. The field of interest comprise the aquifers in the vicinity of Lakes Nyos and Monoun (*Killer Lakes*) located within the Oku volcanoes, near the northern boundary of the Cameroon Volcanic Line in the northwest and west part of Cameroon. Particularly, groundwater is the main source of water supply for multipurpose uses in Nyos and Monoun areas. Despite the great importance of this key resource for people living in this part of the country and since the Lakes' Nyos and Monoun limnic eruptions (in 1984 and 1986, respectively), which led to numerous fatalities, injuries and refugees, the hydrological system "*on the catchment scale*" of Nyos and Monoun areas is poorly understood or totally absent. Additionally, groundwater is being increasingly used in these areas with little or no consideration to its quality, recharge process, residence time and anthropogenic degradation. The lack of the basic and comprehensive data on the water resource in these areas does not only hampers the current understanding of the rule of the hydrological system in the CO<sub>2</sub> flux related issues in both lakes, but also constrains the resettlement process of refugees caused by the disaster and consequently precludes the achievement of the Millennium Development Goal which is intricately linked to the availability and sustainability of water resource.

In this thesis, conventional hydrological field investigations followed by hydro-geochemistry studies, multivariate statistical analysis and environmental tracers

modelling techniques have been used to characterize the water resources in the vicinity of Lakes Nyos and Monoun, in order to provide hydrogeological informations that are needed for development of water resources planning management schemes.

Generally, the water sources in the vicinity of both Lakes Nyos and Monoun are fresh, slightly acidic to neutral and heterogeneous distributed along the hydraulic gradient. They are characterized by the dominance of alkaline earth metals ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) over alkalis ( $\text{Na}^+$  and  $\text{K}^+$ ) with bicarbonate ( $\text{HCO}_3^-$ ) as the most represented anion, given the mixed Ca-Mg- $\text{HCO}_3$  as the main water type in the studied catchments. Standard graphical plots of the hydrochemical composition of the water groups combined with multivariate statistical analysis reveal that the dominant processes responsible for the hydrochemical evolution of groundwater in the vicinity of both Lakes Nyos and Monoun are (i) silicate weathering reactions (water-rock-interaction), (ii) dissolution of carbonate minerals disseminated in the granitic bedrock, (iii) ion exchange reactions and (iv) anthropogenic activities.

In Nyos site, the stable isotope data of rainfall provided evidence for rapid recharge process during a very specific period (late June and earlier August, July not included), and negligible evaporation prior to groundwater recharge while the rainfall in Monoun site seems to be subjected to isotopic enrichment through evaporation prior recharge. The seasonal variations in  $\delta^{18}\text{O}$  and  $\delta\text{D}$  for surface and shallow groundwater in Lake Nyos catchment are barely detectable (well-mixed aquifer) but differs from that of soda springs and that of the bottom waters of the lake. Consequently, the hypothesis of hydraulic connectivity between groundwater, soda springs and deep water of Lake Nyos as suggested in previous studies can be excluded. Instead, recharge is likely to take place in southern part of the Lake Nyos catchment between 1100 and 1600 m above sea level as suggested by the annual isotopic altitudinal gradient ( $-0.24\text{‰ } \delta^{18}\text{O} / 100\text{ m}$ ) and the immature stage (low total dissolved solids) of the groundwater at that location. The effective annual recharge rate of 941 mm/yr (30 % of annual precipitation) has been estimated based on the chloride mass balance method. The chlorofluorocarbons dating revealed young apparent ages of groundwater in the vicinity of Lake Nyos from 21 to 32 (mean of 24) years. The  $\text{SF}_6$  based age of groundwater is biased young compared to CFCs

ages, suggesting an additional geogenic origin of SF<sub>6</sub>; hence, the use of SF<sub>6</sub> ages is constrained in the region.

Consistent with the isotopic results reported in Lake Nyos catchment, the isotopic and hydrochemical investigations of groundwater around Lake Monoun showed no evidence of hydraulic connectivity between deep waters of Lake Monoun and surrounding groundwater. Moreover, the evidence obtained from the hierarchical cluster analysis (HCA) strengthens the ideas concluded from the groundwater and bottom waters of Lakes relationships. The results of the HCA indicated that CO<sub>2</sub>-rich bottom waters of Lakes Nyos and Monoun belongs to an isolated hydrological system within the studied catchments. Therefore, it can be said that the discharge of CO<sub>2</sub> gas which seems to be limited beneath both Lakes has no influence on the chemistry of surrounding groundwater.

With respect to the groundwater quality, a comparison of major concentrations with standards set by two organizations (World Health Organization and Nigerian standards) indicated that groundwater in the vicinity of Lake Nyos is of good quality for human consumption and domestic uses, while in the vicinity of Lake Monoun groundwater partially failed the quality standards with respect to pH, hardness and nitrates. Human related activities such as poor sewer system, spreading of animal manure and use of agricultural fertilizers has been identified as the main factor responsible for the high level of NO<sub>3</sub> in groundwater (especially in shallow wells which are the most used in the area). Quality risk assessment with respect to agricultural uses showed that water sources in the studied areas is of low to moderate salinity and low alkalinity hazard, thus good to excellent quality and can be used safely for irrigation purposes in almost all types of soils.