GROUNDWATER RECHARGE, CIRCULATION AND GEOCHEMICAL EVOLUTION IN THE SOURCE REGION OF THE BLUE NILE RIVER, ETHIOPIA

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INTRODUCTION

This work uses geochemical and isotope hydrological approaches to provide an initial schematic geo-hydrological model on groundwater recharge, circulation, chemical evolution and its subsurface residence time in the poorly known hydrogeologic system of the upper Blue Nile River basin of Ethiopia. The specific objectives of this work are: 1) to characterize the isotopic ($\delta^{18}O$, δD, $\delta^{13}C$, ^{3}H) compositions of the groundwaters of the Blue Nile River basin; 2) to determine sources and mechanisms of recharge of groundwaters in the Blue Nile River basin; 3) to determine the dominant geochemical processes that influence groundwater chemical composition; and, 4) to schematize groundwater flow patterns and nature of aquifers in selected important hydrogeological regions of the basin.

The Blue Nile River basin is located in the Northwestern Ethiopian Plateau. The Main Nile River gets 70 % of its flows from the Blue Nile emerging from the Ethiopian Plateau. The major part of the region is covered by basalt. Mesozoic sedimentary seccession are exposed locally. The lowlands bordering Sudan are covered by Precambrian metamporphic rocks and alluvium. There are two prominent tectonically deformed regions on the plateau. These are the Lake Tana Graben (LTG) and the Yerer-Tullu Wellel Volcanic Lineament zone (YTVL). The majority of geothermal springs, Quaternary volcanoes, and quaternary basalt flows that exist in the Blue Nile basin are located in these two zones. With the exception of the eastern sector of the basin just east of the water divide of the Blue Nile basin where thick intermountain alluvial sediments bear high groundwater yield, the majority of groundwaters in the Blue Nile basin are abstracted from the fractured basaltic or metamorphic rocks. Aquifer transmisivity is highly variable ranging from 1 to 700m^2/day. The Quaternary basalts surrounding Lake Tana are characterized by high transmisivity (100-200m^2/day) compared to the basalts of the trap series. Quaternary alluvial sediments have the highest transmisivity (in places more than 700m^2/day). The metamorphic rocks in the western lowland have the lowest transmisivity (as low as 1m^2/day).

METHODOLOGY AND MATERIALS

The methods used to achieve the objectives includes; a) direct analysis of the raw isotope hydrological and geochemical data; b) statistical classification of the data set accompanied by associating the statistical classes of the waters with hydrogeological variables; and, c) geochemical modeling. Furthermore $\delta^{13}C$, P_{CO2}, pH and carbonate species compositions of the groundwaters were used to gain additional insight on groundwater geochemical evolution.

RESULTS AND DISCUSSION

The majority of the groundwaters are Ca-Mg-HCO3 type. Unlike the Ethiopian Rift groundwaters and the groundwaters of shallow systems of the Sahel region, the groundwaters of the Blue Nile basin are characterized by high (>15) deuterium excess and they all plot above the GMWL (figure 1). The Blue Nile River sampled at Khartoum (Farah et al., 2000) shows similar $\delta^{18}O$ and δD

compositions to the groundwaters of the Blue Nile basin. A clear difference exists between the $\delta^{18}O$ and δD compositions of surface water originating from the Equatorial lakes region and the $\delta^{18}O$ and δD compositions of meteoric waters of the Blue Nile River.

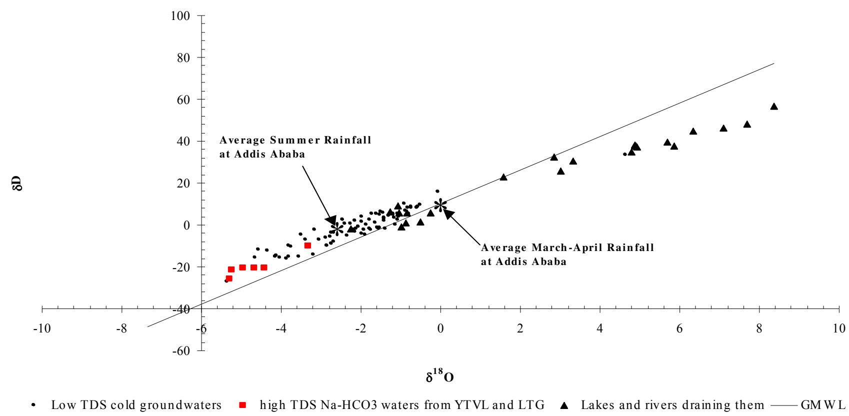


Figure 1: Isotope plot of meteoric waters of the Blue Nile Basin

Statistical classification of the hydrochemical data is used here to elaborate the geochemical types and associated chemical processes. We considered 11 variables (pH, Ca^{2+}, Mg^{2+}, K^+, Na^+, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, TDS) to classify the 86 groundwater samples with complete chemical analysis. In HCA the variables are log transformed and normalized so that each variable will have equal weight. Groups were selected visually from the dendrogram which is the output of the clustering. From the dendrogram, two major groups and nine subgroups were chosen using index of similarity = 0.25.

The two groups have also distinct $\delta^{18}O$, δD, ^3H and $\delta^{13}C$ compositions. Group I waters are depleted in $\delta^{18}O$ and δD, they are nearly tritium free, and they are enriched in $\delta^{13}C$. Group II waters are generally enriched in $\delta^{18}O$ and δD, they contain appreciable amount of tritium and have depleted $\delta^{13}C$. Group I waters have five subgroups and Group II waters have four subgroups. Group I contains five fairly distinguishable subgroups. Group II have three distinguishable subgroups.

We conducted inverse geochemical modeling on the water subgroups that resulted from HCA. The average chemical composition of waters of subgroup IX was assumed to represent a pristine recharge area groundwater. Its composition is therefore taken as 'initial' water in the inverse geochemical modeling. The remaining subgroups were considered to be derived from this subgroup.

The result of the inverse geochemical modeling shows that, except in the evolution towards subgroup I, the hydrolysis of silicate minerals (principally feldspars and ferromagnesian minerals) without a major involvement of the sedimentary minerals (e.g. carbonates, evaporites) satisfy the simulation. The major minerals that are required to dissolve were olivine, pyroxene, plagioclase, K-micas and K-feldspars. Dissolution of gaseous CO_2 is required in all cases. Removal of clay minerals such as illite or Ca-montmorillonite was required during groundwater transition in the aquifers. Precipitation of calcite or chalcedony or both were required in the models. Dissolution of gypsum, dissolution of dolomite and cation exchange (CaX ↔ NaX) were required to simulate the composition of subgroup I.

CONCLUSIONS

The Hierarchical Classification Analysis elaborately classified the groundwaters of the upper Blue Nile basin into two major groups and 9 subgroups. The advantage of the method was *that the subgroups were objective and a clear geohydrological patterns were recognized. The nine subgroups show different degree of water rock interaction, subsurface residence time, aquifer composition, influence of CO_2, and exposure to anthropogenic pollution etc. In a poorly known hydrogeological system the exercise of associating the results of the cluster with geo-hydrological conditions facilitates the understanding of the groundwater flow systems in the basin. Traditionally, it was thought that two groundwater layers (shallow/deep; fresh/saline, unconfined/confined) exist in volcanic aquifers of the region (Chernet, 1982; Chernet, 1990). However, the Hierarchical Classification Analysis and the geochemical approach show that more groundwater flow patterns can be distinguished in the region adding more understanding to the previous knowledge of the Ethiopian plateau volcanic hydrogeology.*

The geochemical, isotopic, stratigraphic, structural data and the Hierarchical Classification Analysis helped to schematize geo-hydrological characteristics of important zones in the Blue Nile basin and to gain for the first time a general picture of the groundwater circulation and its chemical evolution in the basin. Conceptual models that schematize the major geochemical processes and recharge source for the two important regions are presented in figure 3.

In the basaltic plateau recharge is rapid, groundwater circulation is shallow and the waters are characterized by low TDS. Two structurally deformed zones, namely the LTG and the YTVL plays a major role in favoring the existence of regional and probably deeper groundwater flows. The geologic processes which formed the two structural basins resulted in juxtaposition of the Mesozoic sediments with the Cenozoic volcanic cover and this promotes the presence of artesian springs at the contact between the Mesozoic sediment and Cenozoic volcanic cover. Furthermore carbon dioxide from deeper sources (CO_2 produced by metamorphic decarbonation of the Mesozoic sediments underlying the basaltic trap) along the deformed zones influences geochemical evolution of the high TDS thermal groundwaters of the YTVL and the LTG. The CO_2 gas from depth promotes acid hydrolysis of the volcanic covers, which explain generally low pH and high HCO_3^- of these groundwaters.

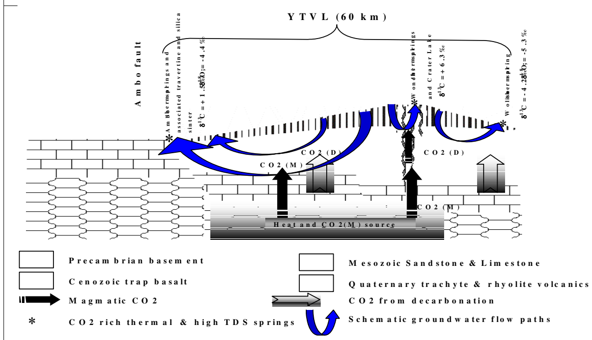
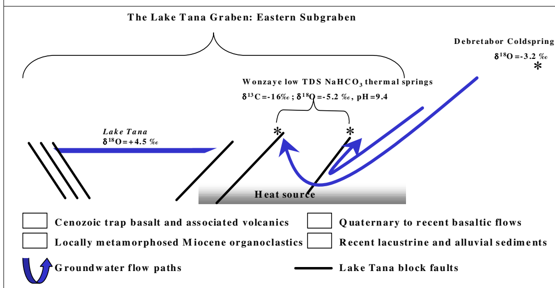
<table>
<tr><th>Schematic groundwater flow pattern</th><th>Source of recharge and main geochemical processes</th></tr>
<tr><td>
</td><td>1. Recharge at high altitude by Ca-HCO$_3$ type waters, major residence in acid volcanic rocks, open system hydrolysis of silicate minerals, lowering of pH by addition of CO_2 from metamorphic decarbonation of the underlying Mesozoic sediments or from direct CO_2 input form deeper sources along the fault zone, release of CO_2 on emergence or before emergence and deposition of travertine and silica sinter, waters with Na-HCO$_3$ characteristics as final composition.</td></tr>
<tr><td>
</td><td>2. Recharge at around Guna Shield volcanoes, flow of Ca-HCO$_3$ type water through a metamorphosed zone of the Miocene lignite beds and sink of CO_2, exchange of Ca for Na and K in the zone, formation of high pH and high SiO_2 water plume, emergence of Na-HCO$_3$ water plume at low TDS and high pH.</td></tr>
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Figure 3: Schematic sections showing origin and evolution of selected groundwater systems/springs. 1-Thermal springs in the YTVL, 2-Wonzaye thermal springs in LTG

Despite the similarity in climatic conditions and the general similarity in Mesozoic lithology, the hydrogeological characteristics of the Blue Nile basin are different from Hydrogeology of Sahelian Africa. The majority of groundwaters of the Blue Nile basin are often highly flushed, young, low TDS groundwaters with rapid recharge through fractured rocks. These characteristics are mainly the result of uplifting and erosional fragmentation of the aquifers of the Blue Nile basin. In the shallow sedimentary aquifers of the Sahel, evaporation prior to recharge seems an important hydrologic process (Sonntag et al., 1982; Dodo and Zuppi, 1997). This process seems unimportant in the upper Blue Nile basin. The classical sedimentary basin aquifer (Intercalaire aquifers) that underlie the majority of the Sahel and Northern African countries (Sudan, Chad, Senegal, Mali, Niger, Tunisia, Egypt etc) containing the late Pleistocene or early Holocene groundwaters (Sonntag et al., 1982; Andrews et al., 1994; Edmunds et al., 2003; Dabous and Osmond 2001) is represented by uplifted Mesozoic sediments which are not accessible to groundwater circulation due to the thick (often greater than 1km) basaltic cover. In some places such as the LTG and the YTVL, however the Mesozoic sediments play an indirect role in influencing the hydrogeochemistry of the groundwaters by supplying CO_2 for water-rock interaction.

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