

Comparative Geochemistry of Surface and Ground Waters in the Central Kenya Rift: A Preliminary Assessment

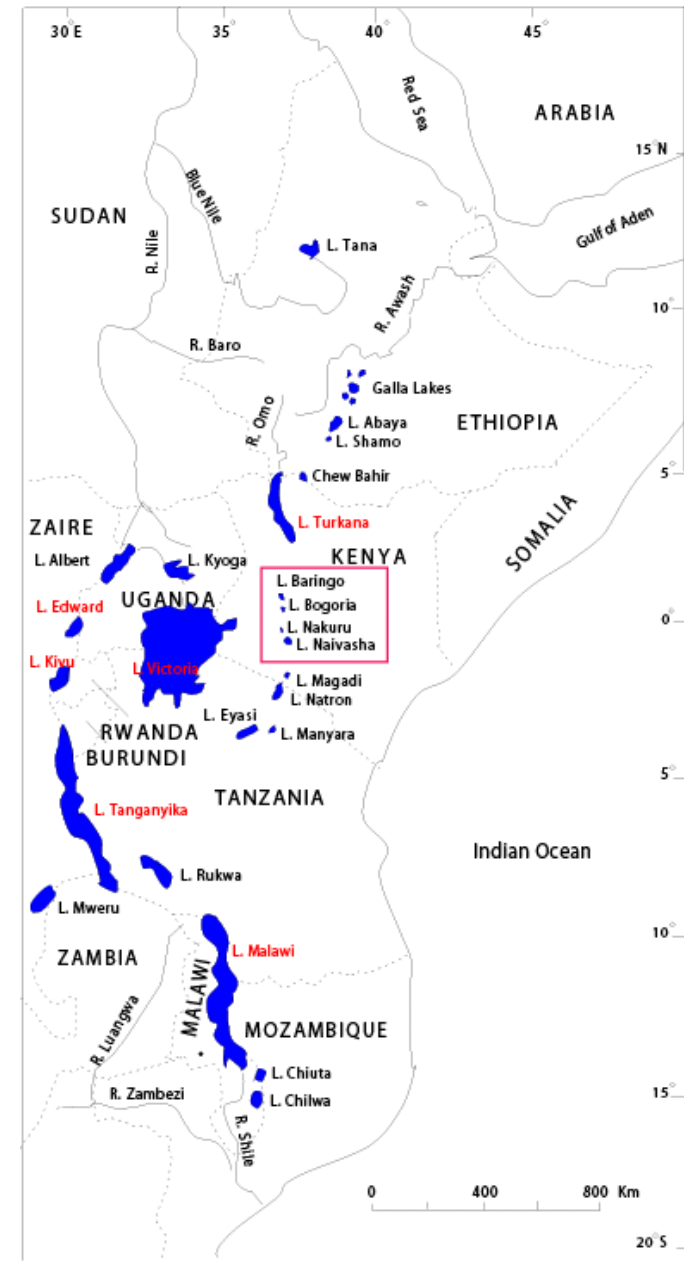
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Introduction

- Most of the larger lakes in East Africa are found within the rift system
- Important influences on the rift hydrology include:
 - Climate (major)
 - subsurface inputs (UN 1973; Gasse and Street, 1978; Yuretich, 1982)
 - location of many of the present lakes is controlled by the local water table e.g. Lake Nakuru (McCall, 1967), Lake Magadi (Eugster, 1970) and Lake Naivasha (Thompson and Dodson, 1963).
 - Rift controlled morphological barriers and volcanic dams intercepting axial and lateral drainage and contributing to formation of many closed hydrological basins
- Study area is located in the central part of the Kenya Rift

Mawari Project

LAKES OF EASTERN AFRICA



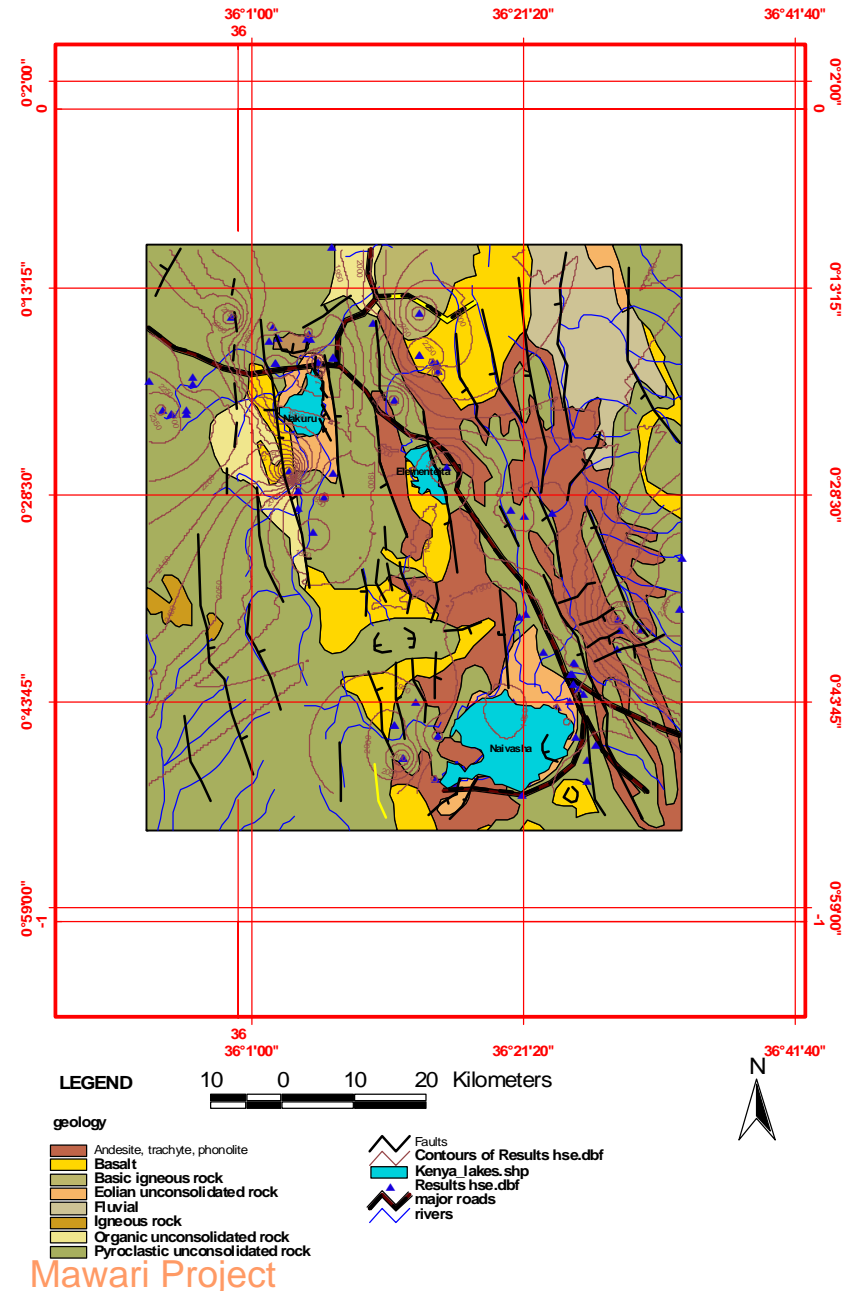
(from Nyamweru C.K., 1983)

Introduction (cont'd)

- High lake levels were recorded during the early and mid 1960s.
- A sharp rise in the level of Lake Naivasha, as well as of Elementeita and Nakuru occurred in 1961 (Richardson and Richardson, 1972).
 - These changes coincided with rise in lake levels in most of the other large lakes of East Africa, e.g. Lake Victoria, Lake Tanganyika and Lake Turkana (Beadle 1981)
- The excessive rainy season of 1961/2 over East Africa coincided with a large anomaly of SST, surface winds and convective cloudiness at the western equatorial Indian Ocean (Flohn, 1987).
- In general, there is a decrease of rainfall from the rift shoulder escarpments into the rift floor and from the highest part in the rift floor at Menengai to the south and north (range:1000 to 1400mm pa)

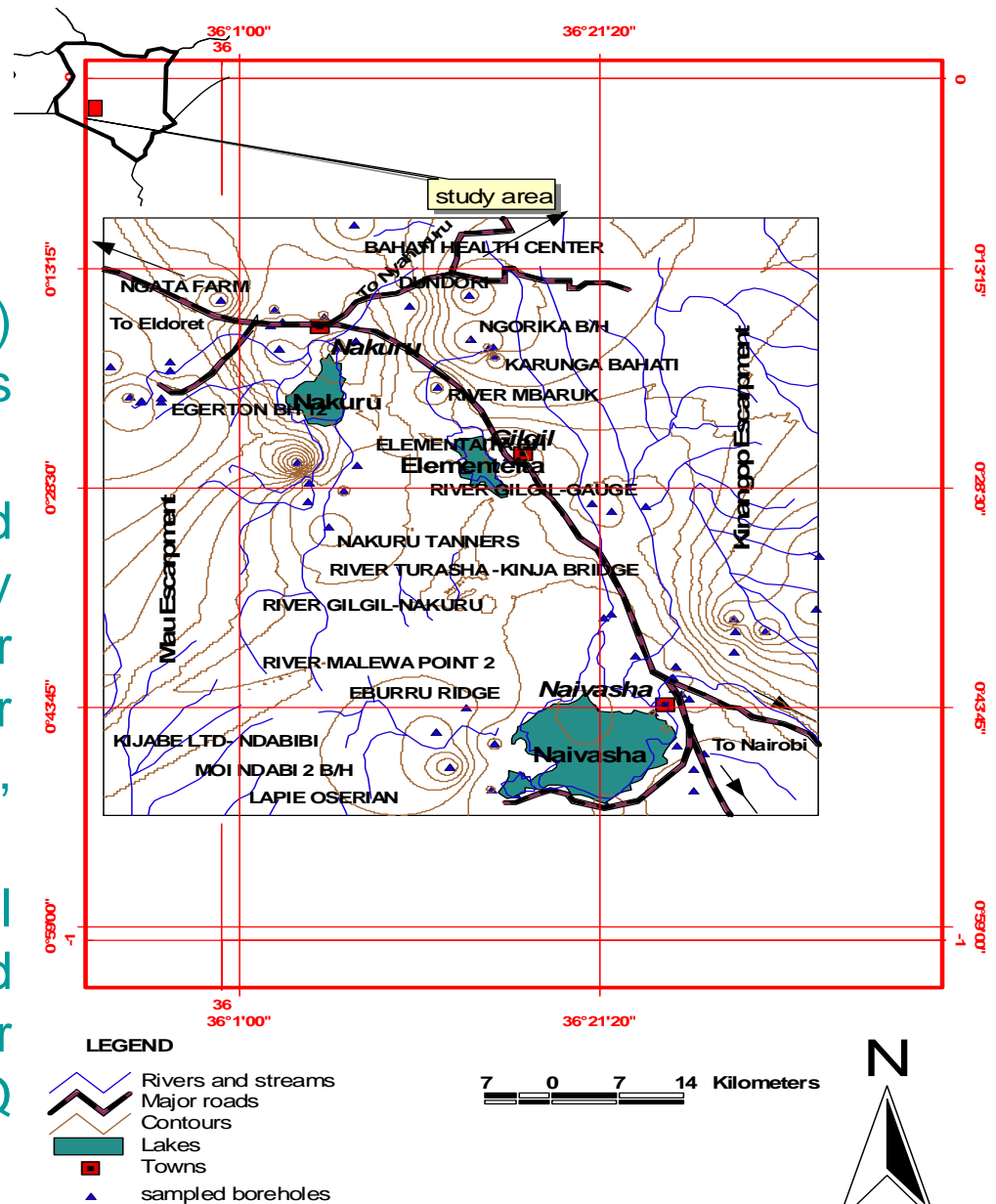
Geology and Structures

- Flood basalts (Miocene), phonolites (Pleistocene) and trachytes (Quaternary), volcaniclastics
- Step faulted central basin of Nakuru-Elmenteita-Naivasha basin.
- The near N-S elongate block structures are detached from the main bounding faults.
- The major rift margin faults have surficial throws of more than 400 m that have generated major tilted blocks



Sampling Points and Methods

- Surface (21 - Lakes; 19 – river) and groundwater (40) samples were collected in October 2006
- Water samples were analysed for major ions and heavy metals at the Ministry of Water and Irrigation Central Water Testing Laboratory, Kenya, using standard methods
- Mineral-water chemical equilibria were determined using the U.S.G.S. computer programme PCWATEQ (Truesdell and Jones, 1974)



Descriptive Statistics of Major Ions

- The most mineralised solutions are the lakes, then groundwater and rivers
- Sodium and total alkalinity show the largest deviation in the data set
- Ca and Mg concentrations are low in lakes and boreholes
- pH is lowest in the rivers and highest in the lakes

	<i>T. Alk.</i>	CA	MG	NA	K	CL	F	NO3	NO2	SO4
Mean	7877.111	20.356	12.066	5130.278	130.089	2044.167	137.828	27.589	0.119	169.251
Standard Deviation	11110.229	44.006	14.655	7700.171	176.398	3891.886	183.049	51.963	0.152	430.646
Range	31090.000	191.200	54.950	22648.500	486.600	13986.000	448.800	159.960	0.616	1828.050
Minimum	110.000	0.800	1.900	27.500	3.400	14.000	1.200	0.040	0.014	0.250
Maximum	31200.000	192.000	56.850	22676.000	490.000	14000.000	450.000	160.000	0.630	1828.300

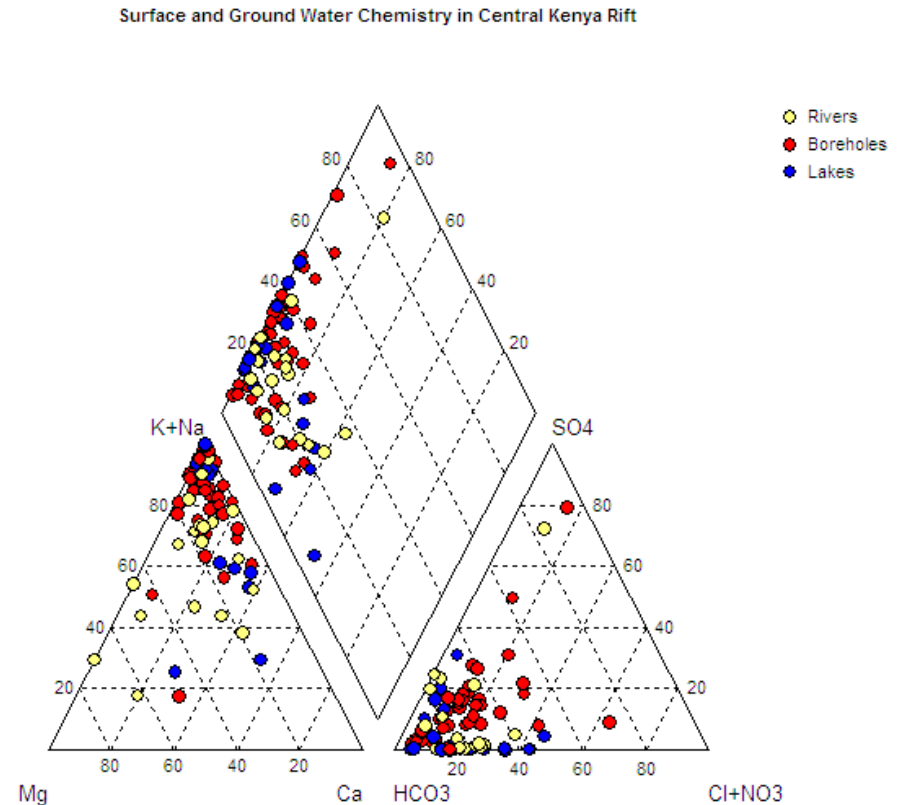
	<i>T. Alk.</i>	CA	MG	NA	K	CL	F	NO3	NO2	SO4
Mean	308.605	9.642	6.183	183.363	12.950	56.579	6.224	2.058	0.029	62.558
Standard Deviation	260.724	8.891	6.293	167.010	9.383	108.704	5.242	5.849	0.089	81.443
Range	1372.000	29.600	26.298	751.500	47.600	666.000	19.440	35.990	0.539	342.350
Minimum	30.000	0.000	0.002	13.500	2.400	1.000	0.560	0.010	0.001	0.250
Maximum	1402.000	29.600	26.300	765.000	50.000	667.000	20.000	36.000	0.540	342.600

	<i>T. Alk.</i>	CA	MG	NA	K	CL	F	NO3	NO2	SO4
Mean	85.667	5.822	5.953	31.611	9.878	11.944	0.798	2.363	0.077	8.030
Standard Deviation	65.405	3.447	4.314	44.820	8.899	19.648	0.739	4.882	0.098	10.035
Range	300.000	11.200	13.810	195.500	32.200	85.000	3.090	20.590	0.279	34.350
Minimum	10.000	0.000	0.290	4.500	1.800	0.000	0.310	0.010	0.001	0.250
Maximum	310.000	11.200	14.100	200.000	34.000	85.000	3.400	20.600	0.280	34.600

	<i>Boreholes pH</i>	<i>Rivers pH</i>	<i>Lakes pH</i>
Mean	8.15	7.69	9.34
Standard Deviation	0.62	0.42	1.14
Range	2.90	1.65	4.19
Minimum	6.33	7.08	6.51
Maximum	9.23	8.73	10.7

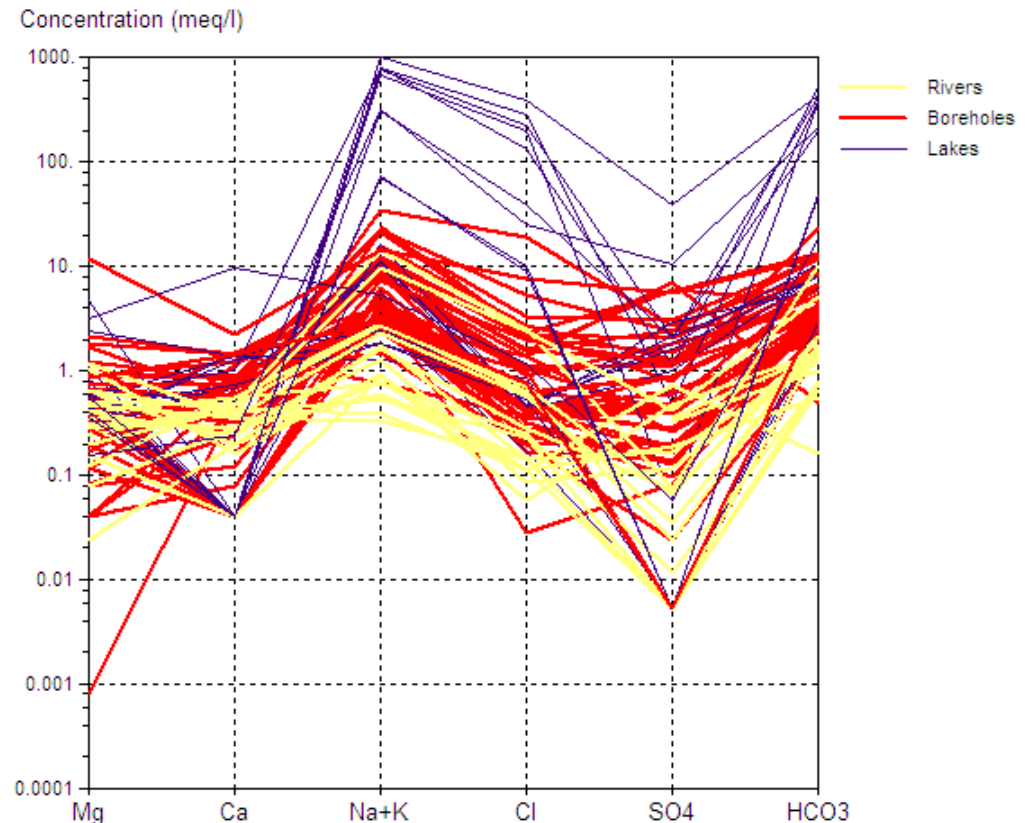
Hydrochemical Facies - 1

- Most of the waters tend to have a sodic/potassic and carbonate/chloride chemical profile
- Largest variability in chemical profile is seen in the rivers (some with dominant Mg rather than Na)
- A few groundwater samples have Cl/SO_4 as dominant anions rather than HCO_3
- These facies are a function of: P:E, solution kinetics, groundwater flow patterns, and lithology



Hydrochemical Facies - 2

- Generally, the waters are Na-Cl-HCO₃ type with very few exceptions
- As expected, the most dilute waters are the river waters, borehole waters have an intermediate chemical concentration
- Lakes have the most concentrated waters
- Lake Naivasha has the lowest aqueous ion concentrations of the lakes as it has a flushing outflow through the groundwater system



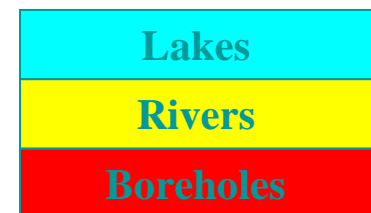
Descriptive Statistics

- Sodium, total alkalinity, and chloride (in that order) show the largest standard deviations in the lakes, rivers and boreholes
- The data indicate that evaporative concentration is the main factor influencing the lake water ionic concentrations
- The groundwater enrichment of Na, F, and SO₄ is through leaching of sodic-rich volcanic rocks and pyroclastics

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Minimum	110.000	0.800	1.900	27.500	3.400	14.000	1.200	0.040	0.014	0.250
Maximum	31200.000	192.000	56.850	22676.000	490.000	14000.000	450.000	160.000	0.630	1828.300

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Range	1372.000	29.600	26.298	751.500	47.600	666.000	19.440	35.990	0.539	342.350
Minimum	30.000	0.000	0.002	13.500	2.400	1.000	0.560	0.010	0.001	0.250
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Maximum	310.000	11.200	14.100	200.000	34.000	85.000	3.400	20.600	0.280	34.600



Correlations

- The similarity in positively correlated elements in the river and lake water support the evaporative enrichment hypothesis
- In the boreholes, correlation between Na, Cl, F and NO₃ may indicate enrichment from surface soils during infiltration, while correlation between Na, SO₄ and F may reflect more deeper seated enrichment through leaching of volcanic rocks and pyroclastics

Lakes
Rivers
Boreholes

	T. Alk.	CA	MG	NA	K	CL	F	NO3	NO2	SO4
T. Alk.	1.000									
CA	-0.225	1.000								
MG	0.200	0.423	1.000							
NA	0.982	-0.244	0.187	1.000						
K	0.965	-0.163	0.330	0.961	1.000					
CL	0.852	-0.211	0.196	0.935	0.876	1.000				
F	0.958	-0.276	0.121	0.944	0.877	0.807	1.000			
NO3	0.640	-0.213	0.257	0.583	0.685	0.425	0.638	1.000		
NO2	0.122	0.760	0.392	0.172	0.199	0.277	0.099	-0.020	1.000	
SO4	0.458	-0.162	-0.153	0.586	0.387	0.738	0.515	-0.137	0.335	1.000

	T. Alk.	CA	MG	NA	K	CL	F	NO3	NO2	SO4
T. Alk.	1.000									
CA	0.001	1.000								
MG	0.113	0.469	1.000							
NA	0.780	-0.063	-0.064	1.000						
K	0.744	0.130	0.263	0.555	1.000					
CL	0.361	-0.016	-0.126	0.789	0.279	1.000				
F	0.369	-0.070	-0.164	0.639	0.040	0.411	1.000			
NO3	0.164	-0.081	-0.130	0.555	0.179	0.904	0.181	1.000		
NO2	0.057	0.210	-0.066	-0.020	0.327	-0.050	-0.066	-0.044	1.000	
SO4	0.248	0.263	0.260	0.538	0.338	0.298	0.518	0.080	-0.036	1.000

	T. Alk.	CA	MG	NA	K	CL	F	NO3	NO2	SO4
T. Alk.	1.000									
CA	0.236	1.000								
MG	0.325	-0.352	1.000							
NA	0.941	0.293	0.045	1.000						
K	0.866	-0.041	0.487	0.752	1.000					
CL	0.917	0.396	0.028	0.984	0.703	1.000				
F	0.775	-0.054	0.210	0.813	0.763	0.765	1.000			
NO3	0.934	0.251	0.107	0.978	0.762	0.955	0.771	1.000		
NO2	0.554	-0.353	0.634	0.438	0.706	0.412	0.634	0.466	1.000	
SO4	0.116	-0.370	0.286	0.167	0.366	0.134	0.519	0.154	0.509	1.000

IAP/KT > 0

IAP/KT = -2 to 0

IAP/KT = -5 to -2

Rivers

- The waters are saturated with respect to a wide range of Fe and Mn oxides and hydroxides
- The waters are slightly undersaturated with respect to calcite, dolomite and fluorite
- The waters are strongly undersaturated with respect to various hydrous and anhydrous sulphate and carbonate compounds of Na

	Njoro Bridge, Njoro	River Gilgil, Marula	River Turasha	River Malewa, Point1	River Gilgil, Nakuru	River Mabruk, Nakuru	River Waseges upstream
PHASE				LOG IAP/KT			
ANHYDRIT	-5.481	-5.252	-3.528	-5.123	-3.951	-6.092	
ARAGONIT	-0.85	-1.594	-1.492	-1.681	-0.844	-2.916	
ARTIN	-6.949	-8.565	-8.298	-9.127	-6.866	-11.773	
BRUCITE	-4.239	-6.166	-5.803	-6.251	-4.612	-6.915	-5.599
CALCITE	-0.703	-1.446	-1.344	-1.534	-0.697	-2.769	
DOLOMITE	-0.83	-3.371	-2.969	-3.156	-1.267	-4.879	
FEOH3A	3.599	3.648	2.914	2.116	3.38	3.237	4.051
FLUOR	-2.672	-2.291	-2.157	-1.996	-1.383	-2.58	
GEOH	10.52	10.569	9.834	9.036	10.3	10.157	10.971
GYPSUM	-5.207	-4.978	-3.255	-4.849	-3.677	-5.819	
HALITE	-8.32	-8.718	-9.04	-8.594	-8.633	-8.622	
HEMATI	20.59	20.688	19.219	17.623	20.151	19.865	21.493
HUNTITE	-4.907	-11.042	-10.039	-10.223	-6.229	-12.922	
HYDMAG	-12.744	-21.86	-20.295	-20.735	-14.888	-23.351	-17.292
MAGHEM	10.599	10.697	9.228	7.632	10.159	9.874	11.502
MAGNESIT	-0.483	-2.281	-1.98	-1.978	-0.926	-2.466	-1.28
MAGNET	13.497	13.643	11.454	9.049	12.852	12.417	14.85
MIRABI	-10.101	-10.871	-9.78	-11.044	-8.916	-10.48	-9.999
NAHCOL	-5.082	-5.888	-6.185	-5.889	-5.286	-5.652	-6.155
NATRON	-9.289	-11.032	-11.562	-11.421	-9.627	-11.122	-11.998
NESQUE	-3.508	-5.305	-5.005	-5.003	-3.951	-5.491	-4.305
SIDERITE	-10.183	-10.006	-10.788	-11.147	-10.458	-9.845	-9.171
THENAR	-11.279	-12.05	-10.959	-12.223	-10.094	-11.659	-11.178
THRAT	-10.956	-12.699	-13.23	-13.088	-11.295	-12.79	-13.666
TRONA	-15.903	-18.452	-19.279	-18.842	-16.445	-18.307	-19.685
MANGANO	-8.326	-8.955	-9.281	-9.885	-8.063	-9.897	-8.045
PYROLUST	9.882	9.257	8.9	8.318	10.117	8.296	10.168
BIRNSITE	8.017	7.391	7.035	6.453	8.251	6.431	8.303
NUSTITE	8.604	7.978	7.622	7.04	8.838	7.018	8.89
BIXBYITE	10.611	9.357	8.674	7.488	11.109	7.455	11.179
HAUSMITE	9.219	7.336	6.327	4.537	9.98	4.492	10.067
MNOH2	-5.445	-6.074	-6.401	-7.005	-5.182	-7.016	-5.164
MNOH3	-1.491	-2.118	-2.459	-3.052	-1.242	-3.069	-1.207
MANGANIT	5.333	4.706	4.365	3.772	5.582	3.755	5.617
RHODOCHR	-0.882	-1.382	-1.771	-1.925	-0.689	-1.76	-0.038

Lakes

IAP/KT > 0

IAP/KT = -2 to 0

IAP/KT = -5 to -2

- The waters are saturated with respect to calcite, dolomite, fluorite, and a wide range of Fe and Mn oxides and hydroxides
- The waters are slightly undersaturated with respect to various hydrous and anhydrous sulphate and carbonate compounds of Na

	Lake Naivasha	Crater Lake, Naivasha	Lake Nakuru	Lake Bogoria, Southern	Lake Baringo, jetty point	Lake Baringo, Smatyang point
PHASE			LOG IAP/KT			
ANHYDRIT	-7.442	-4.094	-4.856	-4.943	-2.981	-2.913
ARAGONIT	0.271	1.002	-0.048	1.468	1.059	0.883
ARTIN	-3.729	-1.895	-3.855	-1.328	-2.723	-3.061
BRUCITE	-1.496	-1.401	-0.779	-1.094	-2.79	-2.579
CALCITE	0.419	1.149	0.1	1.615	1.206	1.03
DOLOMITE	2.056	2.5	1.907	3.622	2.12	2.14
FEOH3A	1.866	0.958	1.951	0.795	3.262	3.095
FLUOR	0.081	1.942	1.134	2.374	0.284	0.23
GEOETH	8.788	7.882	8.883	7.724	10.183	10.015
GYPSUM	-7.17	-3.827	-4.606	-4.686	-2.708	-2.64
HALITE	-5.009	-4.027	-2.359	-2.965	-7.027	-6.97
HEMATI	17.127	15.318	17.329	15.007	19.917	19.582
HUNTITE	1.51	1.38	1.701	3.815	0.126	0.538
HYDMAG	-2.944	-4.006	-1.592	-1.093	-7.131	-6.135
MAGHEM	7.135	5.327	7.338	5.016	9.925	9.59
MAGNESIT	1.282	0.995	1.452	1.651	0.558	0.754
MAGNET	8.314	5.594	8.611	5.152	12.491	11.986
MIRABI	-7.24	-3.089	-1.873	-3.576	-6.239	-6.022
NAHCOL	-2.596	-2.01	-1.593	-1.401	-3.649	-3.67
NATRON	-3.345	-1.812	-0.883	-0.983	-6.017	-6.044
NESQUE	-1.745	-2.039	-1.609	-1.398	-2.467	-2.271
SIDERITE	-12.882	-14.177	-13.345	-13.964	-10.923	-11.109
THENAR	-8.411	-4.235	-2.93	-4.671	-7.416	-7.199
THR NAT	-5.005	-3.45	-2.442	-2.576	-7.683	-7.711
TRONA	-7.467	-5.328	-3.911	-3.85	-11.197	-11.246
MANGANO	-9.783	-11.629	-10.367	-8.756	-7.473	-7.4
PYROLUST	8.401	6.57	7.831	9.394	10.727	10.806
BIRNSITE	6.536	4.705	5.966	7.529	8.861	8.941
NUSTITE	7.123	5.292	6.553	8.116	9.448	9.528
BIXBYITE	7.673	3.997	6.519	9.693	12.309	12.461
HAUSMITE	4.825	-0.697	3.086	7.871	11.77	11.995
MNOH2	-6.903	-8.751	-7.499	-5.884	-4.593	-4.519
MNOH3	-2.961	-4.802	-3.555	-1.962	-0.642	-0.566
MANGANIT	3.864	2.025	3.281	4.87	6.182	6.258
RHODOCHR	-3.318	-5.547	-4.46	-2.331	-0.437	-0.379

Boreholes

IAP/KT > 0
IAP/KT = -2 to 0
IAP/KT = -5 to -2

- The waters are saturated with respect to a wide range of Fe and Mn oxides and hydroxides
- The waters are slightly undersaturated to saturated with respect to calcite, dolomite and fluorite
- The waters are strongly undersaturated with respect to various hydrous and anhydrous sulphate and carbonate compounds of Na

	Egerton University BH2, Njoro	Oserian Kiangazi, Naivasha	Baharini Spring, Nakuru	Ndabibi Kijabe Ltd, West of Naivasha
PHASE	LOG IAP/KT			
ANHYDRIT	-4.524	-3.377	-3.512	-2.925
ARAGONIT	-1.265	-0.427	-0.3	-0.015
ARTIN	-7.964	-5.979	-5.724	-5.044
BRUCITE	-4.87	-7.183	-3.171	-4.902
CALCITE	-1.117	-0.279	-0.153	0.133
DOLOMITE	-1.69	-3.473	0.662	-0.892
FEOH3A	2.729	2.316	3.147	2.403
FLUOR	-1.248	-0.012	-0.839	0.336
GEOH	9.649	9.236	10.067	9.324
GYPSUM	-4.25	-3.104	-3.239	-2.652
HALITE	-7.391	-6.507	-7.186	-7.58
HEMATI	18.85	18.023	19.686	18.198
HUNTITE	-6.658	-13.682	-1.528	-6.763
HYDMAG	-15.157	-27.953	-7.904	-16.995
MAGHEM	8.858	8.031	9.694	8.207
MAGNESIT	-0.929	-3.55	0.46	-1.38
MAGNET	10.887	9.655	12.141	9.922
MIRABI	-7.487	-6.426	-6.941	-7.439
NAHCOL	-4.367	-4.145	-4.273	-4.728
NATRON	-8.046	-7.294	-7.547	-8.346
NESQUE	-3.953	-6.574	-2.565	-4.405
SIDERITE	-10.867	-11.58	-10.76	-11.6
THENAR	-8.665	-7.603	-8.119	-8.617
THRAT	-9.713	-8.961	-9.214	-10.014
TRONA	-13.945	-12.971	-13.352	-14.606
MANGANO	-7.871	-7.375	-7.936	-9.649
PYROLUST	10.338	10.815	10.271	8.533
BIRNSITE	8.472	8.95	8.406	6.668
NUSTITE	9.059	9.537	8.993	7.255
BIXBYITE	11.522	12.495	11.391	7.94
HAUSMITE	10.585	12.054	10.389	5.225
MNOH2	-4.99	-4.494	-5.055	-6.768
MNOH3	-1.035	-0.549	-1.101	-2.826
MANGANIT	5.789	6.275	5.723	3.998
RHODOCHR	-0.241	-0.054	-0.617	-2.439

Discussion - 1

- The Na:Cl ratios are: Rivers – 2.64; Lakes – 2.51; Boreholes – 3.24. This suggests that the river and lake waters are similar in terms of water source, and that there is Na enrichment within the groundwaters as a result of leaching from sodic-rich volcanic rocks and pyroclastics
- Similarity in Na:Cl ratios for river and lake waters indicates that evolution of lake waters occurs principally by evaporation
- Using Cl as a conservative ion, we note: Mg loss (and possible K loss in some samples) in Rivers; Ca and Mg loss in some lake samples (widely scattered data); and Ca and Mg loss in boreholes, again with wide scatter.
 - Rivers: Fixed Mg ions may be exchanging with exchangeable Ca ions in the soil zone during runoff and infiltration of rainwater
 - Ambiguous Ca and Mg loss in lakes may be related to lake individual characteristics with respect to multiple factors such as P:E ratio, biogenic productivity, and initial ionic aqueous species concentrations
 - Possible Ca/Mg loss in boreholes (some) may be related to cation exchange reactions and site-specific lithology

Discussion - 2

- The chemical equilibria calculations indicate that the lake water follows a similar brine evolution pathway as in Lake Magadi but are far from the end-stage of significant loss of HCO_3 and CO_3 with respect to Cl during evaporative concentration
- The pH values and alkalinity increase with the mineralisation of the solutions
- High lake pH results in precipitation of Mg and Ca from solution; biogenic uptake may also be a factor
- Some boreholes have pH above 9 and it is likely that they also precipitate Ca and Mg carbonates from solution
- The waters are generally saturated with respect to a number of Fe and Mn oxides and hydroxides

Conclusions

- The waters of the Central Kenya Rift are of the Na-HCO₃-Cl type
- Lake waters are derived primarily from surface waters and are concentrated by evaporation, but Ca and Mg are lost through calcite precipitation and biogenic uptake
- Groundwaters are additionally enriched in Na and other elements, including F, by leaching and cation exchange through the rock and soil profile
- Fluoride in the groundwaters is contributed to by runoff, leaching and cation exchange in soils on the surface, and by similar processes acting in the soils
- Nitrates are introduced into the groundwater systems via infiltration through the soil horizon – overpumping may also result in a faster water infiltration rate, reducing the capacity of the earths natural filtering mechanisms to mitigate nitrate levels in groundwater

Conclusions

- Saturation of all waters with respect to Fe and Mn and calcite, suggest the following:
 - Pollutant transport in these systems may be abetted by adsorption to Fe-Mn colloids and clays thus enhancing the vulnerability of the rift waters to pollution
 - In addition to defluoridation, the waters need to be treated to reduce iron and manganese content
 - High Fe content is likely to speed up corrosion of borehole casings so corrosion-resistant casings should be used in the area
 - Change in redox conditions such as may be initiated by a borehole breach can result in precipitation from solution of iron-rich sludges

THANK YOU!