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Hydrogeology of the Cradle of Humankind World Heritage Site, South Africa

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ABSTRACT: Dolomitic aquifers are vital sources of water in South Africa and under increasing stress due to expanding urban, mining and industrial developments. The Cradle of Humankind World Heritage Site (COHWHS) is an example of an area where the suitability of the water resource within the karst aquifers is threatened due to acid mine drainage, sewage effluent return flow and agricultural fertilizers. The karstified dolomites of the Malmani Subgroup act as the main aquifer in the area and are characterized by an extreme spatial heterogeneity that strongly influences their hydraulic behaviour and the transport of pollutants. Groundwater – surface water interaction plays an important role in controlling the groundwater chemistry dynamics in the karst terrain. The impact of mining water on the groundwater chemistry in the COHWHS is outlined using hydrochemical plots as well as multivariate statistical analysis (hierarchical cluster analysis) of available water samples.

1 Introduction

The Cradle of Humankind World Heritage Site (COHWHS) is an approximately 800 km^2 trapezoidal area 40 km northwest of Johannesburg (Gauteng province, South Africa, Figure 1), mostly underlain by the Malmani Dolomite of the Chuniespoort Group. Due to its large number of palaeo-anthropological sites of fossilized remains of past life forms, particularly hominids (humans, their ancestors and relatives) found in the over 200 karst caves, the area was declared a UNESCO World Heritage Site in 1999.

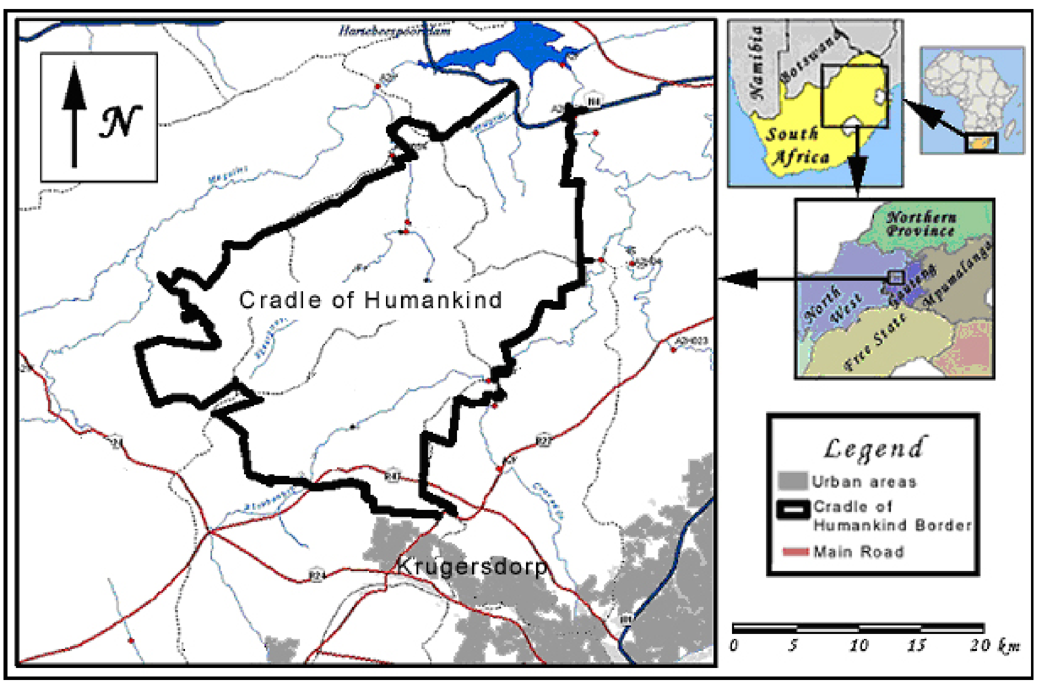

Figure 1. Locality of the study area.

Recently the COHWHS has received great attention since the first mine started to decant in 2002 south of the area near Krugersdorp. The gold-bearing reefs of the Western Witwatersrand Basin have been mined since 1887, but with the ceasing of mining operations and mine dewatering, the rebounding water table has lead to significant pollution of groundwater in the mined areas. Acid Rock Drainage (ARD) caused by the oxidation and hydrolysis of sulphide bearing minerals (e.g. pyrite) in the gold-bearing strata of the Witwatersrand results in extremely low pH values as well as highly elevated heavy metal and sulphate concentrations. Additionally waste water treatment return flows from two municipal sewage treatment plants as well as agricultural/irrigation return flows from commercial farms are discharged into the tributaries of the COHWHS catchment. The polluted surface waters enter the karst aquifer of the COHWHS through swallow holes, dolines and diffuse leakage from the rivers. Such inflows are characteristic of karst terrain (Wang et al., 2001) and pose a threat to existing surface and groundwater resources in the area with many human settlements in the area being dependant on the high-yielding boreholes in the karst aquifer as their sole water resource. The water resources are also needed for the expanding urban and industrial complexes in the province and are therefore considered as one of the most important aquifers in South Africa (Barnard, 2000).

In this paper the spatial extent of hydrochemical impacts from the different anthropogenic sources in the COHWHS will be outlined using a hierarchical cluster analysis in combination with conventional geochemical and spatial analysis.

2 Hydrogeological Setting

The COHWHS is underlain predominantly by strata of the Chuniespoort and Pretoria groups of the Transvaal Supergroup. Rocks of the Halfway House Granites, Ventersdorp Supergroup and Witwatersrand Supergroup underlie minor sections of the area (Figure 2).

The Chuniespoort Group consists of the lower Malmani subgroup (stromatolitic dolomite with chert interbeds) and the upper Penge (banded iron formations) and Duitschland (mixed clastic and carbonate rocks) Formations, which are absent in the study area. Based on the occurrence of interbedded cherts and shales, the variety of stromatolite structures present and the low-angle unconformities the dolomites of the Malmani Subgroup are subdivided into the Oaktree, Monte Christo, Lyttleton, Eccles and Frisco Formations (Button, 1973; SACS, 1980). Karstification has been more active in the chert-rich Eccles and Monte Christo Formations, resulting in good water bearing and storage characteristics (Bredenkamp et al., 1986). An important characteristic of the regional karst aquifer of the Malmani dolomite is its subdivision into 'compartments' isolated hydrogeologically from each other by impervious sub-vertical dykes of dolerite and syenite or by silicified faults (Figure 2).

The entire Transvaal Supergroup originated between 2658±1 Ma and 2224±21 Ma (Eriksson et al., 2001) with the carbonate sequence being deposited over between 2643 and 2520 Ma (Obbes, 2000). The strata dip at angles up to 20º toward the centrally located Bushveld intrusives (Eriksson et al., 1995) in the NW of the study area.

The catchment of the COHWHS forms part of the upper Crocodile River sub-system and is located within the Crocodile (West) and Marico Water Management Area (DWAF, 2003). The area experiences a sub-humid warm climate typical of the South African Highveld. Mean annual precipitation over the area varies between 600-700 mm per annum (DWAF, 1992), with most rains during thunderstorms in the summer month between November and February.

The dolomitic formations generate little surface run-off, suggesting relatively high recharge and predominance of underground water flow, which eventually drains to springs typically associated with dykes, faults or formation contacts. The southern part of the COHWHS is drained towards the NE by the Bloubankspruit and its tributaries to the Crocodile River which eventually feeds the Hartebeespoortdam. The Skeerpoort Riverbed, which is fed from springs as well as surface run-off during periods of high rainfall, drains north towards the Magalies River.

3 Methodology

3.1 Database preparation

The study was carried out by combining three available ground and surface water quality datasets for the COHWHS:

- Samples collected by the Department of Water Affairs and Forestry (DWAF) as part of the National Groundwater Database (NGDB, 1996 to 2007).
- Surface and groundwater (caves and boreholes) samples taken in 2005 by the Council for Geosciences (CGS) on behalf of Gauteng Department of Agriculture, Conservation and Environment.
- Water samples taken during and after the rain season (2005-2006) at the outlet of the wastewater treatment plant, at the decanting mine shaft as well as of a number of boreholes and springs by the University of Pretoria (UP).

While the CGS and UP samples were generally analyzed for major and trace elements, only selected NGDB samples were analyzed for trace elements. Data with unacceptable errors (> 5%) in the charge balance were excluded from further analysis. However, water samples taken at the decanting point of the acid rock drainage showed despite repeated analysis in different laboratories high charge imbalances and the criteria was relaxed to 10% for these highly acidic and mineralised samples. The final dataset contains 148 entries obtained from 47 unused, domestic and agricultural water-supply boreholes, 6 caves, 9 springs and 24 surface water localities throughout the COHWHS (Figure 2).

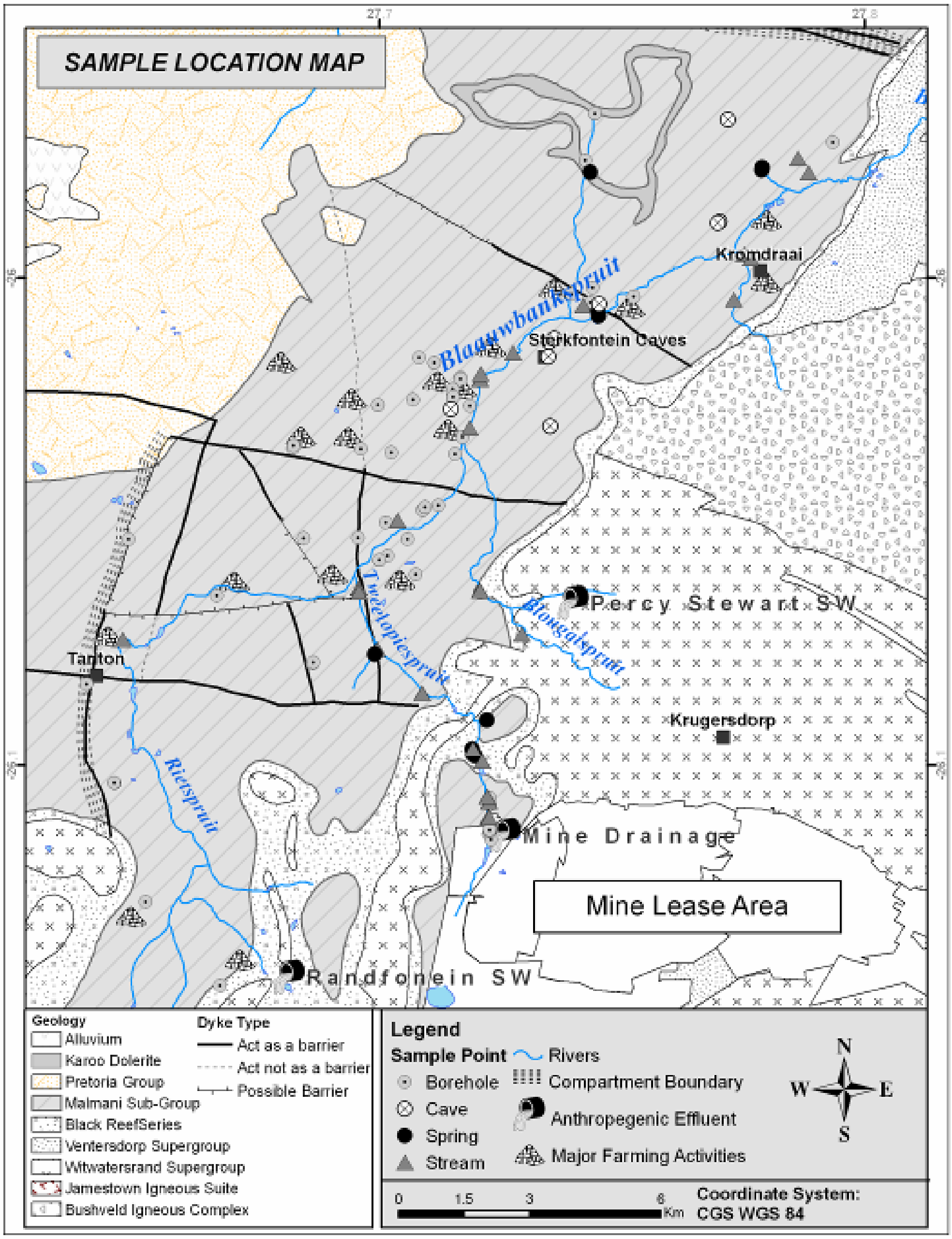

Figure 2. Regional geology and sample locations in the COHWHS.

3.2 Statistical analysis

The applied statistical analysis assumes normally distributed data (Güler et al., 2002) and a studentized range test for normality (Pearson and Hartley, 1970) with a 0.01 level of significance was performed. Some variables (Na, K, HCO3, and pH) were log-transformed to pass the test.

A hierarchical Cluster Analysis (HCA) is commonly applied to classify observations so members of the resulting groups/clusters are similar to each other but dissimilar from other groups (Güler et al., 2002). Ward's linkage rule was used to hierarchically link the groups of observations based on the squared Euclidean distances amongst each other. To ensure equal weighting of each variable in the analyses all variables were standardized by calculating their standard scores (z-scores). Standardization scales the raw or log-transformed data to a range of approximately ± 3 standard deviations centered about a mean of zero.

The dendrogram presentation of the hierarchical grouping along with the corresponding (rescaled) distance to achieve the linkage is used to choose the final number of clusters, i.e. the number of clusters prior a sharp increase in the rescaled distance. Cluster membership of the variables is saved and due to the standardisation only relative deviations of the cluster averages compared to the sample population average. Spatial presentation of cluster membership and Piper plots are used to interpret trends in the water quality as well as the hydrochemical impact of the different sources. Geochemical modelling is used to show the potential mixing effect between end members, represented by samples taken at the sources of pollution itself (decanting ARD and treated waste water outflow into surface waters) as well as from a borehole in a pristine part of the dolomitic catchment.

4 Results

Based on the visual assessment of the rescaled distance in the HCA dendrogram, three distinct hydrochemical clusters were identified (Figure 3). A sub-division of clusters 1 and 3 is used for a more comprehensive interpretation of their respective chemical signatures.

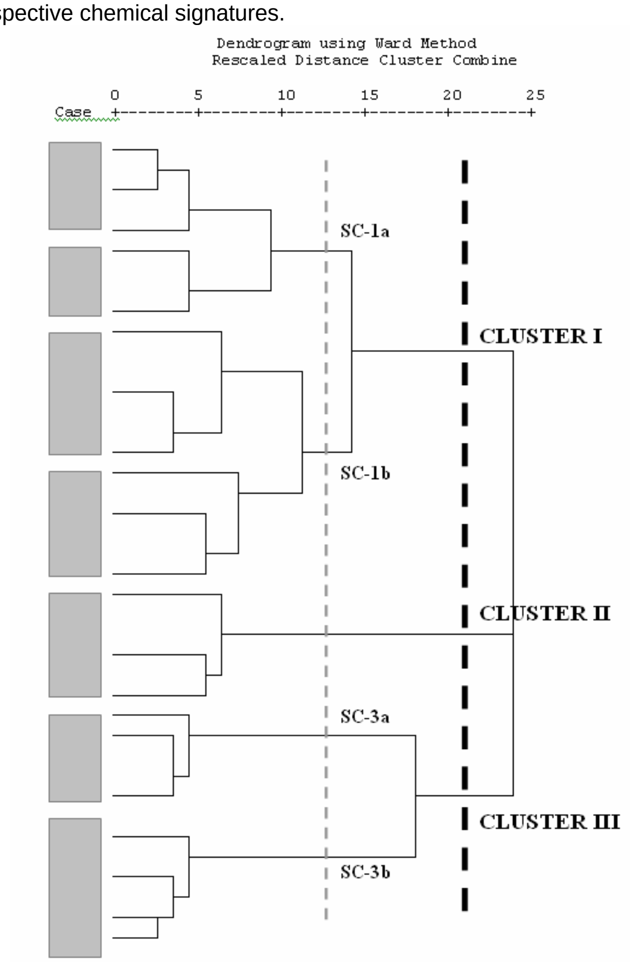

Figure 3. HCA dendogram of the 148 water samples. Dashed line defines chosen number of clusters.

A comparison of the average sample population and cluster parameter is given in (Table 1).
Cluster I, with 88 samples, is characterized by above average sodium, chloride, bicarbonate, nitrate and sulphate concentrations. Especially the elevated nitrate and sulphate concentrations indicate anthropogenic influences on the water quality. The subdivision of cluster I allow a further identification of these potential anthropogenic impacts. SC -1a is characterised by highly elevated nitrate concentrations, most probably related to agricultural

return flows or leaking septic tanks. SC -1b shows elevated concentrations of all major ions, especially sulphate. In the absence of natural sulphate sources in the dolomites, the elevated concentrations suggest a hydrochemical influence of the acid rock drainage on this cluster with pH buffering by the dissolution of dolomite, causing generally elevated ion concentrations. Cluster II is characterised by a general low mineralization of mostly calcium, magnesium and bicarbonate, with all solute concentrations well within the ideal limits for drinking water in South Africa (SANS, 2005). The samples grouped in this cluster represent the pristine dolomitic waters.

Table 1. Arithmetic means of sample population and clusters.

PARAMETER [mg/l]	TOTAL POPULATION	Cluster I			Cluster II	Cluster III		
		Total Group I	SC-1a	SC-1b	Total Group II	Total Group III	SC-3a	SC-3b
Valid N	148	88	32	56	40	20	10	10
pH [-]	6.88	7.35	7.5	7.2	7.28	4.0	3.3*	4.8
EC [mS/m]	111.15	85.01	87.88	83.38	34.09	380.3*	491.8*	268.7
Na	53.19	49.34	53.55	46.93	3.95	168.59	262.5	74.68
Mg	43.85	30.19	37.55	25.99	20.04	151.59	194.3*	108.8*
K	4.68	4.37	2.80	5.27	0.97	13.42	21.9	4.86
Ca	110.11	69.28	67.68	70.19	30.45	449.1	489.7*	408.4*
HCO_3	139.06	151.16	209.32	117.92	174.63	14.67	0.49	28.84
NO_3	19.01	27.96	54.2	12.92	6.04	5.55	9.02	2.09
SO_4	511.92	206.1	141.13	243.08	11.77	2858*	4042*	1673*
Cl	34.25	48.73	63.25	40.43	4.25	30.51	33.63	27.39

* - exceeds acceptable limit for drinking water in South Africa (SANS, 2005).

Cluster III combines samples with exceptionally elevated sulphate concentrations and electric conductivities (EC, table 1), taken directly from or in close vicinity to the mine decanting point and are clearly influenced by ARD. However, partial buffering of the acid rock drainage by the dissolution dolomite in the decanting area itself causes elevated calcium and magnesium concentrations. The cluster is further sub-divided into a source (SC-3a) and partially diluted downstream sub-cluster (SC-3b).

A plot of the statistically derived clusters illustrates the spatial variation of the water quality in the COHWHS (Figure 4). Starting in the upper part of the Tweelopiespruit catchment at the source of ARD in the decanting area all samples are grouped into SC-3a. Dilution of the surface and groundwater along the flow path by springs and regional groundwater flow causes the downstream water samples to fall into SC-3b or Cluster I. While samples in SC-1b indicate a more prominent influence of ARD, SC-1b samples are more influenced by effluent return flows from the Randfontein and Percy Stewart sewage works (Figure 4) or by agricultural land use practices in the catchment.

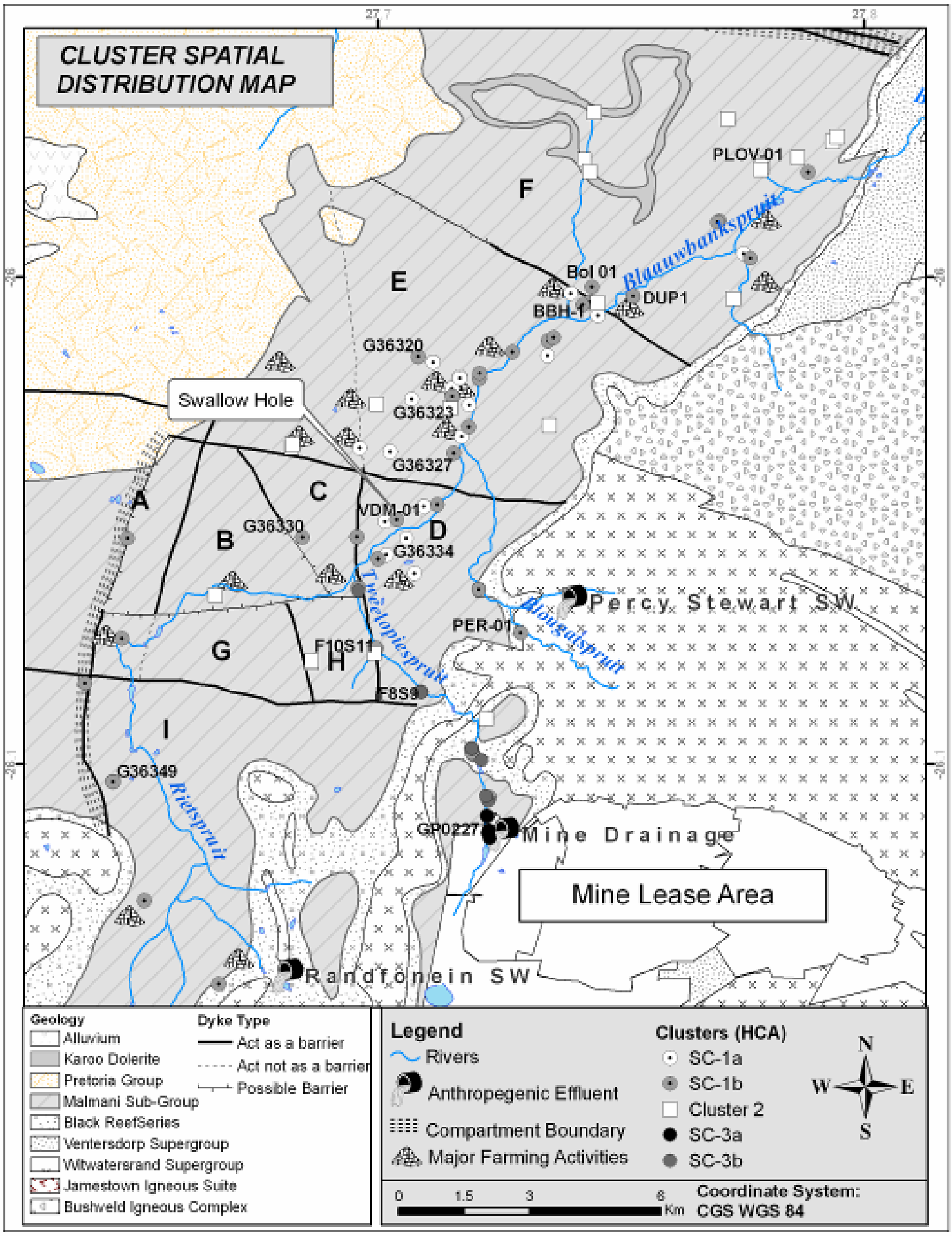

Figure 4. Spatial distribution of clustered samples.

It is evident from figure 5 that the influence of ARD (SC-1b) are already evident in the dolomitic sub-compartment E. Further spreading into sub-compartment F seems to be limited by a SE-NW striking dyke (Figure 4). The natural dolomitic waters of cluster II give a reference frame for the current area of anthropogenic impacts.

A presentation of all samples in a Piper plot (Figure 5) shows the variation of the water quality within the catchment, which appears to evolve downstream of the sources (ARD and sewage works outlets) from a Na-K to a Ca-Mg and from a SO_4 or Cl towards a HCO_3 anion predominance. The direction of these trends is consistent with decreasing total dissolved solid content of the samples from the sources to the pristine water samples. The Ca-Mg-SO_4 facies samples in the upper corner of the diamond were combined in cluster III of the HCA and are clearly influenced by ARD.

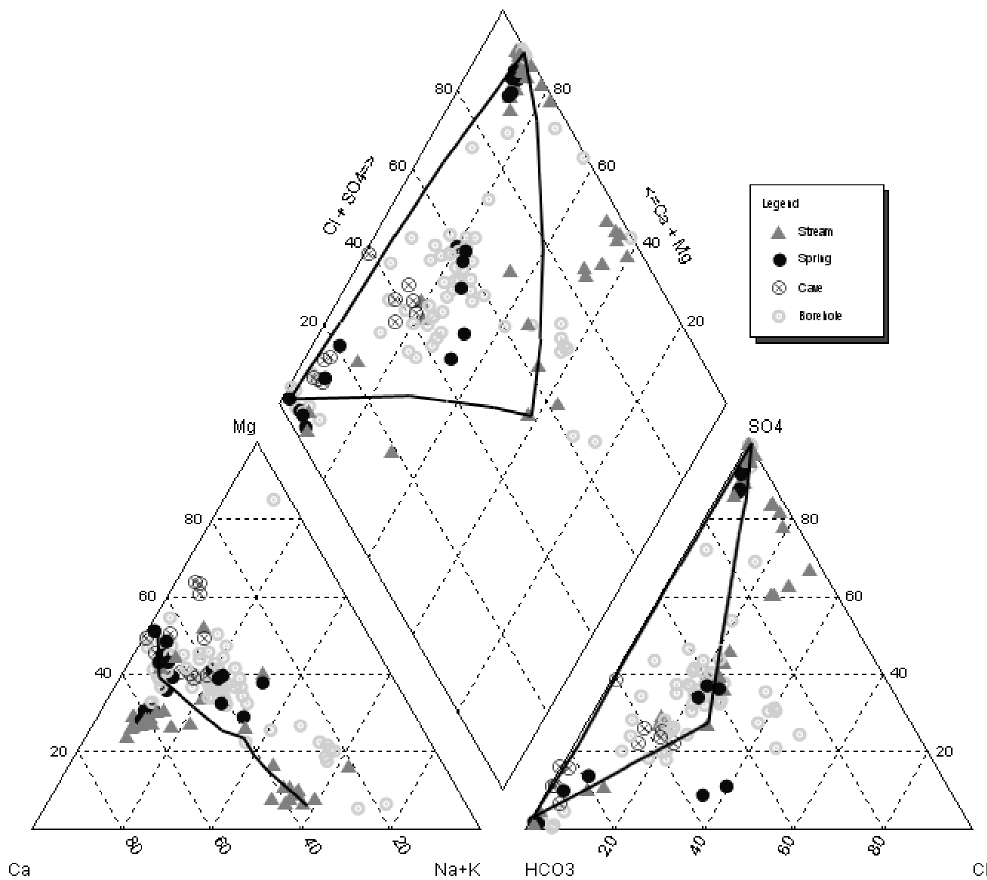

Figure 5. Piper plot of samples according to location type.

The Ca-Mg-HCO_3 facies samples in the left corner of the diamond represent pristine dolomitic water and were grouped above in cluster II. Waste-water treatment return flow samples plot in the right corner of the diamond (Na-Cl facies). However, diffuse agricultural/irrigation return flows along the flow path contribute to the salt load as well, but were not considered in this analysis. The remainder of the samples plot in a mixing field between these three end-members and were grouped into Cluster I of the HCA. PHREEQC 2.8 was used to confirm the potential mixing between the considered three end members. Varying mixing ratios of two consecutive end members were used to calculate the theoretical mixing field indicated in figure 5. Fluid-rock interactions (e.g. dolomite dissolution), reactive transport, as well as influences of agricultural land use practices were neglected. While the observed variations in the anion ratios of the water samples are be relatively well-described with a simple mixing model, the deviations between modelled and observed cation ratios indicate that other processes like ion exchange or dissolution along the flow path are important, but not considered in the model. Hence more complex geochemical models or multivariate receptor models (Christensen et al. 2006) should be used for source apportioning for individual boreholes or springs.

5 Conclusions

The karst aquifers in the COHWHS are characterized by an extreme heterogeneity that strongly influences the transport of pollutants. A hierarchical cluster as well as geochemical analysis of 148 samples taken in the COHWHS was used to classify samples, identify sources and to outline impacted areas. The water quality in the study area is significantly changed by ARD from a decanting mine as well as waste-water treatment return flows. Compartmentalization of the karst aquifer limits the spreading of pollutants in certain areas, although surface waters enable the transport of pollutants across these hydrogeological boundaries. Influences of ARD and effluent return flows are already seen in most parts of the study area and call for urgent intervention to protect this important water resource.

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