Geochemical and Isotopic Characterization of a Local Catchment within Crystalline Basement in Western African Benin

Thorsten Fass & Barbara Reichert
Institute of Geology, University of Bonn, Nussallee 8, D-53115 Bonn, Germany

Abstract

The hydrogeological characterization of a local catchment of about 30 km² in the subtropical savanna of Benin was part of the multidisciplinary IMPETUS project to develop sustainable fresh water management tools. Geochemical and isotopic characterization was done by classical water sampling and analysing methods, accompanied with thorough hydrogeological field work.

On the local scale in Benin the supply with potable water is mainly due to open dug wells. These wells are exploiting the crystalline fractured aquifer. Due to their construction, they are easily influenced by anthropogenic contamination. Additional, the groundwater often shows unpleasant raised salinity. For the Aguima catchment it can be shown, that at least during the end of the wet season from August to October an alternative source of fresh water exists: a temporally saturated saprolite aquifer. Although its yield is poor, its accessibility is good due to a low depth up to 10 m below ground surface. A geogenic barrier on the top of this aquifer gives sufficient protection against anthropogenic contamination. The mineral content of this zone is low. Its source, the recharge processes and the hydraulic parameters are obtained by analyses of environmental tracers ($^{18}$O, $^2$H, $^3$H), performance of dye-tracer tests in the unsaturated zone above the migmatitic basement and catchment wide analyses of soil moisture content with TDR method up to 240 cm below ground level. On the basis of these field investigations a conceptual hydrogeological model has been developed and is been used for further studies on the regional scale in the area.

Introduction

In the framework of the German BMBF (Federal Ministry of Education and Research) project “Global change of the water cycle” (GLOWA), the IMPETUS West Africa project (integrated approach to the efficient management of scarce water resources in West Africa) focuses on water as a scarce resource. In the context of the IMPETUS project, thorough investigations of all aspects of the hydrological cycle are carried out within two river catchments in North and West Africa: the wadi Drâa in the southeast of Morocco and the river Ouémé in Benin. Groundwater and groundwater recharge are of significant importance within the hydrologic cycle. In order to understand the utilization potential of the groundwater resources in the Ouémé catchment research of the 1st part of the project was focused on the development of a conceptional model of the resource groundwater, on a detailed system description of the aquifer including both water quality and quantity and on the investigation of the transport processes within the vadose zone. Together with other disciplines investigations have been performed in the Aguima catchment area (Fig. 1), a ca. 30 km² sized sub-catchment of the Térou, the main tributary of the Ouémé (Diekkrüger et al. 2002).

Fig. 1: Location and instrumentation of the test site Aguima
Methodological approach

Basic requirement for a hydrogeological evaluation of the aquifer system are well-grounded knowledge in both the general geological setting and the structural pattern of the area under investigation. Therefore detailed geological mapping accompanied by thorough literature survey has been performed. Additional information on the different lithological units was derived by mineralogical and geochemical analyses of rock and soil samples. For the understanding of the flow system hydrodynamic measurements such as local and regional piezometric mapping and pumping tests as well as tracing experiments have been carried out. Furthermore the recharge mode in the vadose zone was examined by a monitoring network with TDR measuring tubes and suction cups (Fig. 1). Monitoring has been performed by weekly measurement with a mobile TDR tube access probe and frequent sampling. Climatology data have been collected by other participants of the IMPETUS project (Giertz 2004).

Hydrochemical analyses and environmental labeling with $^{18}$O, $^2$H and $^3$H of groundwater, soil water and surface water samples taken during the dry and wet season allow a hydrogeological classification as well as an evaluation of the origin of the various water types. The sampling locations are given in Fig. 1. Samples representing the fractured basement aquifer were taken in public wells in the village of Dogué. Water samples of the saprolite aquifer were taken in 3 newly (2002) drilled boreholes, soil water samples were taken by suction cups and surface water samples are from the intermittent water courses in the catchment. Standard laboratory analyses were carried out at the laboratory of the Institute of Geology at the University of Bonn, Germany. Analyses of environmental isotopes ($^2$H, $^{18}$O, $^3$H) were performed at the GSF Institute of Hydrology in Neuherberg, Germany. For the environmental labeling a more regional approach was chosen in addition to the sampling sites within the Aguima catchment.

Climatology

The working area is located in the tropical, sub humid sudano-guineen zone. From 1961 to 1990 the mean annual precipitation for Benin was 1039 mm (FAO 2002). Long time observations from the IRD Benin give for the village Parakou an annual mean precipitation of 1179 mm (1921-1999). In the working area, the precipitation value for 2002 was 1145 mm (Giertz 2004). The total evapotranspiration has been computed by Giertz (2004) with a value of 882 mm for the same period. Fig. 2 shows climatic data for reference climatic stations in Parakou and the working area (Dogue) and the distribution of the annual mean precipitation. Applying the climatic water budget, the groundwater recharge in the working area is about 113 mm in the year 2002 (Giertz 2004, Fass 2004).

Fig. 2: Distribution of precipitation in Benin (modified after LES CLASIQUES AFRICAINS 1999) (left), at the meteorological stations Parakou (data from 1921-1999, source: IRD BENIN, after IMPETUS work package A1) (top right) and at the village Dogue in the test (bottom right) (data from the projects’ climatic stations (work package A2 and A3)).
Geologic setting and hydrogeological characterization

As part of the weathered African Precambrian shield the area under investigation is built by a saprolitic weathered zone on the top of a granitoid and gneissic migmatitic basement. Characterized by a NW-SE (fractures) and NNE-SSW striking (faults, dikes) structural pattern (Fig. 2) the crystalline basement forms a fractured aquifer. The vadose zone consists, from bottom to top, of the saprolitic zone, followed by a lateritic decomposition and a sandy, mostly allochthonous soil zone (Fig. 3) (Fass 2004).

Hydraulic parameters

Pump test data in the saprolite zone at test site GWB1 (cp. Fig. 1) during rain season accounts for a leaky aquifer with a low permeable layer as the upper boundary. The curve fitting after HANTUSH-JACOB (1955) gives transmissivities (T) in the range of 0.7 to 2.0 x 10^{-6} m^2 s^{-1}. This leads to a specific yield of the temporally saturated saprolite aquifer in the range of 6 x 10^{-5} m^3 s^{-1}. The low permeability layer on top of the saprolite aquifer coincides with the laterite layer (cp. Fig. 3, ferricrete).

Soil moisture distribution

Comparable to the pumping test data, the low permeability layer between 80 and 130 cm below the ground level was proven with regular measurements of the soil moisture content during all of the year (Fig. 3). This layer acts as an Aquitard. The high soil moisture contents between week 31 and 45 are the results of stagnant water on top of this low permeable horizon. Due to the main precipitation in the wet season between July and October, transport through this zone was only possible during a small ‘saturation window’ between approximately the 31st and 43rd week of the year 2002. Below this layer the soil moisture is raising because of capillary forces.
**Geochemical characterization**

With the multivariate statistic method of cluster analysis three different clusters of water can be distinguished (Fig. 4, Fass 2004).

Cluster 1 is representative for surface discharge and near surface interflow. Even the water samples collected with suction cups up to 150 cm depth are member of the cluster 1. The water is of HCO$_3$-Ca-Na-Mg-type with a very low average electric conductivity (78 µS.cm$^{-1}$). Although the mineral content of the precipitation water is lower, its chemical composition is nearest to the surface- and shallow soil waters, clearly expressed by the common clustering.

Cluster 2 contains exclusively samples from the three wells shown in the magnification window of Fig. 1, thus representing the groundwater of the saprolite zone. Comparable to cluster 1, the water is of the HCO$_3$-Ca-Na-Mg-type, but with a more than two times higher average electric conductivity (217 µS.cm$^{-1}$). With the exception of the higher grade in mineralization and the distinct enrichment in Ca$^{2+}$ and PO$_4^{3-}$ and the highest relative content in iron the general composition of cluster 2 is quite similar to the surface and near surface waters (Fig. 5).

Cluster 3 is representative for groundwater in the migmatitic basement aquifer. The water samples are taken from two public wells in the working area. The water type is HCO$_3$-Na-Mg-Ca-Cl and clearly different from the other water types. Taking the electric conductivity (average 1071 µS.cm$^{-1}$) as indicator for the degree of mineralization, is more than ten times higher mineralized than the surface water (cluster 1) waters and ca. 5 times higher than the saprolite water. Clear indications are higher concentrations of chloride, phosphate, nitrate and nitrite. Furthermore the concentrations of iron, manganese and ammonium are significantly lower (Fass 2004).

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**Fig. 4:** Left side: Dendrogram of cluster analysis C1. The cluster distance value gives 3 separate clusters: Cluster 3, Cluster 1+2 and Cluster 4. the downstream cluster analysis C2 (right side) clarifies the assumption of two different subgroups: Cluster 1 and Cluster 2

**Fig. 5:** SCHOELLER diagram of mean values (main components) of the water types in the AGUIMA working area.

**Fig. 6:** Modelling of hydrochemical mixing ratio of discharging surface water in the Aguima catchment. The best fit composition is that of 73% precipitation water, 25% water from the saprolite aquifer and 2% water from the basement aquifer (modelling with PHREEQC-2 (Parkhurst et al. 1999)).
All analyzed water are mainly of hydrogen carbonate type with higher alkali contents (Fig. 5). As shown with the discussion of the multivariate statistics, the site is characterized by differences in the water composition between the basement and the saprolite aquifer (Fig. 5) and a similarity of the water in the saprolite aquifer with the surface and precipitation water (Fass 2004). The composition of the soil water samples represents the seepage flow composition. The samples taken in the public wells are showing high nitrate content. This fact points to an anthropogenic contamination. In general the water from the basement aquifer is more salinated than those from the saprolite aquifer. This is a result of longer residence times in the fractured basement aquifer, thus increasing the possibility of water-rock interactions. The water in the saprolite zone shows only slightly reactions with the adjacent rock. The unsaturated saprolite zone is the result of long lasting weathering processes, therefore the underground passage of the infiltration rainwater is characterized by clearly depleted weathered material. This can be stated by XFA analysis of samples from the weathered rock in comparison to unweathered basement material and soil (Fass 2004). Hydrochemical modeling has shown, that mixing processes with basement aquifer waters as well as the contribution of basement water to the surface flow is negligible (Fig. 6).

Environmental labeling

The δ¹⁸O/δ²H signatures of the analysed water samples (Fig. 7) plot around the global meteoric water line after Craig (1961). Therefore, recent meteoric water has to be the main source of the investigated water types in the region. Also the results of ³H-analysis (Fig. 8) certifies the assumption of recent meteoric water as the source of the ground waters in the region. There is no evidence for the existence of fossil- or palaeowater. Some samples are affected by evaporation effects. These samples are from reservoirs or storage lakes. The groundwater samples showing no evaporation effects, which leads to the assumption, that infiltration from reservoirs plays no major rule in groundwater recharge. The different values in deuterium-excess between water samples from the basement aquifer in the dry season and water samples from the temporarily saturated saprolite aquifer in the wet season provides evidence for different recharge modi and different recharge regions of these two aquifers. Similar high deuterium-excess values in some samples from regional water courses seems to be the result of re-evaporation effects in precipitation. In conjunction with the analysis of trajectories, done by the projects’ meteorological group (IMPETUS work package A1), the reason for the differences in the d-excess value can be different ‘overland times’ of air masses. If air masses have longer overland times, the enrichment with evaporated water vapour could produce significant re-evaporation effects in their isotopic composition (Kendall & McDonnell 1998, Clark & Fritz 1997). Anyway, there is also the possibility of long time mixing effects in the basement water, which have to proven by ongoing sampling.

Artificial labeling

While the environmental labeling gives information on the regional long-term effects the goal of the artificial labeling was the detailed description of the transport processes within the unsaturated zone. A dye
tracer experiment with uranin was conducted on a 16 m² test site, where suction cups are installed in every square meter in depths of 50, 100 and 150 cm. The tracer test was performed in the wet season of 2002, where the matrix potential was below field capacity. The breakthrough curves (Fig. 9-10) have been modelled with a multi-dispersion model (MDM, Maloszewski et al. 1992) on the basis of the well known convection-dispersion model (CDM), as analytical solution of the one-dimensional transport equation for conservative tracers (Lenda & Zuber 1970, Maloszewski & Zuber 1984, Maloszewski et al. 1992). With this model it could be proved, that above the lateritic hardened horizon, preferential flow is the most important transport process for vertical flow, whereas within the low permeable zone, if transport occurs, dispersive processes prevail (Fass 2004, Bauer 2004). This also proves the aquitardic function of the laterite.

Fig. 9: Uranin BTC 3C-I from test site FE01.

Fig. 10: Uranin BTC 2B-III from test site FE01.

Conceptual hydrogeologic model

The analyses shown above, together with soil physical analyses (Fass 2004) combined with results from other interdisciplinary parts of the IMPETUS project (Giertz 2004, Junge 2004) give a clear description of the hydrogeologic properties of the different geogenic compartments and can be summarized to an conceptual hydrogeologic model (Fig. 11). A fractured migmatitic basement aquifer on the bottom, which has only slight influence on the hydrogeology of the above zones, is the main aquifer in the research area. As given by the hydrochemical and isotopic properties, this aquifer is not recharged in the 30 km² working area. The identification of its recharge area is subject to the ongoing research project. This Aquifer is overlaid by a weathered saprolite zone which acts as a porous aquifer but is only saturated during the rain season. The main source of the saprolite aquifer water is actual precipitation. This is proven not only by the chemical composition (Fig. 5) but also by isotopic labeling. Transport of seepage flow into this aquifer most probably is restricted to preferential pathways, as verified by vadose zone tracer tests. Groundwater recharge of the saprolite aquifer can only take place during July to September. Only in this time the excess in the water balance is high enough to produce notable seepage flow. The saprolite aquifer is partially overlain by a lateritic horizon, which acts as an aquitard. On top of this Aquitard follows a sandy top soil zone in which lateral processes are predominant (see also Giertz 2004). Interflow is therefore the main source of the intermittent water courses in the studied area.

Fig. 11: Conceptual hydrogeologic model.
Conclusions

The main aquifer in the working area is a fractured migmatitic basement aquifer, where most of the fresh water wells in the region obtain their water. This is a widespread method for the local withdrawal of potable water in most African countries with similar conditions (Chilton J.P. et al., 1995, Hazell J.R.T., 1992, Taylor R.G et al. 1998). An alternative, often disregarded source of freshwater is the saprolitic weathered zone on the top of the crystalline basement. This aquifer shows a fast recharge through preferential flow. Although a sufficient saturation can only be found in parts of the rain season (August to September) and the specific yield is comparative low, the easy accessibility (hand dug possible) and the good quality of water in combination with a sufficient protection to anthropogenic contamination (lateritic horizon) as well as the fast saturation during rain season counts for a useful additional source of potable water on the local scale. The detailed knowledge of recharge processes and hydrogeologic character on the local scale gives the basis for further studies and for hydrogeological modeling on the regional scale. However, a serious ground check for regional modeled data is necessary and the presented study provides the background for validation.

Outlook

The main focus of this study was to analyze the hydrogeology of a catchment on the local scale and to develop a conceptual hydrogeologic model. This model should provide the basis for further studies on the regional scale. First results of environmental labelling on a larger scale (Fig. 12) provide information on a superior groundwater recharge area. A general survey of the phreatic surface, done once in the dry and once in the wet season of 2002, confirming the general groundwater flow direction (Fig. 12). The development of a regional groundwater model is therefore the next step to gain a better knowledge of the hydrogeological properties on the regional scale in the country.

Fig. 12: Regional isopiestic line map, based on measurement campaigns in dry and wet season of 2002.

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References


Biographical Sketches

Dr. Thorsten Fass
Institute of Geology, University of Bonn
Nussallee 8
D-53115 Bonn, Germany
Email: thorsten.fass@uni-bonn.de
Phone: +49 228 734723, Fax: +49 228 799037

1993 - 2000 Study of geology at University of Bonn, Germany
2000 Diploma in geology about radon and thoron in soil air
2000 - Research assistant at University of Bonn, Germany
2004 Ph. D. in hydrogeology about the hydrogeology of a local scale catchment in Benin/West Africa

Prof. Dr. Barbara Reichert
Institute of Geology, University of Bonn
Nussallee 8
D-53115 Bonn, Germany
Email: b.reichert@uni-bonn.de
Phone: +49 228 732490, Fax: +49 228 799037

Barbara Reichert is full professor of hydrogeology in the Geological Institute of University of Bonn since 1998. She received her Ph. d. and her diploma in geology from the Department of Applied Geology, University of Karlsruhe. Current research topics and projects include groundwater management, transport and transformation processes in heterogenous aquifer systems, unsaturated zone hydrogeology, hydrochemistry and tracerhydrology.