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Development of a water balance for the Atankwidi catchment, West Africa - A case study of groundwater recharge in a semi-arid climate

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Grenouille - Emblème du Dieu de l'Eau Tohoussou

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ABSTRACT

Regolith aquifers in the weathered zone overlying Precambrian basement rocks serve as the main source of groundwater in a large part of the Volta River basin in West Africa. A prerequisite for sustainable groundwater resources management is the knowledge of recharge processes and the annual recharge rate. This research assesses the water balance, and in particular the groundwater recharge rate, for the Atankwidi catchment, a 275 km² sub-catchment of the White Volta in northern Ghana. Large uncertainties are typically inherent in any singular method to determine groundwater recharge. For this reason, an integrated approach is developed in this work which makes use of several field methods and combines results from these methods with water budget modeling. Field methods included in this approach are groundwater level observations, isotope analyses and a Chloride mass balance.

The Atankwidi catchment falls within the semi-arid Sudan-Savanna climate zone. The climate is characterized by high temperatures and a single rainy season from May to October with an average annual rainfall of 990 mm. The hydrogeological system consists of three aquifers: The discontinuous, shallow aquifer, the regolith aquifer and the fracture aquifer. The principal aquifer is the regolith aquifer in the weathered mantle, which is usually targeted for drinking water supply. It forms a continuous aquifer with an average saturated thickness of 25 m and a hydraulic conductivity of 2.5E-6 to 2.5E-5 m/s.

Recharge rates vary considerably between wet and dry years and between locations, with a range of 2 % to 13 % of annual rainfall. The long term recharge rate is determined by the Chloride mass balance to be approximately 6 % of average annual rainfall. The research emphasizes the importance of high rainfall intensities in creating groundwater recharge. Interannual comparison of water level fluctuations shows that a decrease in annual rainfall of 20 % causes a reduction of groundwater recharge of 30 % to 60 %. The impact of changing quantities of annual rainfall on groundwater recharge is overestimated by methods that do not account for infiltration by preferential flow. A long term average groundwater recharge of 60 mm/y compares to a total current groundwater abstraction of 4 mm/y in the study area, which is one of the areas with the highest groundwater use per km² in the Volta River basin. Recharge is therefore currently not a limiting factor for groundwater resources development.

Water budget modeling using WaSIM-ETH calculates that 63 % of annual rainfall is lost to evapotranspiration in a wet year (2003), and 82 % in a dry year (2004). In the investigated mesoscale catchment 23 % and 11 % of annual rainfall end up as surface run-off in a wet year and a dry year, respectively. Approximately 40 % of surface run-off consists of interflow, while the main fraction is direct run-off. Base flow from groundwater is negligible.

Groundwater flow in the regolith aquifer is modeled with Visual Modflow, assuming average hydraulic conductivities as determined by pumping test evaluation. The model calculates that only about 5 % of groundwater recharge leaves the basin as groundwater flow. This is evidence that the regolith aquifer does not contribute to a large extent to regional groundwater flow. Leakage to localized zones of high hydraulic conductivity of the fracture aquifer, which underlies the regolith aquifer, could act as a main sink of groundwater recharge. However, the exact location and hydraulic properties of fracture zones are largely unknown, so that the flux from the regolith aquifer to these fractures as well as the amount of flow through fractures is impossible to estimate at present.

Pumping tests with observation wells to assess the specific yield, long-term pumping test at the basin outlet and a continuation of groundwater hydrograph recording at high temporal resolution could largely enhance the knowledge of hydraulic properties in the future. The groundwater model could then be improved and extended to gain certainty on the characteristics of groundwater flow.

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LIST OF ACRONYMS AND ABBREVIATIONS

		Units
α	Isotope fractionation factor	(-)
ε	Isotope enrichment factor	(-)
δ	Delta-value of isotope fractionation	(-)
$\Delta\varepsilon$	Kinetic enrichment factor	(-)
d	WaSIM drainage density	(-)
DEM	Digital Elevation Model	
DIRH	Direction d'Inventaire des Ressources Hydraulique	
ET	Evapotranspiration	(L/t)
ET_0	Potential evapotranspiration for grass	(L/t)
ETa	Actual evapotranspiration	(L/t)
ET_c	Potential crop evapotranspiration	(L/t)
ETr	WaSIM evapotranspiration	(L/t)
f	Residual liquid fraction	(-)
FAO	Food and Agriculture Organisation of the United Nations	
FC	Field capacity	(L)
GNIP	Global Network for Isotopes in Precipitation	
GW	Groundwater	
h	Humidity	(-)
HDW	Hand dug well	
K_c	Crop coefficient	(-)
K_D	WaSIM storage coefficient for direct run-off	(L)
k_f	Hydraulic conductivity	(L/t)
K_I	WaSIM storage coefficient for interflow	(L)
krec	WaSIM vertical recession constant	(-)
K_s	Crop stress coefficient	(-)
ksat	Saturated vertical hydraulic conductivity	(L/T)
l	Liquid phase	
LAI	Leaf area index	(-)
LMWL	*Local* meteoric water line	
MWL	Meteoric Water Line	
P	Rainfall	(L/t)
Q	Surface run-off	(L/t)

		Units
Qd	WaSIM direct run-off	(L/t)
Q_e	Event flow	(L/t)
Qges	WaSIM total river run-off	(L/t)
Qifl	WaSIM run-off from interflow	(L/t)
Q_{pe}	Pre-event flow	(L/t)
Q_t	Total run-off	(L/t)
R	Groundwater recharge	(L/t)
R	Isotope ratio	(-)
RAW	Readily available water	(L)
rs	Surface resistance during evapotranspiration	
SARI	Savanna Agricultural Research Institute	
SM	Soil moisture	(L)
SMD	Soil moisture deficit	(L)
SRI	Soil Research Institute	
SURFSTOR	Near surface water storage	
S_y	Specific yield	(-)
T	Transmissivity	(L^2/T)
t	Time	(T)
TAW	Total available water	(L)
UTM	Universal Transverse Mercator	
$_v$	Vapor phase	
VSMOW	Vienna Standard Mean Ocean Sea Water	
WP	Wilting point	(L)
Δh	Change in water level	(L)
ΔS	Change in water storage	(L/t)
Ψ	Suction	(L)
Θ_{FC}	Water content at field capacity	(-)
Θr	Residual soil water content	(-)
Θs	Saturated soil water content	(-)
Θ_{WP}	Water content at wilting point	(-)

1 INTRODUCTION

1.1 Scope and aims of this research

The research on which this study is based was carried out under the GLOWA-Volta project, one of 5 projects currently funded by the GLOWA program (Globaler Wandel des Wasserkreislaufs) of the German Ministry for Education and Research (BMBF). The project carries out interdisciplinary research on sustainable water use in the West African Volta River basin under changing land use, population and climate conditions. The overall objectives of the GLOWA-Volta project are “the analysis of the physical and socio-economic determinants of the hydrological cycle, and, based on this, the development of a scientifically sound Decision Support System for the assessment, sustainable use and development of water resources in the Volta Basin.” (Rheinische Friedrich-Wilhelms-Universität Bonn, 2002).

The starting point for this research was the question of the role of groundwater in the Volta River basin. The aim is to determine the availability of groundwater as a safe source of drinking water and to identify how groundwater flow feeds the river system. Knowing that borehole drilling in West African countries, funded mostly through development aid, has been intense over the past decades, two interconnected strands of questions arise. The first relates to the contribution of groundwater to water supply:

- Where and how much groundwater is currently used?
- Is there a potential for increasing groundwater use in the future?

These questions are addressed on the Volta River basin scale on the basis of existing data related to hydrogeology and groundwater use, which were collected from organizations in Burkina Faso and Ghana. The results from this analysis are summarized in chapter 2.

However, this analysis cannot shed much light on the processes governing groundwater dynamics in the region, which is a prerequisite in forecasting the impact of changes on groundwater resources and the hydrological cycle. This leads to a second strand of questions:

- How do groundwater levels vary in time and space?
- How much recharge do groundwater resources receive?
- How does groundwater interact with surface water?

To improve the understanding of the hydrogeological system and through this be able to answer the above mentioned questions, a study area was selected in the Upper East Region of Ghana, where groundwater is intensely used for rural and town water supply. The study area falls within the semi-arid Sudan-Savanna climate zone and is underlain by Precambrian basement rocks. The main source of groundwater is the regolith aquifer in the thick weathered zone overlying the fresh basement rocks. While the study area cannot be representative for the whole Volta River basin, its geology and climate are typical for a large part of the basin and in fact for many regions in Africa.

Due to the understandable priority of the development of groundwater resources for drinking water supply, very few groundwater studies have been carried out in the region. Estimates of groundwater recharge and aquifer behavior that are currently used in groundwater resources planning are mostly drawn from limited experience in other African countries. Water resources planning is therefore characterized by uncertainty concerning the sustainability of groundwater production. At the core of the research is the quantification of groundwater recharge as one of the most important factors in groundwater resources management. Large uncertainties are typically inherent in any singular method to determine groundwater recharge. For this reason, an integrated approach is developed in this work which makes use of several field methods and combines results from these methods with water budget modeling. It is this integration of methods which allows delivering a more complete picture of recharge processes and a more reliable assessment of the recharge rate.

After a description of the study area (chapter 3) and its instrumentation (chapter 4), hydraulic properties of the aquifer are derived from the evaluation of borehole drilling profiles, pumping test data and groundwater level monitoring (chapter 5). A water balance is then developed from field measurements for the years 2003 and 2004 (chapter 6). As the emphasis is on the quantification of groundwater recharge, several approaches to determine recharge are applied. The results from the different approaches are discussed and compared. To complement the assessment of water budget components by field methods, inverse water balance modeling using the water balance simulation model WaSIM-ETH is applied (chapter 7). Finally groundwater modeling using Visual Modflow (chapter 8) is carried out to determine groundwater run-off.

1.2 The Volta River basin

The Volta River basin covers an area of 400.000 km² in West Africa. Burkina Faso and Ghana equally share 85 % of the basin area, while the remaining area is distributed over Togo, Benin, Mali and the Ivory Coast. The main rivers are the Black Volta, the White Volta and the Oti River, which all end in the man-made Volta Lake, a large reservoir serving the generation of hydropower.

The basin stretches over four climatic regions in West Africa (Figure 1.1). From south to north these are the humid equatorial forests in southern Ghana, the Guinea Savanna, the semi-arid Sudan Savanna and finally the arid Sahel of northern Burkina Faso. Average annual rainfalls decrease from 1400 mm in the south to 500 mm in the north. While two rainy seasons occur in the southern end of the basin, most of the river basin experiences a single rainy season triggered by the northward shift of the inter-tropical convergence (ITC) causing the inflow of moist air from the sea by the southern trade winds (south west monsoon rain). The distinct dry season is of increasing duration from south to north. Rainfalls exceed the high evapotranspiration caused by high temperatures only in the wettest months. Consequently streams in the region are typically ephemeral, except for the Black Volta, which receives sufficient groundwater base flow to be perennial. Of major concern to agriculture and water resources management is the high interannual variability of rainfall in the semi-arid and arid regions.

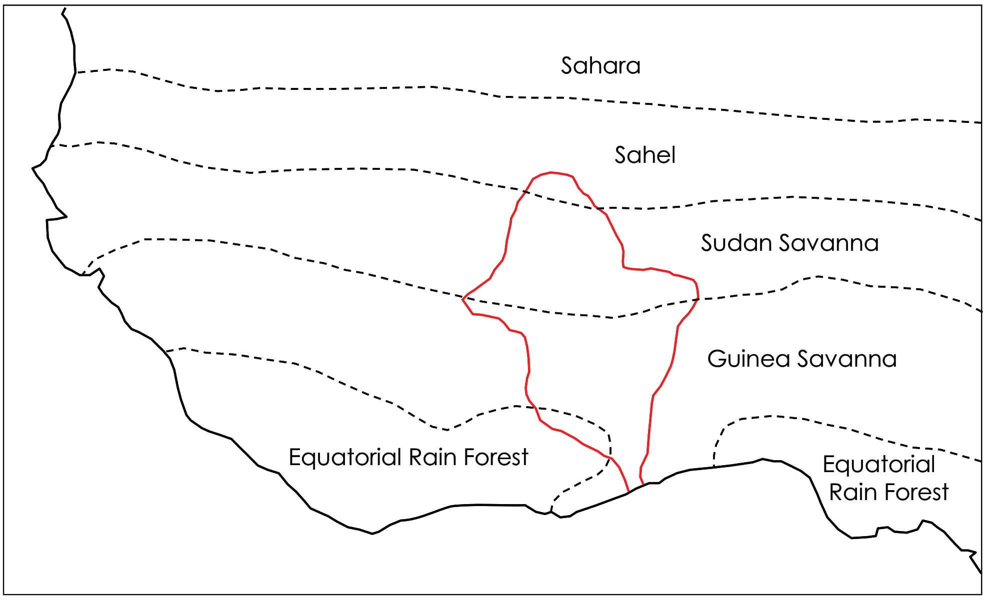

Figure 1.1: Climate zones in West Africa

2 GROUNDWATER IN THE VOLTA RIVER BASIN: HYDROGEOLOGY, DEVELOPMENT POTENTIAL AND CURRENT USE

This chapter presents a regional overview of the groundwater situation in the Volta River basin. The hydrogeological frame is outlined, which builds the basis for the definition of the scope of field research and the selection of a study area.

Relevant information was gathered from (hydro)geological maps (Castaing et al., 2003; CIEH, 1979; CIEH, 1986; Geological Survey Department of Ghana, 1969) and reports (Bannert et al., 1980; BRGM / Aquater, 1991; Dapaah-Siakwan and Gyau-Boakye, 2000; Gombert, 1998; Wardrop & Associates Ltd., 1977). In addition a borehole database was developed containing information for 26,000 boreholes in the basin. A digital groundwater potential map of the basin was derived on this basis, which is presented in the first section.

Groundwater production and its spatial distribution are also assessed. This information was developed from data on boreholes, hand dug wells and mechanized systems relying on groundwater in order to find out the importance of groundwater resources in present day water supply.

2.1 Hydrogeology and groundwater development potential

The largest part of the Volta river basin is made up of basement rocks of the West African craton. These are Precambrian (Birimian) metasediments and metavolcanics which have been syn-tectonically and post-tectonically intruded by granitoids. Thick layers of sandstones, schist and carbonates of the Zone Sédimentaire and sandstones of the tertiary Continental Terminal form the geology of the north-western part of the basin.

The central part of the Volta River basin consists of a flat extended depression of Cambrian sediments which make up the Voltaian basin. The concave edge of this basin builds escarpments towards the neighboring Precambrian rocks. While the Upper and Lower Voltaian consist of fine grained, consolidated sandstones, the lower Middle Voltaian (Obosum) consists of shales and consolidated sandstones, which are exposed to tectonic stress towards the eastern edge of the Obosum, where it borders the fault zone of the mobile belt. The upper Middle Voltaian (Oti) mostly consists of sandstones.

A major fault zone runs from southwest to north east along the metamorphosed and folded metasediments of the Togo and Buem formations, which build a hill range along the eastern border of the Volta River basin. The Togo formation consists of highly folded and fractured shale, conglomerates and limestone, while the Buem is made up of quarzites, phyllites and sandstone.

The definition for groundwater potential is not uniform, and different hydrogeological parameters have served as parameters in the evaluation of groundwater potentials. Dapaah-Siakwan and Gyau-Boakye (2000) have qualitatively described the groundwater potential of geological formations in Ghana based on drilling success rates and borehole yields. Attempts have also been undertaken to regionalize point data of borehole yields (WRI, 1994) or specific capacity (Darko & Krasny, 2003) irrespective of the boundaries of geological formations. Geostatistical approaches remain problematic given the overall poor data quality especially regarding actual borehole locations, the very high spatial variability of hydraulic properties and the bias of borehole densities for areas of good success rates and high population densities.

An approach introduced by the Inter-African Committee for Hydraulic Studies (CIEH, 1986) is used instead. Rather than being based entirely on hydraulic characteristics, the scheme also considers required capital costs for construction of a borehole, the suitability of the aquifer for village or urban water supply and the reliability of the groundwater resource in the event of a drought. The scheme is modified and applied to geological spatial units as described in Martin and van de Giesen (2005). It evaluates the groundwater potential as a function of

- Accessibility (depending on borehole drilling success rates)
- Exploitability (depending on borehole yield and extraction depth), and
- Supply reliability (depending on the amount of water stored in the aquifer, the mobility to the well and on the amount of recharge in non-drought years).

Figure 2.1 combines geological units and the resulting groundwater development potential. A region of very good groundwater potential is in the area of the ‘Zone Sédimentaire’ in the north-western part of the basin, which lies in the West of Burkina Faso. This region extends across the headwaters of the Black Volta, which due to the discharge of groundwater to the river is the only perennial river in the basin. At the other end of the scale is the area of the Middle Voltaian Obosum sediments, which consists of alternating layers of predominantly shale, siltstone and consolidated sandstone, and the massive Dahomeyan gneisses south of the Volta Lake. These two geological formations have a poor groundwater potential. The large area underlain by Birimian granitoids, metasediments and metavolcanics has a moderate or moderate to good groundwater potential. Even though the hydrogeology of the Voltaian sedimentary basin is not yet well known, the borehole records suggest that a good groundwater potential occurs in the Middle Voltaian Oti beds, which consist predominantly of sandstones. The Buem formation, which stretches from the eastern shore of the Volta Lake to the eastern corner of Burkina Faso also has good groundwater potential as well as the sandstones of the Continental Terminal at the north-western edge of the basin.

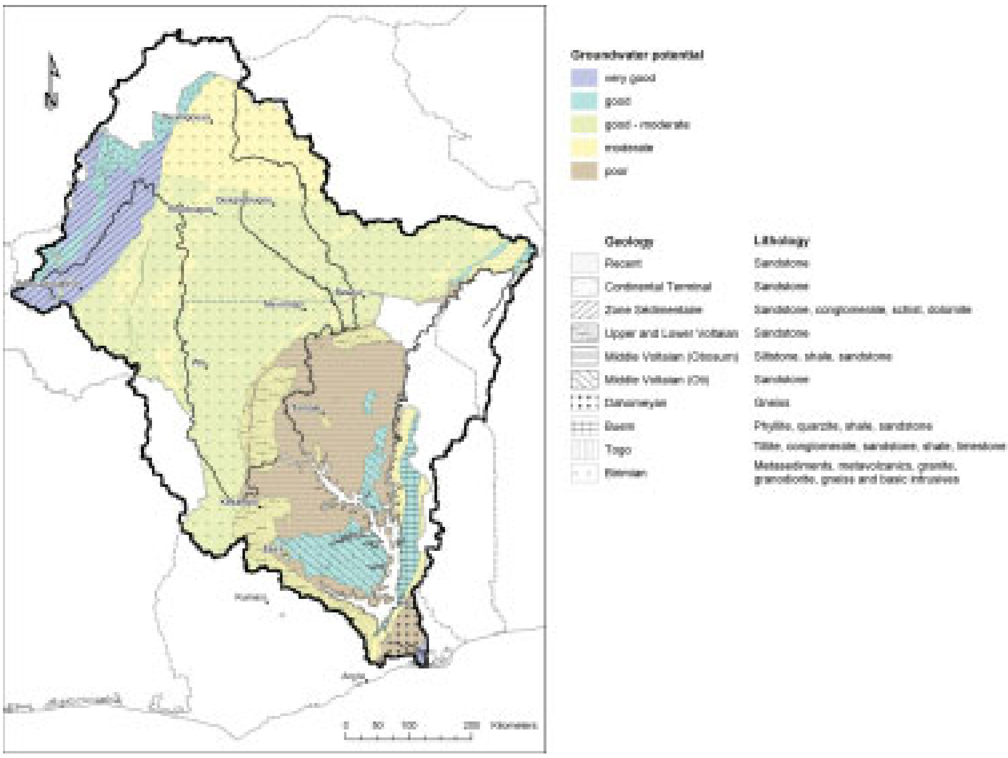

Figure 2.1: Geology and groundwater potential in the Volta River basin

2.2 Current groundwater use

Due to the rapid development of groundwater resources over the past 30 years, groundwater has become an important and secure source of rural and urban water supply. An estimated 44 % of the total population in the Volta River basin now depends on modern means of groundwater supply (Martin and van de Giesen, 2005). Boreholes equipped with hand pumps are the main means of groundwater extraction with an estimated total groundwater production of 61 Mm^3/y for the year 2001. Despite their large number, hand dug wells supply a much smaller amount of water than boreholes (12 Mm^3/y). Abstraction through piped systems using groundwater is 15 Mm^3/y, less than one fifth of total groundwater production.

The spatial distribution of boreholes equipped with hand pumps (Figure 2.2) and of mechanized systems using groundwater for urban water supply (Figure 2.3) shows that most groundwater production is located within the Birimian, which underlines the importance of this geological formation for water supply.

Despite the strong increase in groundwater production over the past decades, almost half of the population still has inadequate access to safe drinking water so that further development of groundwater resources is desirable. This raises the question of the natural limit of groundwater production, i.e. the quantity of renewable resources. The recharge rate determines an upper limit for sustainable abstraction of groundwater, and recharge rates between 2.5 % and 10 % of average annual rainfall have been used in the past in groundwater resources planning. Using a rough estimate that recharge amounts to 5 % of annual rainfall indicates that only a small fraction of renewable groundwater resources are currently exploited. Nonetheless in the absence of data from field investigations fears repeatedly surface that current groundwater abstraction already exceeds sustainable levels. Such fears are fuelled by the occurrence of falling groundwater levels and the drying up of wells.

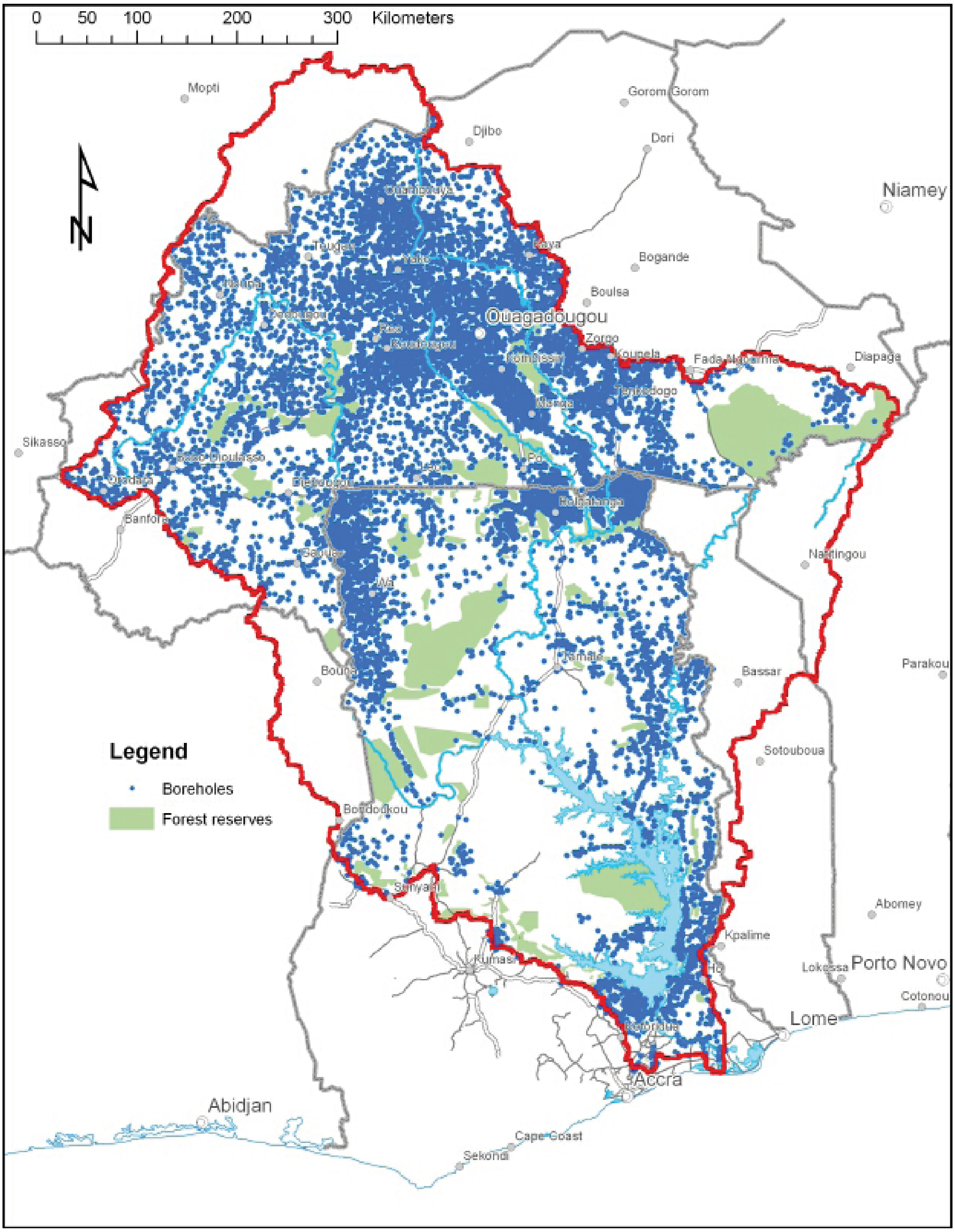

Figure 2.2: Location of boreholes with hand pumps