



**British
Geological Survey**

NATURAL ENVIRONMENT RESEARCH COUNCIL

BGS Consultancy: UNICEF IWASH Project, Northern Region, Ghana. Final Report

Groundwater Science Programme

Open Report OR/11/017



BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

OPEN REPORT OR/11/017

BGS Consultancy: UNICEF IWASH Project, Northern Region, Ghana. Final Report

The National Grid and other
Ordnance Survey data are used
with the permission of the
Controller of Her Majesty's
Stationery Office.
Licence No: 100017897/2010.

Ó Dochartaigh B É, Davies J, Beamish D and MacDonald A M

Keywords

Northern Region, Ghana,
groundwater development,
Voltaian Basin.

Front cover

Participants and facilitators on
the training course, Tamale,
Northern Region, Ghana.

Bibliographical reference

Ó DOCHARTAIGH B É, DAVIES J,
BEAMISH D AND MACDONALD A
M. 2011. BGS Consultancy:
UNICEF IWASH Project,
Northern Region, Ghana. Final
Report. *British Geological
Survey Open Report*, OR/11/017.
69pp.

Copyright in materials derived
from the British Geological
Survey's work is owned by the
Natural Environment Research
Council (NERC) and/or the
authority that commissioned the
work. You may not copy or adapt
this publication without first
obtaining permission. Contact the
BGS Intellectual Property Rights
Section, British Geological
Survey, Keyworth,
e-mail ipr@bgs.ac.uk. You may
quote extracts of a reasonable
length without prior permission,
provided a full acknowledgement
is given of the source of the
extract.

Maps and diagrams in this book
use topography based on
Ordnance Survey mapping.

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgs london@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Contents

Contents.....	i
Executive Summary	iv
1 Introduction.....	1
1.1 BGS role	1
1.2 Background to UNICEF IWASH programme.....	1
1.3 Background to Groundwater Development in the Northern Region, Ghana	1
2 Summary of Activities.....	3
2.1 Terms of reference.....	3
2.2 Review and interpretation of existing data and practices	3
2.3 Workshop and training course.....	7
2.4 Groundwater development potential map.....	7
3 Workshop and training with groundwater practitioners in the Northern Region	9
3.1 Aims of workshop and training	9
3.2 participant selection.....	9
3.3 Development and content of training course.....	9
3.4 Evaluation of workshop and training.....	13
4 Hydrogeology of the Voltaian Basin in the Northern Region	15
4.1 General geology.....	15
4.2 Summary of hydrogeology	16
4.3 Hydrogeology of individual geological units	17
4.4 Groundwater quality	24
5 A groundwater development potential map for the Northern Region.....	27
6 Summary and assessment of current geophysical borehole siting and development practices observed	32
6.1 Geophysical borehole siting	32
6.2 borehole drilling and testing procedures	36
6.3 Data management	38
7 Recommendations for future groundwater development practices by practitioners....	40
7.1 General.....	40
7.2 Siting boreholes: reconnaissance desk and field surveys	40
7.3 Geophysics.....	41
7.4 Drilling, constructing, developing and testing boreholes	43
7.5 Data management	47
8 Conclusions: key issues and recommendations	48
8.1 General.....	48
8.2 Current practices and recommendations.....	49
8.3 Wider research issues	50

References	51
Glossary.....	53
Appendix 1 Workshop and Training Course, 7-17 February 2011, Tamale, Northern Region: Attendees and Feedback.....	54

FIGURES

Figure 1	Ghana regional boundaries, with the Northern Region labelled and the area of the Voltaian Basin project highlighted.....	2
Figure 2	Geological map of the Volta Basin study area, showing the boundary of the Northern Region	6
Figure 3	(i) reprocessed magnetic intensity across the Voltaian Basin; and (ii) depth interpretations (conductivity depth images or CDi) of electromagnetic response along flight lines across the Voltaian Basin	7
Figure 4	Enlarged section of magnetic intensity image showing examples of regional scale, potentially water bearing lineations	8
Figure 5	The geology of the Northern Region (based on recently revised geological mapping and nomenclature; extended specifically for this project to cover the Northern Region, by reference to national geological map of Ghana at 1:1 million scale).	16
Figure 6	Borehole depths and measured yields in the Obosum Group, Bunya Sandstone Member, Chereponi Sandstone Member and Bimbila Formation. Note the different vertical scales.	20
Figure 7	Borehole depths and measured yields in the Afram Formation, Anyaboni Sandstone Formation and Panaboko Sandstone Formation. Note the different vertical scales....	21
Figure 8	Percentage of non-dry boreholes (i.e. any yield more than zero) from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects; IWASH boreholes; and monitoring boreholes).....	22
Figure 9	Median yields of non-dry boreholes by geological formation, from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects); IWASH boreholes; and monitoring boreholes). The number of boreholes in each geological unit is given above each bar.	23
Figure 10	Borehole success rates (boreholes yielding 10 l/min or more) by geological formation, from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects; IWASH boreholes; and monitoring boreholes). The number of boreholes in each geological unit is given above each bar.	23
Figure 11	Groundwater conductivity (SEC – specific electrical conductivity) across the Northern Region.....	24
Figure 12	Piper plots for (i) the Obosum Group, (ii) the Bunya Sandstone Member and (iii) the Bimbila Formation	25
Figure 13	Fluoride concentrations in groundwater across the Northern Region.....	26
Figure 14	Nitrate concentrations in groundwater across the Northern Region	26
Figure 15	Groundwater development potential map for the Northern Region.....	29

Figure 16	Example of a detailed ‘photo log’ for a section of a dry borehole drilled at Kpachaa village, Northern Region, during the training course. Numbers are depth below the ground surface in metres	46
-----------	---	----

TABLES

Table 1	Summary of hydrogeological and related geological information collated within the Northern Region and used by the BGS team	5
Table 2	Schedule of workshop and training in Tamale	11
Table 3	Training course content	12
Table 4	Attribute table showing groundwater development potential in the main geological units of the Voltaian Basin rocks in the Northern Region	30
Table 5	Criteria for ranking VES points for drilling on sandstone and granite (from CSIR 2009).....	35

BOXES

Box 1	Associated notes for map and attribute table	31
-------	--	----

Executive Summary

Introduction

The British Geological Survey (BGS) were commissioned to investigate the low drilling success rates encountered by the UNICEF IWASH (Water, Sanitation and Hygiene) programme in the Northern Region of Ghana. BGS's activities have focussed on gathering existing hydrogeological data generated by the IWASH programme; reviewing the groundwater development practices used by IWASH consultants; building the capacity of key implementing IWASH partners and other groundwater development agencies through a two week workshop and training course held in the Northern Region; and producing a preliminary groundwater development potential map for the Northern Region.

Overview of the hydrogeology of the Northern Region

The rocks beneath most of the Northern Region form low or very low productivity aquifers with limited groundwater potential. Borehole success rates (boreholes capable of supplying a hand pump) are typically between 40 and 60%, but range from 20% in the lowest productivity aquifer to around 70% in the highest. Fractures in sandstones are the most important groundwater target. Only small amounts of groundwater are found in fractures in siltstones. Groundwater is rarely found in mudstones. The most important zone of groundwater flows is thought to be between approximately 30 and 70m depth. There is little groundwater inflow below 70m, particularly in mudstones and siltstones, but sandstones do sometimes show significant inflows up to 100m and occasional smaller inflows below 100m. However, there is no evidence in the available data of significant groundwater flows at depths of over 100m.

Overview of good groundwater development practice

Good practice in developing groundwater resources should start with a detailed reconnaissance survey involving both a desk study of available information – such as geological, hydrogeological and lineation maps and results of previous siting and drilling in the same area – and field observations of existing water sources and any surface indicators of groundwater. The knowledge gained by interpreting this information is used to choose appropriate geophysical techniques and locate lines for geophysical surveys. Ideally, geophysical surveys should first involve profiling (using EM34 and/or 2D resistivity equipment) over long lines that are designed to cross potential linear water bearing features. Deeper penetrating VES resistivity surveys could then also be carried out over promising features to provide more detailed lithological information, such as the likely presence of sandstone which is more likely to contain water bearing fractures. Ideally, more than one geophysical technique should be used and the results compared to look for features present in all sets of results. All geophysical surveying should be undertaken with good field procedure; deep penetration (i.e. using as wide an equipment spacing as possible); rigorous analysis using the correct geophysical models; and interpreted with respect to the known geology and hydrogeology of the area. Borehole drilling should be treated as an opportunity to gain valuable geological and hydrogeological information, as well as to develop a water source, with rigorous collection and recording of data throughout the drilling process. Borehole construction should be designed to maximise potential groundwater inflows, which may mean screening boreholes throughout most of their length. Borehole development should be done thoroughly until the hole is fully clear, and in mechanised boreholes the pump should be used to further develop the borehole before test pumping.

Review of the IWASH programme

The success rate of boreholes drilled during the IWASH programme is generally slightly higher than in previous projects, but is notably lower than for the Hydrogeological Assessment Project (HAP) monitoring boreholes. The higher success of the HAP boreholes may be due to the greater

degree of attention paid to borehole siting, using appropriate geophysical techniques, in the HAP project. Across many of the IWASH consultants there appears to be poor understanding of the physical basis of geophysical siting, and in consequence some geophysical techniques are being carried out wrongly and others are not being used to their full potential. Even where techniques are carried out and geophysical data are analysed correctly, they are often not interpreted appropriately, because of a lack of detailed understanding of the hydrogeology of the Northern Region and therefore of the hydrogeological relevance of the geophysical data.

Workshop and training

A two day workshop followed by a seven day training course was run in Tamale, Northern Region, from 7 to 17 February 2011, aimed at practitioners actively involved in developing groundwater resources in the Northern Region. Between 25 and 30 people attended every day, the largest group of whom worked for private consultancies, with other organisations represented including universities, NGOs, and regional and district government departments. The aims were to achieve a consensus on the groundwater development issues faced by practitioners in the region; raise awareness of potential alternative borehole siting techniques; address specific aspects of groundwater development that had been identified as particularly problematic in the Northern Region; and promote an understanding of the detailed hydrogeology of the region, including introducing a preliminary groundwater development potential map.

The course was largely successful in meeting these aims, and a further key benefit for participants was the rare opportunity of bringing together groundwater professionals from across the Northern Region and Ghana to share professional experience. A key outcome of the course was the recognition that further targeted in-depth training in specific aspects of groundwater development will be needed for practitioners to meet the challenges of successfully developing groundwater in this difficult region. The most critical needs are for further training in geophysical techniques and the science behind them; and for a development of a better understanding of the detailed geology and hydrogeology of the region which can be used to inform borehole siting and development decisions.

Wider recommendations

The Northern Region is a very difficult area in which to find and develop groundwater resources. It should be accepted that borehole success rates here will always be lower than in most other areas. Particularly in the most difficult areas dominated by mudstones, more resources – time and money – need to be focussed on careful siting of boreholes in order to maximise potential success, including detailed desk reconnaissance surveys and the effective use and interpretation of geophysical siting methods.

No single technique will find groundwater in the Northern Region. Improving success requires the effective implementation of a combination of many different approaches. Practitioners need a better understanding of groundwater targets; how to identify these using geological, geophysical and other surveying techniques; and how to develop groundwater effectively and sustainably once it is found. All this will rely on careful collection, analysis and interpretation of field data, and the central collation and interpretation of these data to develop a better regional understanding, which in turn needs to be used by practitioners to better inform groundwater development. Even if detailed hydrogeological data are only collected, collated and interpreted from a small percentage of boreholes drilled, the benefits in terms of improved knowledge and understating of groundwater resources, and corresponding increase in success rates, are likely to be significant.

In areas of particularly low success, such as areas underlain by unfractured mudstones where there has been continued failure to drill successful boreholes, other water supply options should be considered, such as piping in water from higher potential areas at distance, treating surface water, or rainwater harvesting.

Groundwater development practitioners in the Northern Region, especially those working in the private sector, appear to be to varying degrees isolated from the wider hydrogeological community. More opportunities for contact and sharing experience between the private, government, NGO and academic sectors would promote the development of improved skills, a deeper understanding of the hydrogeology of the region, and the adoption of potentially beneficial new or alternative techniques.

Future research

Two particular areas for research could help take the current hydrogeological understanding of the Voltaian Basin sedimentary rocks to another level. Recent new airborne geophysical data could help to identify potential groundwater targets, but further investigation is needed to show just how useful they could be, by means of a systematic programme to use the new data in borehole siting, and assessing whether and how success rates improve. Another means by which more detailed and relevant hydrogeological information could be obtained would be a systematic programme to drill and investigate in detail a series of deep cored boreholes, which would provide direct information on the detail of lithological changes, weathering styles and depths, and the occurrence, distribution and nature of water-bearing fractures.

1 Introduction

1.1 BGS ROLE

BGS were commissioned to investigate the low drilling success rates encountered by the UNICEF IWASH programme in the Northern Region of Ghana. The BGS project was split into three phases:

- (1) situation analysis and collation of available information on current methods of groundwater development in the Northern Region, in particular in the districts where the IWASH programme operates;
- (2) synthesis, examination and interpretation of the collated data in terms of (i) current groundwater practises; (ii) developing an understanding of the hydrogeology of the Northern Region and capturing this within a new groundwater development potential map for the Northern Region, in particular for the districts where the IWASH programme operates; and (iii) developing recommendations for improving borehole siting methods.
- (3) based on the activities in (2), above, hold a workshop and training course focussed on improving groundwater development practises in the Northern Region.

Phase 1 of the project, in October-November 2010, involved a visit to Ghana to rapidly assess groundwater development procedures and to collate available data (MacDonald and Davies 2010). Phase 2 took place partly in the UK and partly in Ghana throughout the workshop and training course. This workshop and training course formed Phase 3, which took place in Tamale, Northern Region, Ghana from 7 – 18 February 2011.

1.2 BACKGROUND TO UNICEF IWASH PROGRAMME

In June 2007, the European Commission (EC) and UNICEF agreed the start of the IWASH Project for *An Integrated Approach to Guinea worm eradication through Water Supply, Sanitation and Hygiene In Northern Region, Ghana*, to run from 2007 to 2011. The project aim was to support an integrated delivery of water supply, sanitation and hygiene (WASH) services in guinea worm endemic communities in the Northern Region of Ghana. Experience had shown that most of the remaining Guinea worm endemic communities in Ghana are located on the very hydrogeologically difficult rocks of the Northern Region, which have limited permeability and where borehole drilling success rates are very low (between 30% to 50%), resulting in a very slow pace and high cost of implementation. UNICEF therefore provided this technical support to improve borehole drilling success rates and to accelerate delivery of safe water to endemic communities, thus contributing in breaking transmission of Guinea worm and sustaining the status towards eventual certification of eradication. The overall objective of the water supply component of the project was to develop an approach for improved borehole siting in the Northern Region of Ghana through establishing a process for groundwater evaluation in difficult hydrogeological terrain, building the capacity of key partners for implementing the approach and documenting the approach in the form of a manual for replication in other parts of Ghana with similar hydrogeology.

1.3 BACKGROUND TO GROUNDWATER DEVELOPMENT IN THE NORTHERN REGION, GHANA

The Northern Region of Ghana (Figure 1) is a particularly difficult place to find groundwater. The region is largely underlain by ancient, indurated sedimentary rocks of the Voltaian Basin, which vary from dominantly sandstone, to dominantly mudstone with interlayered siltstone and, rarely, sandstone. Unsuccessful boreholes have been drilled throughout the region, but are

particularly common in areas that are underlain by mudstones, which are generally poorly fractured.

The recent history of groundwater development in the Northern Region has included ongoing work by long-term operators in the region; large donor-led projects; and scientific research. Long-term operators include Church of Christ and World Vision. Groundwater aspects of recent large projects include EU-funded and an AFD-funded work to provide new boreholes equipped with hand pumps and some hand dug wells, with concurrent work to build local, district and regional capacity in management of water infrastructure. A few papers or academic theses detailing hydrogeological research related to the Northern Region are available, including Ewusi (2006), Pelig-Ba (2004) and Teeuw (1995). Other research has looked in more detail at similar Voltaian Basin sedimentary rocks to the south (e.g. Acheampong and Hess 1998). The most recent large groundwater project has been the CIDA-funded Hydrogeological Assessment Project (HAP), which carried out systematic data collection during siting, drilling and testing of dedicated monitoring boreholes across the Northern Region. This project complemented existing monitoring boreholes established by the CSIR Water Research Institute (WRI), of which only three were in the Northern Region. Not directly linked to groundwater but of direct application to groundwater development is a recent airborne geophysical survey combined with geological mapping of the Voltaian Basin, including a large part of the Northern Region (Jordan et al. 2009).

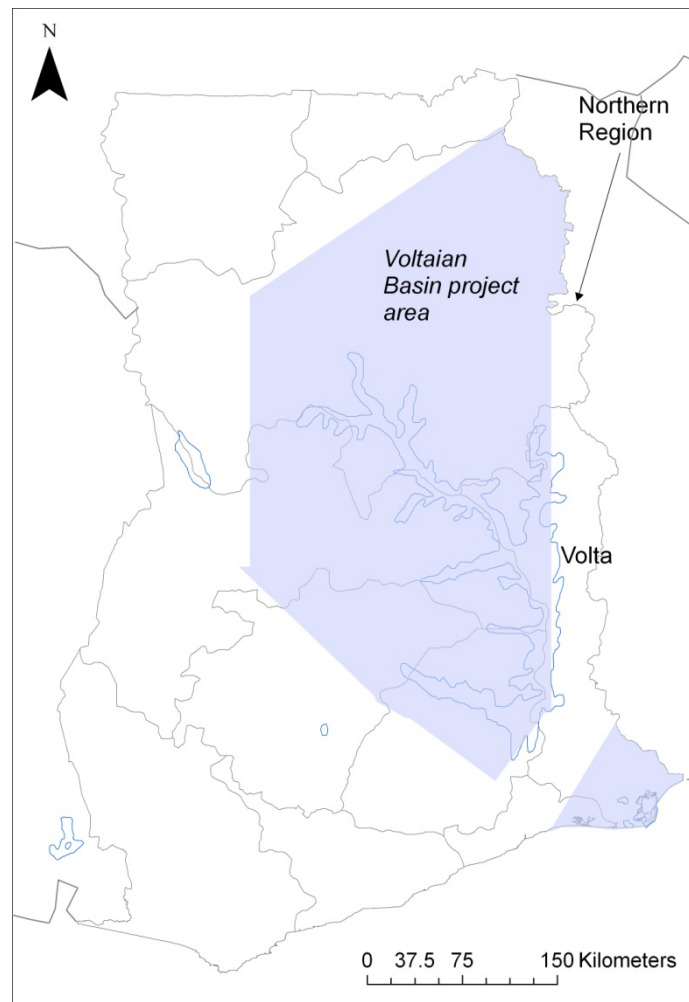


Figure 1 Ghana regional boundaries, with the Northern Region labelled and the area of the Voltaian Basin project highlighted

2 Summary of Activities

2.1 TERMS OF REFERENCE

The terms of reference for the project are listed below. Each is addressed in this report, and against each item is indicated (*in underlined italics text*) the relevant section of the report.

1. Documentation of the desk and scoping study on the hydrogeological situation of the ten IWASH districts in the Northern Region (*Sections 2.2 and 4*) and the approaches which have been used in Ghana in well siting (*Section 6*). This will also include
 - a. a review of all new geological mapping data, existing drilling programme success and failure and geophysics (*Sections 2, 5, 6 and 7*)
 - b. targeted field studies to help ground truth reports (*field investigations done as part of training exercises – Section 3*)
2. Development of the process for evaluating groundwater resources and siting water points in the different hydrogeological areas of the ten IWASH districts using existing available information. (*A general best practice process for evaluating and developing groundwater resources is described in the training manual provided during the course: the book ‘Developing Groundwater’ (MacDonald et al. 2005). During the training course, recommendations for specific techniques and/or adaptations relevant to local conditions in the Northern Region were presented, which are summarised in Section 7*)
3. The production of a preliminary groundwater development map for the area (based on the available information) to aid decision making on groundwater abstraction and development (*Section 5*).
4. Development of the approaches for groundwater abstraction and supply in the difficult hydrogeological areas of the 10 districts (*Section 7*).
5. A training manual on groundwater resources assessment in difficult hydrogeological terrain reviewed and adapted for use in Ghana. (*The training manual used was ‘Developing Groundwater’ (MacDonald et al. 2005), which was supported by recommendations for specific techniques and/or adaptations relevant to local conditions and practices in the Northern Region practices in the Northern Region. These were presented during the training course (Section 3) and summarised in Section 7*).
6. Building the capacity of up to 25 hydrogeologists of key implementing partners and other agencies working in the Northern Region, with training on groundwater resources assessment in difficult hydrogeological terrain (*Section 3; Appendix 1*).
7. A report documenting the process finalised, including a roadmap for further support (*this report. Key recommendations – the roadmap – are specifically outlined in Section 8*).
8. A subsidiary output of this activity should include recommendations (and a list) of cutting edge/state-of-the-art technology of geophysical prospecting equipment best suited for the procedures developed above for evaluating ground water resources in the different hydrogeological areas of the ten IWASH districts (*Section 7*).

2.2 REVIEW AND INTERPRETATION OF EXISTING DATA AND PRACTICES

During the initial BGS visit, data and information from previous projects in the Northern Region were collated, including project reports; siting (geophysical) and borehole drilling and testing data; and the Hydrogeological Assessment Project (HAP) database. Additional geological and geophysical data from the previous EU funded Mining Sector Support Programme (MSSP) were also obtained in the UK. Using this information, the following activities were carried out:

2.2.1 Data consolidation and systemisation

There is a large amount of data and information available on groundwater development activities in the Northern Region, and it is varied; held by many different organisations (government, NGO and private consultancy); and in many different formats. During Phase 1, considerable effort had to be made to identify and collate useful hydrogeological data from the relevant organisations, including photocopying and/or scanning numerous paper copies of data and reports. At the start of Phase 2, more considerable effort was made to sort through, consolidate and systemise this information, including pulling together all the different types of data on individual boreholes (e.g. location coordinates; borehole depths geological logs and construction; geophysical siting details) so they could be usefully interpreted.

Due to the large amount of information and the limited time available in this project, the two groundwater development projects which have generated most data were focussed on: the HAP project to develop new monitoring boreholes, and the IWASH programme. Available summary data from two previous projects, the EU (through CWSA) and AFD projects, and the basic information on other existing water boreholes across the Northern Region provided in the HAP database, were also used to inform understanding of the regional hydrogeology, but were not reviewed and assessed in the detail that the HAP monitoring borehole and IWASH data and practices were. The data were sorted according to the overall project; the type of data; and the collecting organisation. Duplicates between different datasets were identified as far as possible. Particular effort was made to link location data (coordinates) for geophysical surveys and boreholes to attribute data, so that spatial analysis could be carried out. Key data were summarised in spreadsheets to allow statistical analysis and export to GIS. The collated data from previous projects in the Northern Region are summarised in Table 1.

Additional geophysical and related geological data were derived from the EU-funded Mining Sector Support Programme (MSSP), which had the overall objective of sustaining the country's mining sector economic performance. A series of airborne geophysical surveys were carried out, combined with ground reconnaissance geological mapping. These datasets do not extend over the whole of the Northern Region, but cover a large part of the central and southeastern part of the region (Figure 2; Figure 3). The MSSP datasets used in this project are listed in Table 1, and two are illustrated in Figure 3. The geological map developed during the project (at 1:250,000 scale) is shown in Figure 2.

BGS undertook a preliminary assessment of the airborne geophysical data, primarily the electrical conductivity and magnetic data, as part of interpreting the hydrogeology of the Northern Region. These two datasets in particular provide a valuable framework for understanding in relation to future geophysical and hydrogeological assessments and borehole siting in the region; they are illustrated in Figure 3, and a larger scale example of the magnetic data is illustrated in Figure 4. BGS also extended the new geological map to cover the whole of the Northern Region, by simplifying linework available from an older national geological map of Ghana. This map (Figure 5) has been used throughout this project to provide the geological basis for hydrogeological interpretations, and also forms the basis of the groundwater development potential map (Figure 14).

2.2.2 Review and assessment of current practices

The BGS team reviewed the available information on hydrogeology and groundwater development practices IWASH programmes, by means of the data provided by consultants working on the IWASH programme. The aim of the review was to assess the effectiveness of groundwater development practices and whether improvements could be made to try and improve success rates. A number of key issues were identified, which became the focus of much of the subsequent training course. In particular, the review of geophysical data from the IWASH programme highlighted a number of issues related to the efficacy of the geophysical siting

methods used and whether the geophysical data produced can and are being used to support the development of hydrogeological understanding.

2.2.3 Interpretation of available data in terms of the hydrogeology of the Northern Region

Using the available hydrogeological information from the Northern Region collated during Phase 1 (Table 1), and additional geophysical and related geological data from MSSP (Table 2), the BGS team developed an interpretation of the hydrogeology of the Voltaian Basin within the Northern Region. Spatial data were plotted, overlaid and analysed in GIS; and a number of statistical analyses of the datasets were done in Excel. Non-numeric and non-spatial data were examined as relevant – e.g. analysing borehole lithological logs and/or downhole geophysical logs in relation to the results of geophysical surveys. The aim of the interpretation was to produce a conceptual model of how groundwater occurs and behaves across the area (Section 4). This conceptual model, and understanding, was captured in a draft of the groundwater potential map (Section 5).

Table 1 Summary of hydrogeological and related geological information collated within the Northern Region and used by the BGS team

Data source	Comments	Available data
HAP Database	Collating groundwater data for Northern Region. Lots of data but variably available – e.g. many boreholes have no location (coordinates) or yield information	Database of production wells with attribute information including (variably) borehole coordinates, depth, airlift yields, current status (functional or not) and groundwater chemistry
HAP monitoring wells	Monitoring wells drilled for HAP, and earlier wells drilled for WVB	Detailed lithological borehole logs; downhole geophysical logs; surface geophysics; pumping test data; groundwater levels; groundwater chemistry, plus summary reports with hydrogeological interpretations including recharge estimates
IWASH	Church of Christ	EM34 profiles; detailed borehole logs
	Prohydro	Drilling logs; VES; raw pumping test data; water quality
	Terrahydro	Borehole logs; test pumping; resistivity surveys; some chemistry
	Terrex	Drilling logs & VES
	Watersites (2009 & 2010)	Resistivity surveys, pumping test data, some chemistry
EU	EU-Rural Water Supply and Sanitation Project. Main consultants IGIP. No summary reports, lithological log or water chemistry data easily available in NR; available data provided in various spreadsheets and Word documents	Summary spreadsheets with borehole location, depth and yield data; some test pumping data and geophysical siting data
AFD	AFD funded Rural Water and Sanitation Project in the Northern Region. Collaboration between CWSA and consultant consortium BCEOM–FOSAT–UNIHIDRO–HYDROCONSEIL (AFD 2008). No detailed geophysical, lithological log, test pumping or water chemistry data easily available in NR	Project reports; summary spreadsheets with borehole location, depth and yield data.
MSSP	Government of Ghana/EU Development Fund/BGS/Fugro. An airborne geophysical survey and ground reconnaissance mapping of the Volta River and Keta Basins, Ghana (Jordan et al. 2009)	Digital terrain model (DTM); differential GPS survey; 1:250,000 scale geological map; ternary radiometric; magnetic intensity variations; electromagnetic (EM).

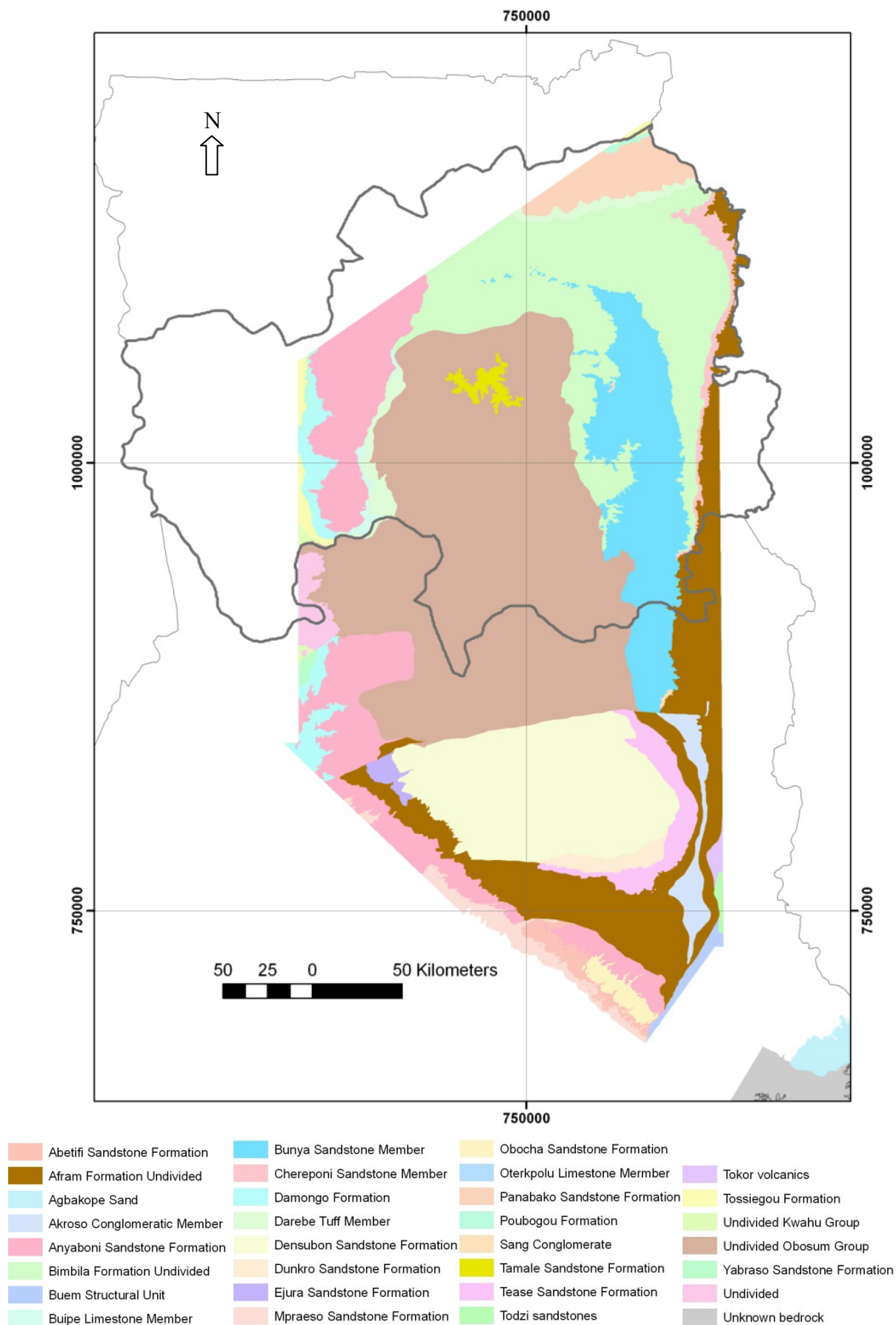


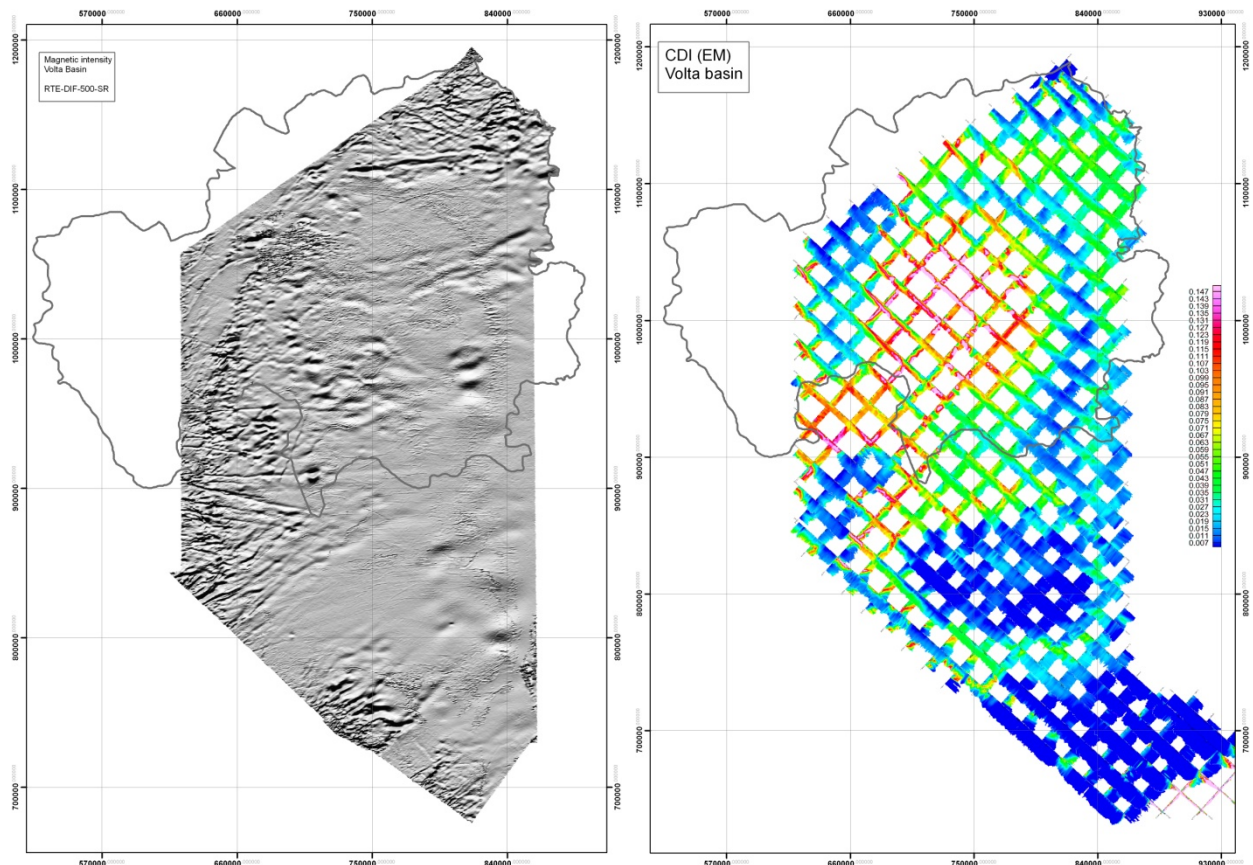
Figure 2 Geological map of the Volta Basin study area, showing the boundary of the Northern Region

2.3 WORKSHOP AND TRAINING COURSE

A two week workshop and training course was run in Tamale from 7 to 17 February 2011, facilitated by the BGS team. The course is discussed in detail in Section 3.

2.4 GROUNDWATER DEVELOPMENT POTENTIAL MAP

A key output from the project is the production of the first regional groundwater development potential map for the Northern Region. This is of necessity only an initial version of what such a map should and could become in the future, as understanding of groundwater potential across the Northern Region grows. The map is described in Section 5.



(i) Potentially water bearing lineations are not visible at this scale. See Figure 4 for a larger scale example

(ii) The colour range represents blue: lowest conductivity to pink: highest conductivity. Lower conductivities indicate sandstone; higher conductivities indicate mudstone

Figure 3 (i) reprocessed magnetic intensity across the Voltaian Basin; and (ii) depth interpretations (conductivity depth images or CDI) of electromagnetic response along flight lines across the Voltaian Basin

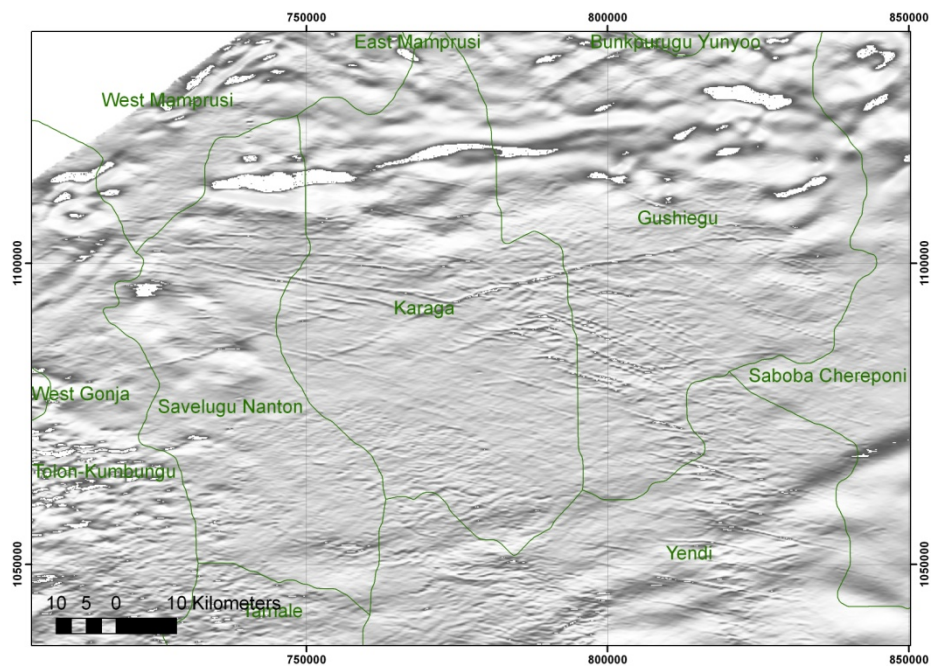


Figure 4 Enlarged section of magnetic intensity image showing examples of regional scale, potentially water bearing lineations

3 Workshop and training with groundwater practitioners in the Northern Region

3.1 AIMS OF WORKSHOP AND TRAINING

A two day workshop followed by a seven day training course was run in Tamale, organised and supported by UNICEF and CWSA (particularly by Mr John Aduakye) and facilitated by the BGS team. The course was aimed at practitioners actively involved in developing groundwater resources in the Northern Region. The aims of the workshop and training were to:

- Assess the collective experience of consultants and other practitioners engaged in developing groundwater resources in the Northern Region, and establish a consensus of opinion on the issues they face
- Put these issues in context with reference to experience and best practice from other areas around the world
- Raise awareness of potential alternative or additional groundwater development techniques relevant to hydrogeological conditions in the Northern Region
- Provide training in specific aspects of groundwater development highlighted by BGS as of particular importance, in particular:
 - geophysical siting techniques;
 - borehole drilling and construction; and
 - data management and interpretation.
- Promote understanding of the detailed geology and hydrogeology of the Northern Region; reach a consensus on the current understanding of the hydrogeology, and capture this in a groundwater development potential map.

3.2 PARTICIPANT SELECTION

The selection criteria for participants were that they should have experience of the development of groundwater resources either in the Northern Region or in similar geological environments elsewhere in Ghana, and/or have a good understanding of the geology and/or the hydrogeology of the Voltaian Basin. Private consultancies were particularly targeted, as much groundwater development work is contracted out to the private sector. Participants were invited from a large number of relevant organisations who are or have been active in the Northern Region. A list of invited organisations is in Appendix 1.

In the event, between 25 and 30 people attended every day throughout the workshop and training. Most attended every day; a few attended only selected sessions. The largest group of participants worked for private consultancies; other organisations represented were universities, NGOs, and regional and district government departments. Some participants were based in Tamale; some elsewhere in the Northern Region; some elsewhere in northern Ghana; and some in Accra. A list of the participants and their organisations is in Appendix 1. The level of experience of the participants in groundwater development ranged from high (more than 30 years experience as a hydrogeologist) to low (only a few weeks experience as a working hydrogeologist, or still a student).

3.3 DEVELOPMENT AND CONTENT OF TRAINING COURSE

The content of the training course was based primarily on the review of current practices and available hydrogeological information that was done during Phase 1 (MacDonald and Davies

2010) and the first part of Phase 2. It was also informed by discussions held with individuals from UNICEF, Ghana's CWSA, and other international consultants; in particular: Othniel Habila and Kabuka Banda (UNICEF Ghana), David Ede, John Aduakye (CWSA Ghana) and James Racicot (CIDA).

The course **addressed specific aspects of, or techniques for, groundwater development that were identified as relevant to the situation in the Northern Region. It was not a comprehensive guide to groundwater development.** It focussed on the main issues identified during Phase 1 and the early parts of Phase 2 (MacDonald and Davies 2010; Section 6, this report).

Much of the content of the course has been described in detail in an existing training manual: 'Developing Groundwater' (MacDonald et al. 2005), and is similar to previous training exercises undertaken by BGS in Malawi and Nigeria. Specific additions or alternatives were included where relevant to the Northern Region. Twenty copies of the training manual 'Developing Groundwater' were distributed by the BGS team to participants for use as reference during and after the course. Because of the size of the group, there were not enough books for every participant to have a personal copy, but at least one copy per organisation was distributed. A number of the participants who did not receive a copy requested whether they might receive one in the future.

The final course content had to take into account the diverse range of experience and knowledge of the participants, which ranged from high (more than 30 years experience as a hydrogeologist) to low (only a few weeks experience as a working hydrogeologist, or still a student). The training sessions had to both facilitate debate amongst those with much experience and involve those with less experience. Throughout the course and to meet the aspirations of both UNICEF/CWSA and the participants, the BGS team had to be flexible in the content of the course and responsive to the ideas and issues raised by the participants.

The schedule of the workshop and training course is presented in Table 2. The content of the training course is presented in Table 3 by reference to the titles of the presentations made throughout the training course programme. Digital copies of these presentations are available on a CD-ROM attached to this report.

Table 2 Schedule of workshop and training in Tamale

Date	Activity
Monday 7 February	Workshop: Tamale <ul style="list-style-type: none"> • Introduction to workshop and training • Introduction by BGS team • Introduction by and aims of participants for the course • Facilitated discussion to clarify key groundwater development problems experienced by participants and start making connections between different people's experience
Tuesday 8 February	Workshop – Tamale <ul style="list-style-type: none"> • Presentation of how HAP, IWASH and other data have been synthesised and interpreted in GIS • Examples of groundwater development potential maps from other areas and presentation of draft map attribute table • Group discussion on the groundwater potential, groundwater targets and geophysical techniques appropriate for of different geological units in the Northern Region (NR), starting to fill in the attribute table for the NR map
Wednesday 9 February	Training – Tamale and Kpachaa village <ul style="list-style-type: none"> • Theory behind geophysical siting techniques • Field demonstration of geophysical siting techniques
Thursday 10 February	Training – Kpachaa village <ul style="list-style-type: none"> • Field demonstration of geophysical siting techniques
Friday 11 February	Training - Tamale <ul style="list-style-type: none"> • Review of field demonstration
Saturday 12 February	Optional field trip – south of Tamale <ul style="list-style-type: none"> • Visit hydrogeological features, including artesian borehole, springs, and exposures of alluvial gravels near White Volta river.
Monday 14 February	Training - Tamale <ul style="list-style-type: none"> • Theory and examples of drilling, data collection, borehole construction and development
Tuesday 15 February	Training – Kpachaa village <ul style="list-style-type: none"> • Field demonstration of drilling and related techniques
Wednesday 16 February	Training - Tamale <ul style="list-style-type: none"> • Review of field demonstration • Discussion of test pumping • Discussion of groundwater quality, sustainability and monitoring
Thursday 17 February	Training – Tamale <ul style="list-style-type: none"> • Introduction to GIS • Summary and closing ceremony

Table 3 Training course content

Title of Training Presentation	Summary of presentation content
HAP-IWASH Data Systemisation and GIS Analysis	Overview of how the HAP monitoring borehole and IWASH data were consolidated, systemised and interpreted using GIS and Excel
Northern Region Groundwater Data – Additional Maps and Charts	Additional maps and charts (graphs/plots) to support the previous presentation
Overview of Geophysical Techniques	Theory and application of EM and resistivity geophysical siting techniques used in Northern Region; analysis of and comments on geophysical procedures and data from HAP and IWASH programmes
Geophysics practical field session in Kpachaa village – 1.5 days	Practitioners demonstrate standard procedures for EM34 surveys, dipole-dipole VES/profiling procedure, and 2D resistivity profiling. BGS demonstrate and VES Schlumberger technique and recommended improvements to EM34 survey technique
Results and Recommendations from Kpachaa Borehole Siting Exercise	Round up of experiences and lessons from geophysics practical field session
Groundwater Abstraction Systems	Overview of types of groundwater abstraction systems from around the world
Borehole Drilling Systems	Overview of different borehole drilling systems
Data Collected During Borehole Drilling	How to collect good quality data during borehole drilling
Borehole Construction	Overview of the theory and practice of borehole construction
Drilling practical field session in Kpachaa village – 1 day	BGS demonstrate good practice in data collection during drilling
Summary of Kpachaa Drilling Exercise	Round up of experiences and lessons from drilling practical field session
Borehole Test Pumping	Overview of the theory and practice of borehole test pumping
Groundwater Monitoring	Brief overview and discussion of groundwater monitoring and sustainability issues
Groundwater Quality	Brief overview of general groundwater chemistry and quality issues, both natural and pollutant, and brief discussion of groundwater quality in the Northern Region
GIS Introduction	Introduction and practical exercise in using GIS for data presentation and analysis
Summary of Training	Summary of workshop & training achievements and of key observations and recommendations for groundwater development practitioners in the Northern Region

3.4 EVALUATION OF WORKSHOP AND TRAINING

The two week course was very well attended, with between 25 and 30 participants every day, drawn from a wide spectrum of the groundwater development community. Most of the participants attended the full course. The course therefore successfully reached the target audience.

The participants took an active role, and shared extensive information about their experience of the known hydrogeology of the Northern Region, and the particular issues they face in groundwater development. Throughout the course, there was extensive in-depth, open and even fervent debate about many of these issues, from technical to contractual. Although there was disagreement about a small number of technical issues, overall there was agreement about the key points, and a general consensus about the problems faced in groundwater development in the Northern Region.

As always, some of the participants played a greater active role than others. The more junior participants were typically less active in discussions, but generally appeared to be paying close attention, in many cases asking questions of the facilitators after the sessions or during less formal fieldwork sessions.

The course covered a wide range of subjects, providing many examples of alternative or additional groundwater development techniques used successfully in other parts of the world, and where relevant illustrating how these could be applied in the Northern Region.

The course was also extremely beneficial in bringing together groundwater professionals from across the Northern Region and Ghana, which is a rare opportunity. Many of the participants commented favourably on this, and expressed a wish to have more regular opportunities for sharing professional experience in the future.

The aim of providing training in specific aspects of groundwater development highlighted as being particularly important was partly met. Given the number of important issues, there was not enough time to go into some, in particular the more technical aspects, to the depth and detail that many of the participants required or desired. This was particularly the case for the geophysical techniques, which were both the most technical and the most challenging in terms of local hydrogeological conditions in the Northern Region. A key outcome of the course was the recognition that **further targeted in-depth training in specific aspects of groundwater development will be needed for practitioners to meet the challenges of successfully developing groundwater** in this hydrogeologically difficult region. The most critical needs are for further training in geophysical techniques and the science behind them; and for a development of a better understanding of the detailed geology and hydrogeology of the region which can be used to inform siting and development decisions.

The large group of participants, with a wide range of skills and levels of experience, also meant it was impossible to ensure that everyone received an appropriate level of instruction to their needs. It was particularly difficult in the field to ensure that all the participants observed all of the field demonstrations.

The direct coupling of the training in field techniques to an actual borehole siting and development example – for a new borehole in Kpachaa village where the field training was carried out – added pressure to the field training; again, this was particularly the case for the geophysics. While it was very beneficial to be able to show the practical relevance of the field techniques, it would have been more effective for training purposes to demonstrate and explore each of the techniques in full in its own right, focussing more time and attention on particular techniques as necessary. But instead, a number of different geophysical techniques had to be carried out at the same time, and not all of the participants observed in full all of the techniques

being demonstrated. This is reflected in the evaluation comments of some of the participants (Appendix 1).

It also had the effect of diluting another training message, linked to the reconnaissance survey prior to geophysical surveying. It was not intended that the training would comprehensively cover the whole of a borehole development activity, but would focus on aspects in particular need of attention in the Northern Region. However, the linking of the training to an actual borehole development example meant that there needed to be a reconnaissance stage, which was consequently done hurriedly; only partially; and partly in retrospect, which was not ideal. Again, this was noted by some of the participants in their evaluation comments (Appendix 1).

4 Hydrogeology of the Voltaian Basin in the Northern Region

This summary of the current understanding of the hydrogeology of the Northern Region is based on the assessment and interpretation of available data collated from organisations in the Region (Table 1); on additional geological and geophysical data from the previous EU funded MSSP programme (Table 2); on discussions with Northern Region groundwater practitioners during the workshop and training; and on observations made by BGS during the two visits to the Northern Region during this project.

This understanding of the hydrogeology of the Northern Region is the key input to the groundwater development potential map produced during this project (Section 5).

4.1 GENERAL GEOLOGY

The basis of hydrogeological understanding is to understand the geology. The geology of the Northern Region, and of the area underlain by the Voltaian Basin in particular (which is the focus of this study), is still relatively poorly understood.

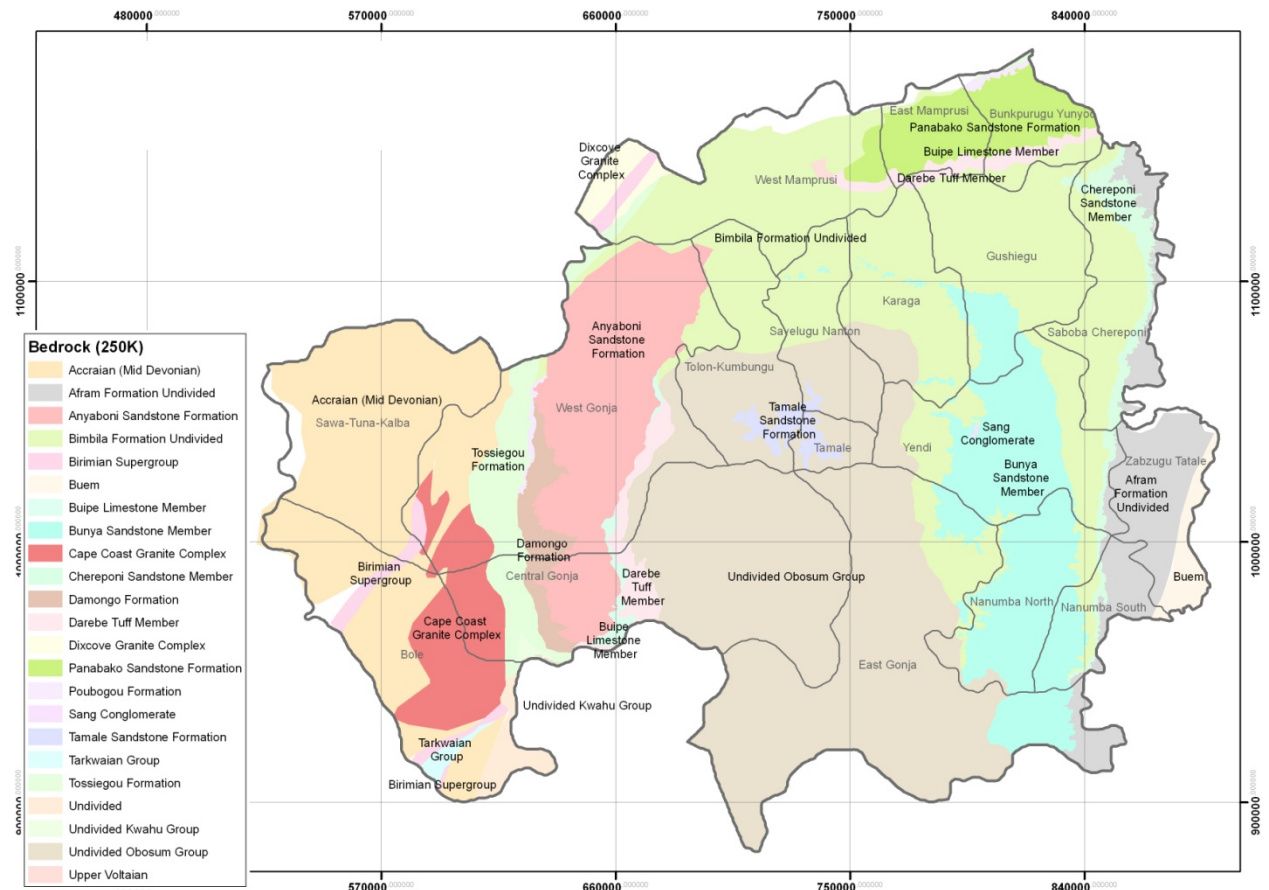
At the ground surface across most of the area, the rocks are covered by a layer of laterite (generally red tropical soils that are rich in iron and aluminium). When it overlies mudstones, the laterite is usually thicker – generally thought to be between 2 and 5m thick – and often nodular or tubular (formed into hollow tubes through which water can move). There is also typically a layer of kaolin clay between the laterite and the underlying mudstone. When it overlies sandstones, the laterite is typically thinner – thought to be only 1 to 2m thick, if present at all – and generally gravelly or sandy in nature.

Below the laterite, all the rocks in the region are typically highly weathered to a depth of at least 10m and often to between 30 and 60m. Few rock outcrops are visible at the ground surface, and so it is difficult to map, in detail, changes in geological units across the area; and it is impossible to have any detailed understanding of the nature of the unweathered rocks at depth. The characteristics of the rocks at depth, and lithological changes from one area to another, must largely be either inferred from remote sensing – and confirmed where possible by ground truthing – or observed from evidence gained by borehole drilling. The recent new geological mapping based on airborne geophysical sensing from MSSP has provided data that has been used to help refine the existing geological maps for part of the Northern Region, but even this was based on limited ground truthing. There has been little or no drilling for geological research in the Northern Region: what downhole information is available has been derived from drilling for water or minerals. Even the most recent geological map and understanding, therefore, still lacks considerable information about the detailed lithology of the geological units in the Northern Region, and in particular the interbedded mudstones, siltstones and rare sandstones of the Obosum Group and the Bimbila Formation that underlie a large part of the region (Figure 5).

The geology of the Northern Region is shown on the map in Figure 5. The rocks of the far west are not part of the Voltaian Basin, and are also outside the area of the IWASH programme, and they have not been investigated as part of this project. The rest of the region is underlain by mixed sedimentary rocks of the Volta Supergroup, which infills one of the major sedimentary basins within the older metamorphic and igneous West African rocks. The rocks of the Volta Supergroup form a Neoproterozoic (late Precambrian) to Early Palaeozoic, largely clastic, but lithologically very diverse sedimentary sequence. Mudstones, siltstones, sandstones, conglomerates and limestones occur in varying proportions across the region. They thicken progressively from west to east, where they terminate abruptly against a older Precambrian

basement rocks of the Buem and Togo Formations. These older rocks were once part of an ancient mountain range, which was eroded to provide the sediment that infilled the Voltaian Basin and formed the rocks of the Volta Supergroup.

The supergroup is traditionally divided into three main lithostratigraphical units: from oldest to youngest, these are the Kwahu/Boumbouaka, Oti/Pendjari, and Obosum/Tamale groups. These groups are subdivided into a number of formations and members, which can be seen in the legend of the map in Figure 5.



Geological map for the Voltaian Basin project area provided by BGS with permission from the Director of the Geological Survey of Ghana.

Figure 5 The geology of the Northern Region (based on recently revised geological mapping and nomenclature; extended specifically for this project to cover the Northern Region, by reference to national geological map of Ghana at 1:1 million scale).

4.2 SUMMARY OF HYDROGEOLOGY

Although there is no direct evidence yet, the unweathered rocks of the Voltaian Basin in the Northern Region are likely to be well-cemented and with little primary porosity or permeability. Groundwater storage and flow in the unweathered rocks occurs mainly in fractures. Most of the rocks in the Northern Region have low or very low aquifer productivity and groundwater potential. **Success rates are typically between 40 and 60%, but are as low as 20% in the lowest productivity aquifer, and often not more than 70% even in the highest productivity aquifer** (the Anyaboni Sandstone Formation). A successful borehole is defined as one capable of supplying a hand pump: the nominal criteria for success have differed slightly across different projects and also between theory and practice, but are generally between 8 and 13.5 l/min. For the purposes of this project, an average nominal yield of 10 l/min has been taken to indicate success.

In the upper weathered zone of the rocks, particularly in sandstones and less so in siltstones, weathering of fractures can increase aquifer permeability and allow enhanced groundwater flow and storage. **Fractures in sandstones are the most important groundwater target in the Northern Region.** Only small amounts of groundwater are found in fractures in siltstones. Groundwater is rarely found in mudstones. In some formations, particularly the Bimbila Formation, it is recognised that groundwater can be found in thin zones at lithological boundaries between mudstone and siltstone.

The available information shows that **the most important zone of groundwater flows is between approximately 30 and 70m depth.** The small number of deeper boreholes that have been drilled, particularly during the HAP project – most of which have also been flow logged – generally show that there is little groundwater inflow below 70m, particularly in mudstones and siltstones. The exceptions are in sandstones which sometimes do show significant inflows up to 100m and occasional smaller inflows below 100m. **There is no evidence of significant groundwater flows at depths of over 100m.**

A reprocessing of recent airborne magnetic data by the BGS team has revealed the locations of what appear to be an extensive set of regionally extensive lineations that cross much of the Voltaian Basin, including much of the Northern Region. These have been previously interpreted as fracture zones, although they have not yet been confirmed, and there has been no investigation of them in relation to groundwater potential. If their presence is interpreted and confirmed (e.g. by controlled ground magnetic measurements and by ground geological assessment) and further work shows that they are related to groundwater-bearing features (e.g. surface geophysical surveys and drilling results show they correlate to zones of increased fracture flow), knowledge of these lineations may help define local fracture strike directions, which could improve the success of borehole siting. The subject warrants further research.

There has been a relatively long history of interest in the hydrogeology of the Northern Region. Early geological surveys in the Volta Basin were carried out in support of water supply programmes and the main outcomes were summarised by Junner and Hirst (1946). Later work was carried out by a number of practitioners and described in project reports, papers or academic theses, such as Gill 1969, Tod 1981, Bannerman 1990, Sander et al. 1996, Kwei 1997, Ofusu 2005 and Teeuw 1995.

4.3 HYDROGEOLOGY OF INDIVIDUAL GEOLOGICAL UNITS

In decreasing order of age from youngest to oldest, the hydrogeology each of the main geological units of the Voltaian Basin in the Northern Region is described. Within the area of IWASH interest (in Figure 5 this is effectively from the Anyaboni Sandstone in the eastern part of West Gonja district to the Afram Formation in Zabzugu Tatale district), there are significant amounts of hydrogeological information for the seven most widespread geological units. A number of other units have smaller outcrops, and hence have been drilled into less often, and little is known about their hydrogeology; additionally, some of these are relatively thin, and may not be significant in terms of groundwater flow. A summary of the known detailed lithology, weathering, surface expression and hydrogeology of the seven most widespread units is described here.

4.3.1 Obosum Group

Dominated by interbedded, thinly-laminated and highly variegated (yellow/brown/grey/purple/green) micaceous mudstones and purplish-grey, micaceous siltstones. Rare beds of very fine-grained sandstones, and sporadic but highly distinctive beds of pebble conglomerate, particularly near the base of the group. Thinnest at its western edge, the maximum thickness is unknown but likely to exceed 400m.

In the Northern Region the Obosum Group forms gently undulating terrain, with extensive formation of tubular and nodular laterite at the surface, overlying a weathered zone of kaolin clay.

The recorded boreholes in the Obosum Group are usually between 30 and 90m deep, with a small number drilled up to 150m deep. Most boreholes drilled are dry – less than 30% show any yield at all (Figure 8). In non-dry boreholes, recorded yields range from 2 to 1000 l/min (Figure 6), with median yields ranging from 10 to 15 l/min (based on statistics from the three main borehole datasets: the HAP database of abstraction boreholes; IWASH boreholes; and monitoring boreholes – Figure 9). In the IWASH and previous programmes, between 20 to 25% of boreholes were high enough yielding to be able to supply a hand pump – taken as a nominal yield of 10 l/min (Figure 10). Taking this value of 10 l/min to indicate success, the success rate of boreholes in the Obosum Group drilled during the HAP monitoring well programme was higher, at 50%, although only six boreholes were drilled during this programme. There is little indication that deeper boreholes consistently show higher yields (Figure 6).

The Obosum Group therefore generally forms a very low productivity aquifer. The mudstones which often dominate much of the unit do not appear to contain significant groundwater, either when weathered or unweathered. The siltstones occasionally contain water-bearing fracture or weathered-out fracture zones. Occasional high yielding boreholes have been drilled in this group, but typically only where significant thicknesses of sandstone are encountered; thin fracture zones in the sandstone are thought to be the most important groundwater targets in this case. However, not all boreholes drilled into sandstones within the Obosum Group have produced high yields, which indicate that fractures are not well-developed everywhere in the sandstone.

4.3.2 Bunya Sandstone Member (Oti-Pendjari Group)

The Bunya Sandstone Member is thought to be generally about 50m thick, and consists of minor maroon, green and grey, slightly micaceous siltstones overlying the dominant lithology of grey-green, medium-grained, micaceous, poorly sorted sandstones, which are rich in feldspar and lithic grains of quartz, red jasper and meta-volcanic rocks.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

The recorded boreholes in this unit are usually between 30 and 70m deep, with a small number drilled up to 150m deep. The deeper of these boreholes are therefore likely to have been drilled through the total thickness of the Bunya Sandstone Member and into the underlying Bimbila Formation.

Only around 40% of drilled boreholes give any yield at all (Figure 8). In non-dry boreholes, recorded yields range from 5 to 1000 l/min (Figure 6). The median yield of boreholes that were not dry is variable in the different programmes, from 7 to 180 l/min (Figure 9). Success rates in this unit in the IWASH programme (17%) were lower than in previous programmes (40%) or the HAP monitoring borehole programme (all of the four boreholes drilled) (Figure 10). There is little indication that deeper boreholes consistently show higher yields (Figure 6).

The Bunya Sandstone Member therefore appears to form a moderately to highly productive aquifer if conditions are favourable, with the key groundwater target likely to be thin fracture zones within the sandstones. However, the high percentage of dry boreholes drilled indicates that there may be great variability in the development of fractures across the unit, and that where fractures are not well-developed, yields can be negligible.

4.3.3 Chereponi Sandstone Member (Oti-Pendjari Group)

This member is thought to be 40-60m thick, and is made up of hard, possibly siliceous, dark olive-green to grey, fine- to medium-grained micaceous and lithic-rich feldspathic, arkosic sandstone.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

The recorded boreholes in this unit are typically between 20 and 70m, with an occasional borehole down to 90m. The deepest of these boreholes are therefore likely to have been drilled through the total thickness of the Chereponi Sandstone Member and into the underlying Bimbila Formation. Only around 40% of drilled boreholes provide a yield (Figure 8). In non-dry boreholes, recorded yields range from 3 to 300 l/min (Figure 6). The median yield of boreholes that were not dry appears is around 40 l/min, although the two non-dry boreholes drilled in this formation for the IWASH programme gave a lower median yield of 15 l/min (Figure 9). Success rates (boreholes yielding 10 l/min or more) were between approximately 40 and 50% in the IWASH and previous programmes (Figure 10). There is little indication that deeper boreholes consistently show higher yields (Figure 6).

The Chereponi Sandstone Member appears to form a variably productive aquifer, from low to high. The main groundwater targets are likely to be thin fracture zones, but the high percentage of dry boreholes, and the variability in yields, indicates that fractures are not well-developed everywhere.

4.3.4 Bimbila Formation

This unit consists of green-grey mudstones and siltstones interbedded with subordinate green-grey, feldspathic sandstones.

Overlying the unit there is typically tubular laterite at the surface with weathered kaolin clay below; the clay layer tends to be thinner below low-lying areas than beneath higher ground.

The recorded boreholes in this unit are typically between 20 and 80m, with an occasional borehole down to 170m. Only around 40% of drilled boreholes are not dry (Figure 8). In these non-dry boreholes, recorded yields range from 4 to 1000 l/min (Figure 6). The median yield of boreholes that were not dry is between 20 and 27 l/min for boreholes in the IWASH and previous programmes, but the ten monitoring boreholes drilled showed a much higher median yield of 85 l/min (Figure 9). Two of the monitoring boreholes had particularly high yields of 700 l/min. There is little indication overall that deeper boreholes consistently show higher yields (Figure 6); the two boreholes with yields of 700 l/min were 106 and 120m deep, but most of the deeper boreholes (120 to 166m deep) had yields of less than 20 l/min. Success rates (yields of 10 l/min or more) for boreholes in the Bimbila Formation appear to have increased from previous borehole development programmes (40%) to the IWASH programme (55%) to the HAP monitoring well programme (80%) (Figure 10).

The Bimbila Formation therefore appears to form a moderate to low productivity aquifer, probably largely dependent on the lithology. The main groundwater targets are likely to be weathered-out fracture zones in siltstones and sandstones; and it is observed that groundwater flows also occur in thin zones at lithological boundaries between mudstone and siltstone. Higher yields may also occur in thicker sandstone units.

4.3.5 Afram Formation

This unit mainly consists of olive-green to grey mudstones and siltstones, with occasional thin limestones. The formation tends to readily weather to an ochreous, ferruginous tubular laterite over kaolin clay, which is thinner below low-lying areas than beneath higher ground.

The recorded boreholes in this unit are generally between 30 and 70m. Some 50% of drilled boreholes are dry (Figure 8). In non-dry boreholes, recorded yields range from 6 to about 550 l/min (Figure 7). The median yield of boreholes that were not dry ranges from approximately 20 to 35 l/min (Figure 9). Success rates for boreholes in the Afram Formation in previous programmes were around 40%, and for the IWASH programme were 55% (Figure 10). No boreholes deeper than 70m have been recorded.

The Afram Formation therefore appears to form a moderately productive aquifer. The main groundwater targets are likely to be weathered-out fracture zones, especially in siltstones and rare limestones. These fractures are not likely to be well-developed everywhere.

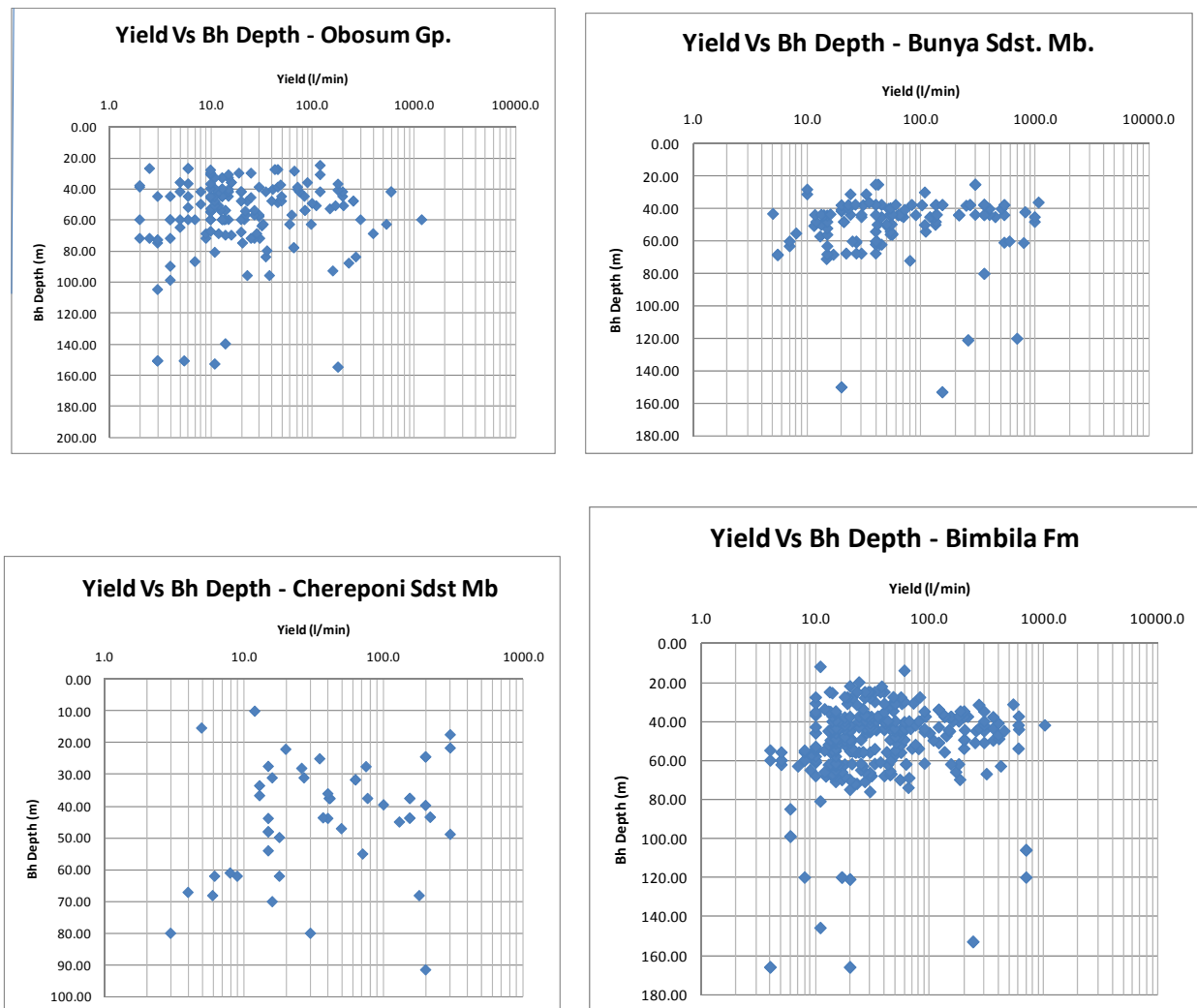


Figure 6 Borehole depths and measured yields in the Obosum Group, Bunya Sandstone Member, Chereponi Sandstone Member and Bimbila Formation. Note the different vertical scales.

4.3.6 Anyaboni Sandstone Formation (Kwahu Group)

This has been mapped as a 150-200m thick unit, comprising finer-grained, argillaceous and micaceous strata at its base, passing upwards into grey to pink, medium-grained, feldspathic, mainly sub-arkosic sandstones, which are at least partly aeolian in origin.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

The recorded boreholes in this unit are typically between 40 and 60m, with a very small number of boreholes between 100 and 120m. Some 70% of drilled boreholes provide a yield (Figure 8). In these non-dry boreholes, recorded yields range from 7 to 1000 l/min (Figure 7). The median yield of boreholes that were not dry is high, from 150 l/min in previous programmes to 260 l/min in the HAP monitoring boreholes programme (Figure 9). Success rates (boreholes yielding 10 l/min or more) are also high, from around 70% in previous programmes to 100% in the HAP programme (Figure 10). There is some indication that higher yields can be found with depth: all the boreholes between 100 and 120m had yields of between 300 and 600 l/min (Figure 7).

The Anyaboni Sandstone Formation therefore appears to form a moderate to high productivity aquifer. The main groundwater target is likely to be thin fracture zones, which are likely to become less frequent and productive with depth, but the limited evidence from the deeper monitoring wells, which have been flow logged, indicates that there can be significant inflows at depths of up to 100m, and occasional inflows below 100m.

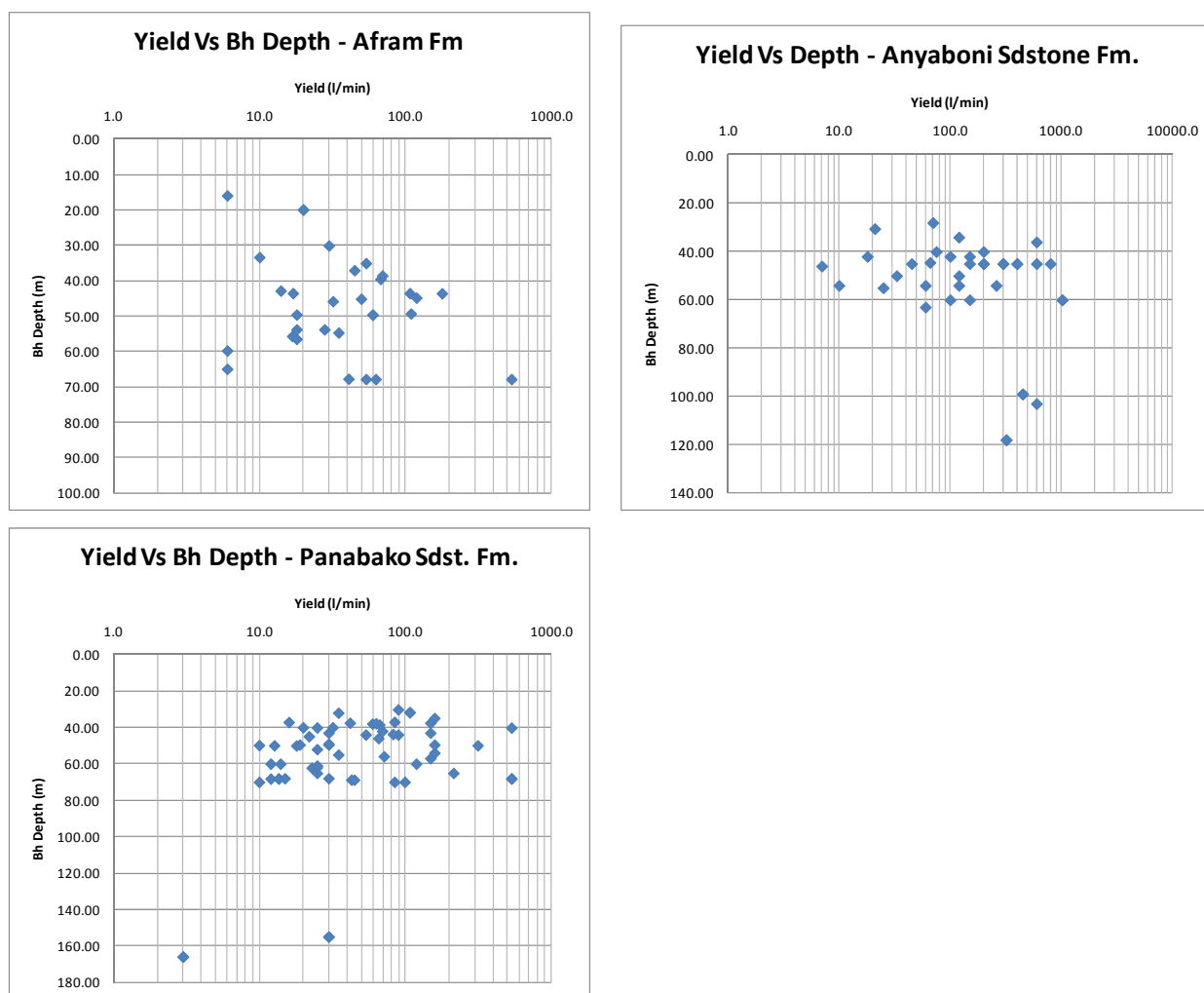


Figure 7 Borehole depths and measured yields in the Afram Formation, Anyaboni Sandstone Formation and Panaboko Sandstone Formation. Note the different vertical scales

4.3.7 Panaboko Sandstone Formation (Kwahu Group)

This unit is estimated to be 150-200 m thick, and comprises hard, well-cemented, well sorted, medium-grained, quartzose sandstones (quartz arenites or quartzites), with minor feldspar content, which are typically white or locally stained ochre.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

Of the recorded boreholes in this unit, all but two are between 30 and 70m deep, with two new monitoring wells around 160m deep. Some 40% of drilled boreholes are not dry (Figure 8), and in these boreholes, recorded yields range from 2 to about 550 l/min (Figure 7). The median yield of boreholes that were not dry is between 15 and 35 l/min (Figure 9). The two deep monitoring wells drilled in the HAP programme showed relatively low yields, with one in particular, at more than 160m deep, yielding only 3 l/min. Based on the evidence of the only two deep boreholes, there is no indication that higher yields are found with depth (Figure 7).

The Panaboko Sandstone Formation appears overall to form a moderate to high productivity aquifer. The main groundwater target is likely to be weathered-out fracture zones in the shallow zone to about 20 to 30m depth, and largely unweathered fracture zones below this, which are likely to become less frequent and productive with depth. In the two deep boreholes, flow logging showed there were small inflows below 100m, but these did not increase the yield significantly.

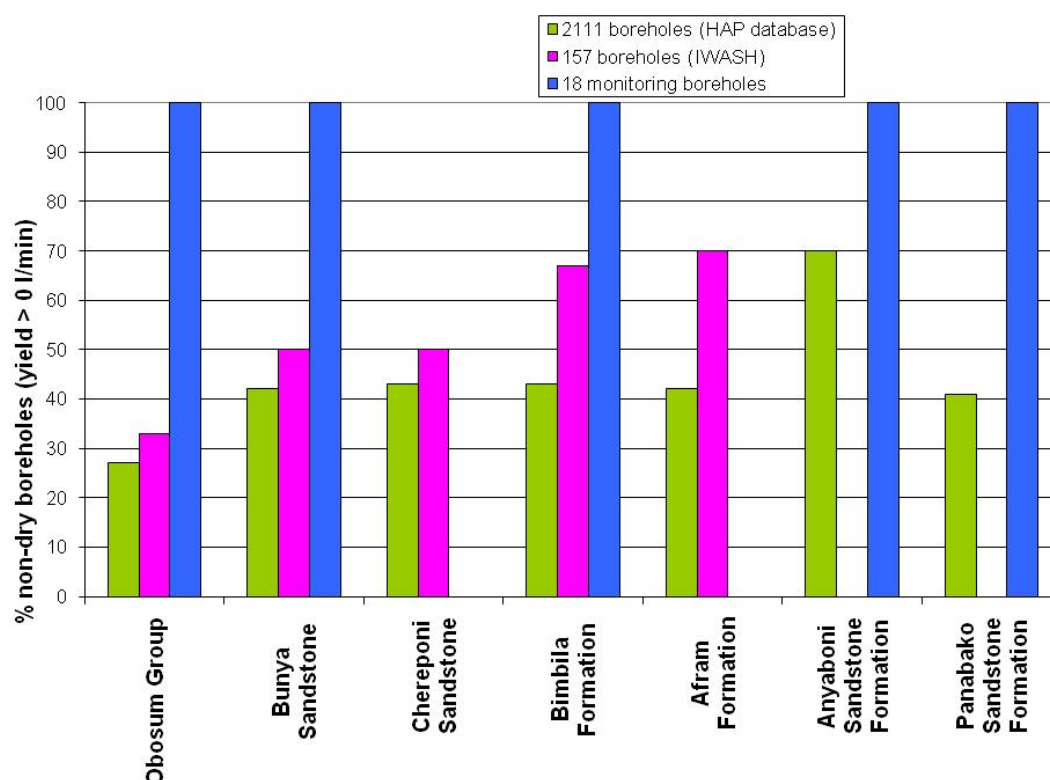


Figure 8 Percentage of non-dry boreholes (i.e. any yield more than zero) from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects; IWASH boreholes; and monitoring boreholes)

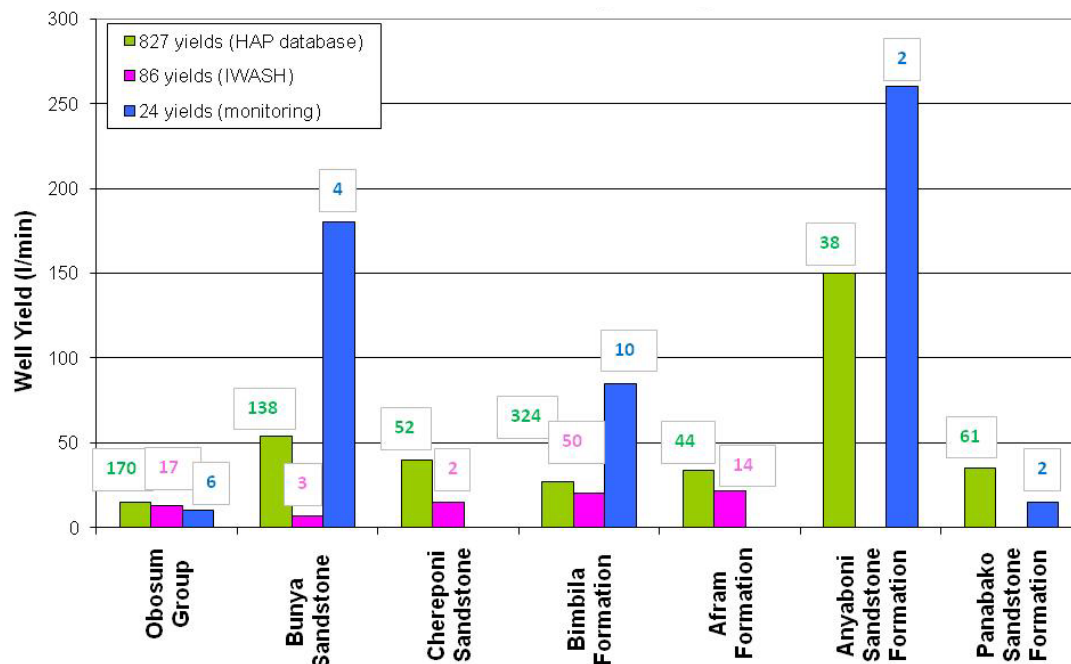
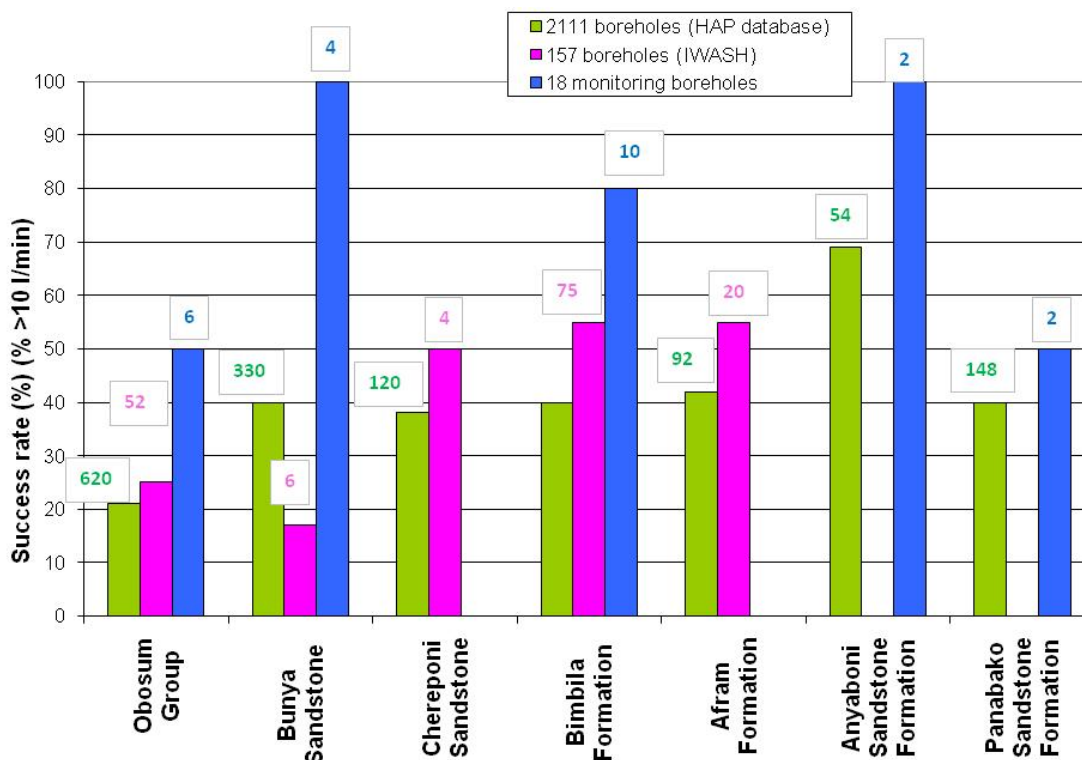


Figure 9 Median yields of non-dry boreholes by geological formation, from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects); IWASH boreholes; and monitoring boreholes). The number of boreholes in each geological unit is given above each bar.



Note that different borehole success criteria – defined as the nominal yield required to support a hand pump – have been used in different projects in the Northern Region, but these are generally between 8 and 13.5 l/min: 10 l/min is used here as an average.

Figure 10 Borehole success rates (boreholes yielding 10 l/min or more) by geological formation, from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects; IWASH boreholes; and monitoring boreholes). The number of boreholes in each geological unit is given above each bar.

4.4 GROUNDWATER QUALITY

The available chemistry data indicates there is often a difference in the degree of mineralisation of groundwaters in sandstones and in mudstones/siltstones. Groundwater from sandstones, such as the Bunya Sandstone and the Anyaboni Sandstone, appears to be generally less mineralised, with lower conductivity (measured by SEC – specific electrical conductivity). Groundwater from units dominated by mudstones and siltstones, such as the Obosum Group, often has higher conductivity, and in certain areas – such as near Tamale – very high conductivity (Figure 11).

There is only enough full major ion analysis to characterise water types for the Obosum Group, Bunya Sandstone Member and Bimbila Formation. Most of the groundwaters for which major ion analysis are available have a cation dominance by Na-K (Figure 12), with a few having no overall dominant cation. For most of the samples the dominant anion is HCO_3 , or there is no dominant anion, but a small subset of groundwaters from the Obosum Group are dominated by Cl (Figure 12).

The most prominent natural groundwater chemistry issue in the Northern Region is the presence of elevated fluoride concentrations. These occur sporadically across the region, but are much more common in the eastern corridor (Figure 13). There is also evidence that fluoride is more common in sandstones than in mudstones or siltstones. There is little obvious relationship from the Northern Region data between fluoride concentrations and other parameters which are often correlated with fluoride, such as pH, Ca, HCO_3 , or Na. There may be a relationship with the feldspar content of the sandstones, which is thought to be higher in the eastern part of the region, linked to the mineralogy of the basement rocks to the east which formed the sediment source for the rocks of the Voltaian Basin.

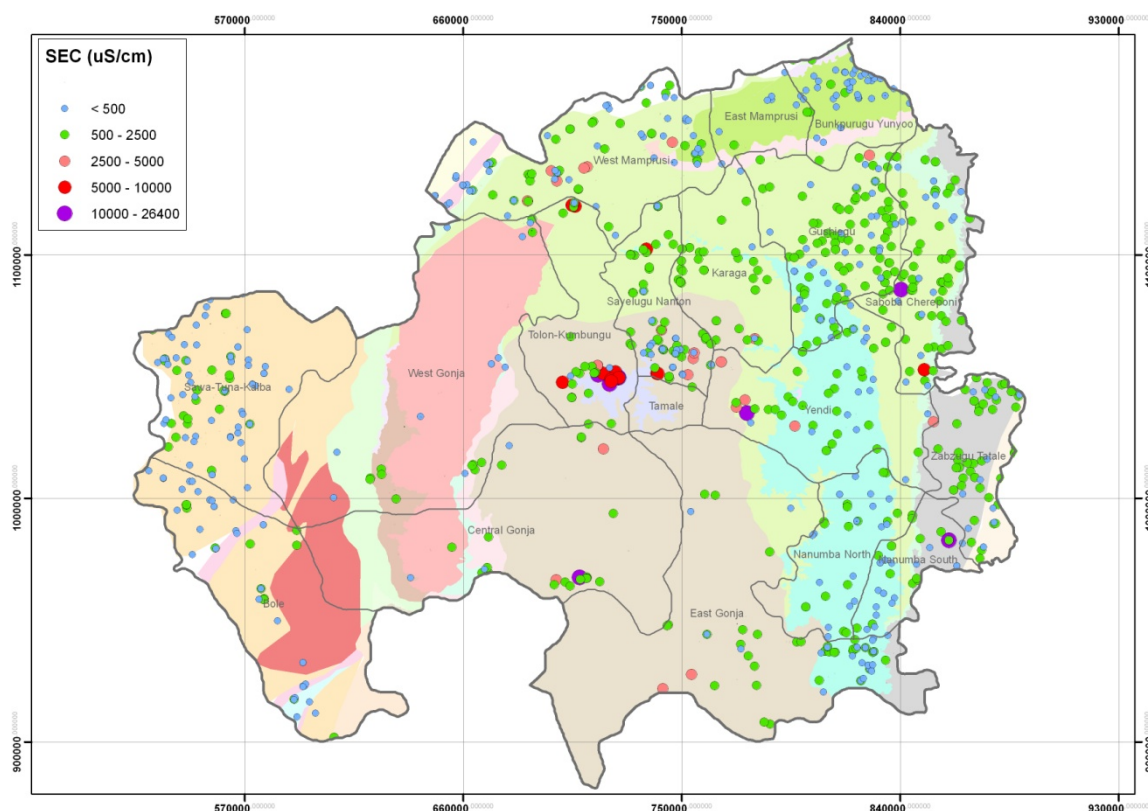


Figure 11 Groundwater conductivity (SEC – specific electrical conductivity) across the Northern Region

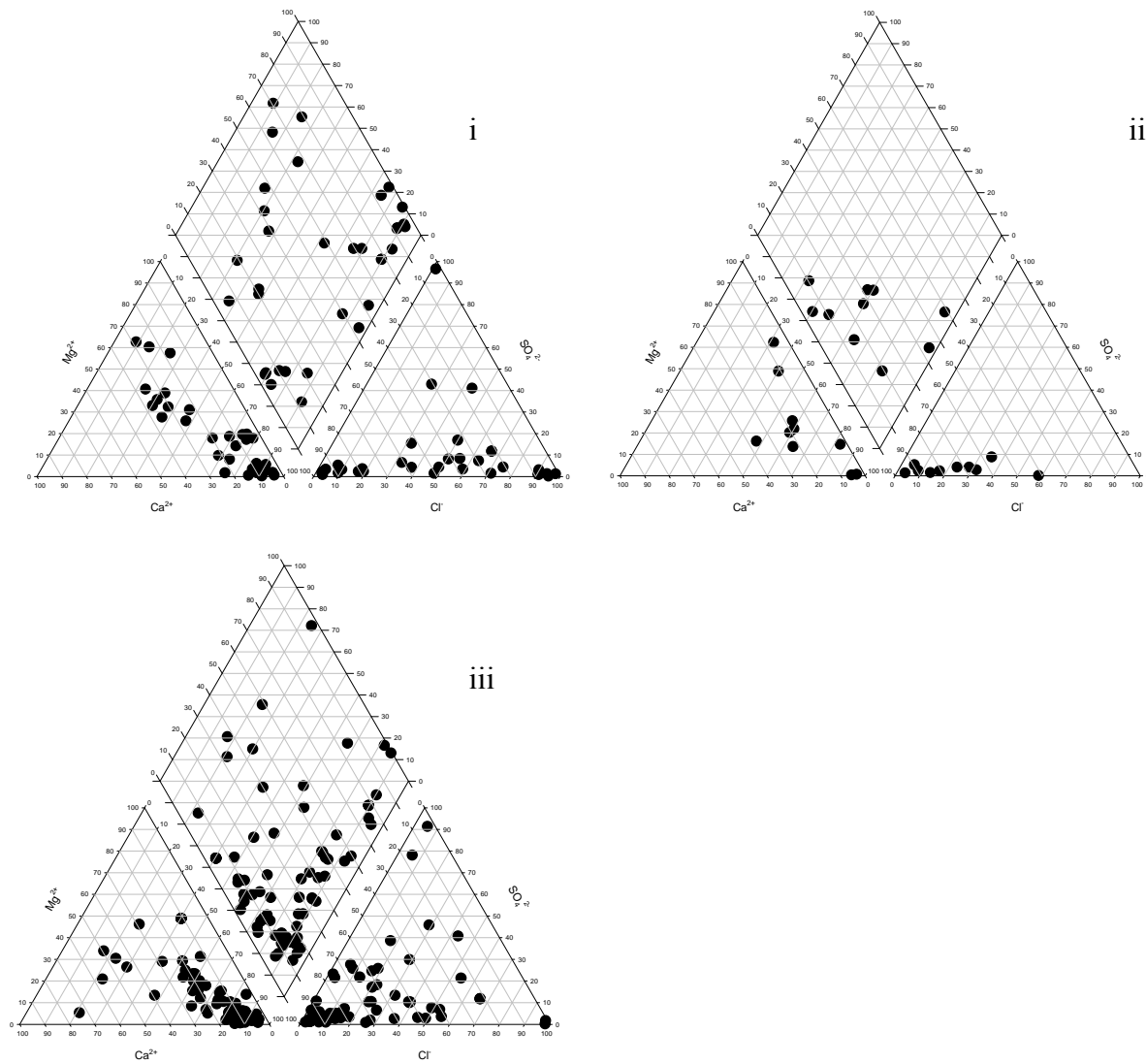


Figure 12 Piper plots for (i) the Obosum Group, (ii) the Bunya Sandstone Member and (iii) the Bimbila Formation

Nitrate is the most commonly recorded pollutant of groundwater in the region, although recorded instances of high nitrate concentrations are still rare and isolated (Figure 14). They are thought by most practitioners to be linked to the increasing use of artificial fertiliser by farmers, although there may also be a link between increased nitrate concentrations and local contamination by human and/or animal waste.

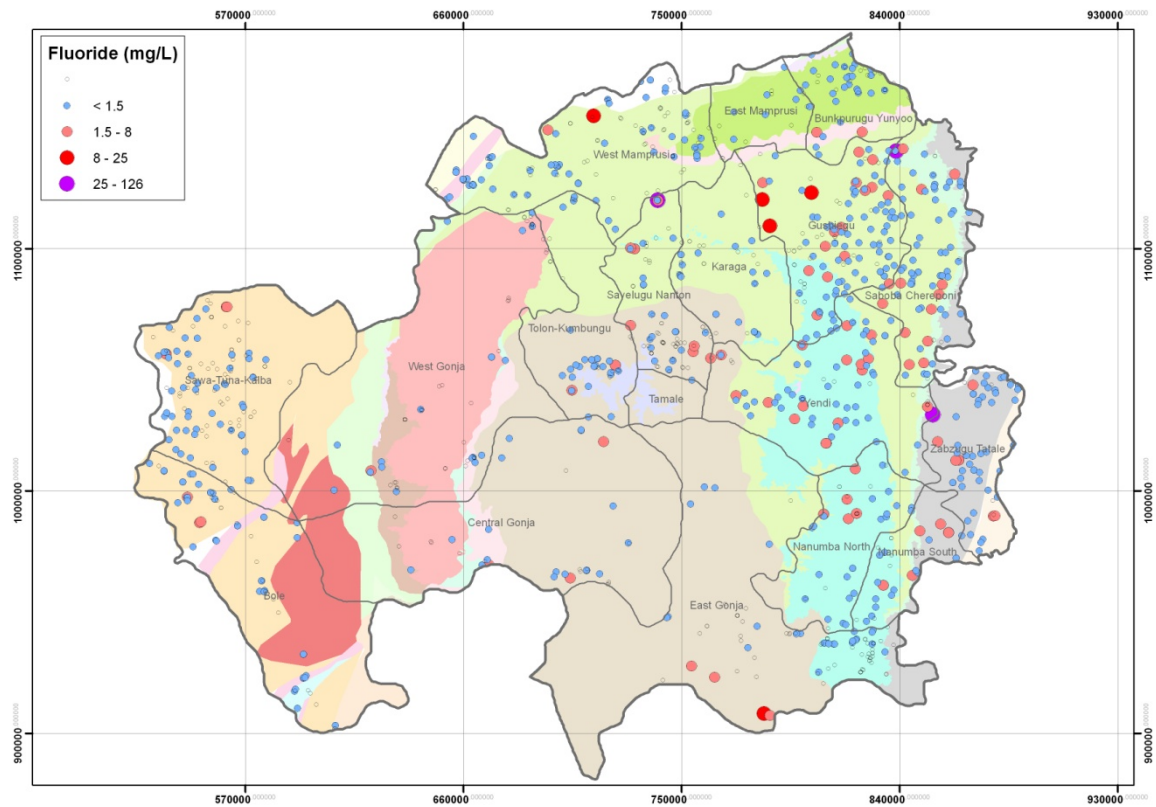


Figure 13 Fluoride concentrations in groundwater across the Northern Region

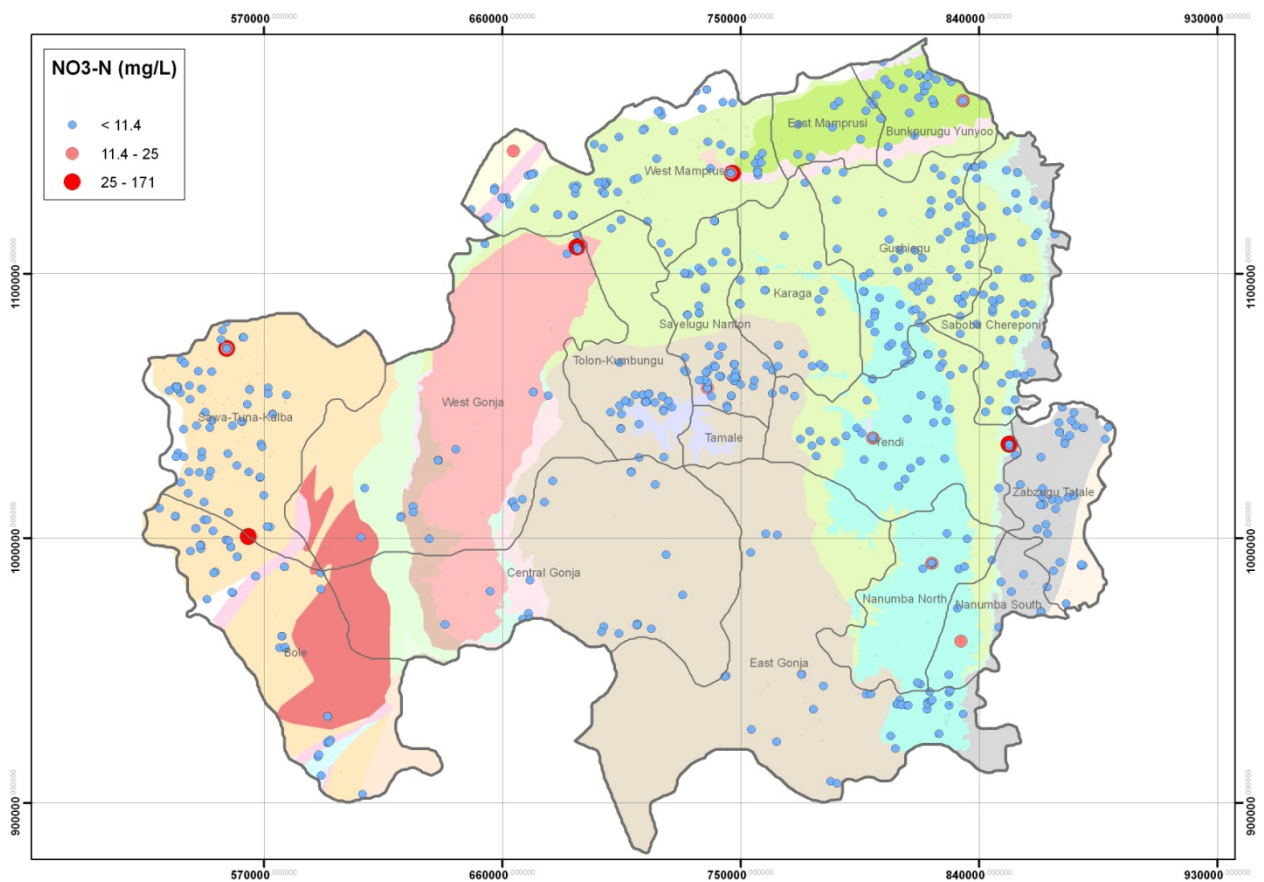


Figure 14 Nitrate concentrations in groundwater across the Northern Region

5 A groundwater development potential map for the Northern Region

Using the hydrogeological understanding described in Section 4, a map of the different geological units in the Northern Region, together with an associated attribute table indicating groundwater development potential in the geological units, and recommendations for appropriate development techniques, has been produced (Figure 15; Table 4). Each geological unit was categorised by groundwater potential: Low, Moderate or High potential. Although these are qualitative categories, they are based on the recorded yields of boreholes drilled into the geological units, and correspond in general to:

Low groundwater development potential: <15 l/min

Moderate groundwater development potential: 15-80 l/min

High groundwater development potential: >80 l/min

If recorded borehole yields in a geological unit vary significantly, the groundwater potential is described as two or more categories, with the first named category reflecting the most common category. For example, Moderate to High groundwater potential describes a geological unit which generally has Moderate potential but sometimes has High potential; while High to Moderate groundwater potential describes a unit which generally has High potential but sometimes has Moderate potential. One of the geological units – the Chereponi Sandstone Member – shows very variable yields, and is categorised as having Low to High groundwater potential.

The map and associated table were created initially based on the data collated by BGS at the start of this project (Section 2), and were refined by discussions with and feedback from Northern Region groundwater practitioners during the workshop and training (Section 3; Appendix 1), and by observations made by BGS during the two visits to the Northern Region as part of this project.

The map is designed to directly aid groundwater development practitioners in selecting locations for groundwater development. Additionally it could inform donor and other funding organisations in setting realistic goals and standards for future project success in what is a very difficult region to develop groundwater resources.

The map focuses on the seven main geological formations that underlie the areas in which the IWASH programme has been operating: that is, across the central and eastern parts of the Northern Region. Most of the water boreholes in the region have been drilled into these formations, and so most hydrogeological information is available for them. Other minor formations occur in this area, but they cover a relatively small area, and little hydrogeological information is available for them.

The map highlights known variations in aquifer productivity (i.e. potential groundwater yield) and relevant groundwater development issues in different geological units.

It also has an overlay highlighting the areas where airborne geophysical data (electromagnetic/EM coverage) indicate there are more likely to be sandstones at shallow depth (less than 100m). As fractures in sandstones are thought to be a critical groundwater target in the Northern Region, a better knowledge of where sandstones are likely to be may significantly improve borehole siting success. Note, however, that there has as yet been no ground truthing of this information, and so at present it must remain only a potential indicator of the presence of sandstone.

Another potential use of the airborne geophysical data would be to add, as another overlay on the groundwater potential map, the regionally extensive lineations identified from the reprocessed magnetic data during the current project. These have been tentatively identified as fracture zones. However, extracting a map of these lineations from the magnetic data is a lengthy task that is outside the scope of the current project. As well, as yet there has been no ground truthing or hydrogeological investigation of these features, so it is not yet known whether they do have hydrogeological significance. It may well however be an important subject for future research.

The geological linework of the map, with hydrogeological attributes in an associated table, is available as a GIS shapefile, with a separate GIS shapefile of the overlay of dry and successful boreholes. An image file and a pdf file version of the map, with the borehole overlay, are also available. The pdf version is designed to be printed with the attribute table on the reverse and suitable for use in the field. All these digital files are available in the CD-ROM attached to this report.

Figure 15 Groundwater development potential map for the Northern Region

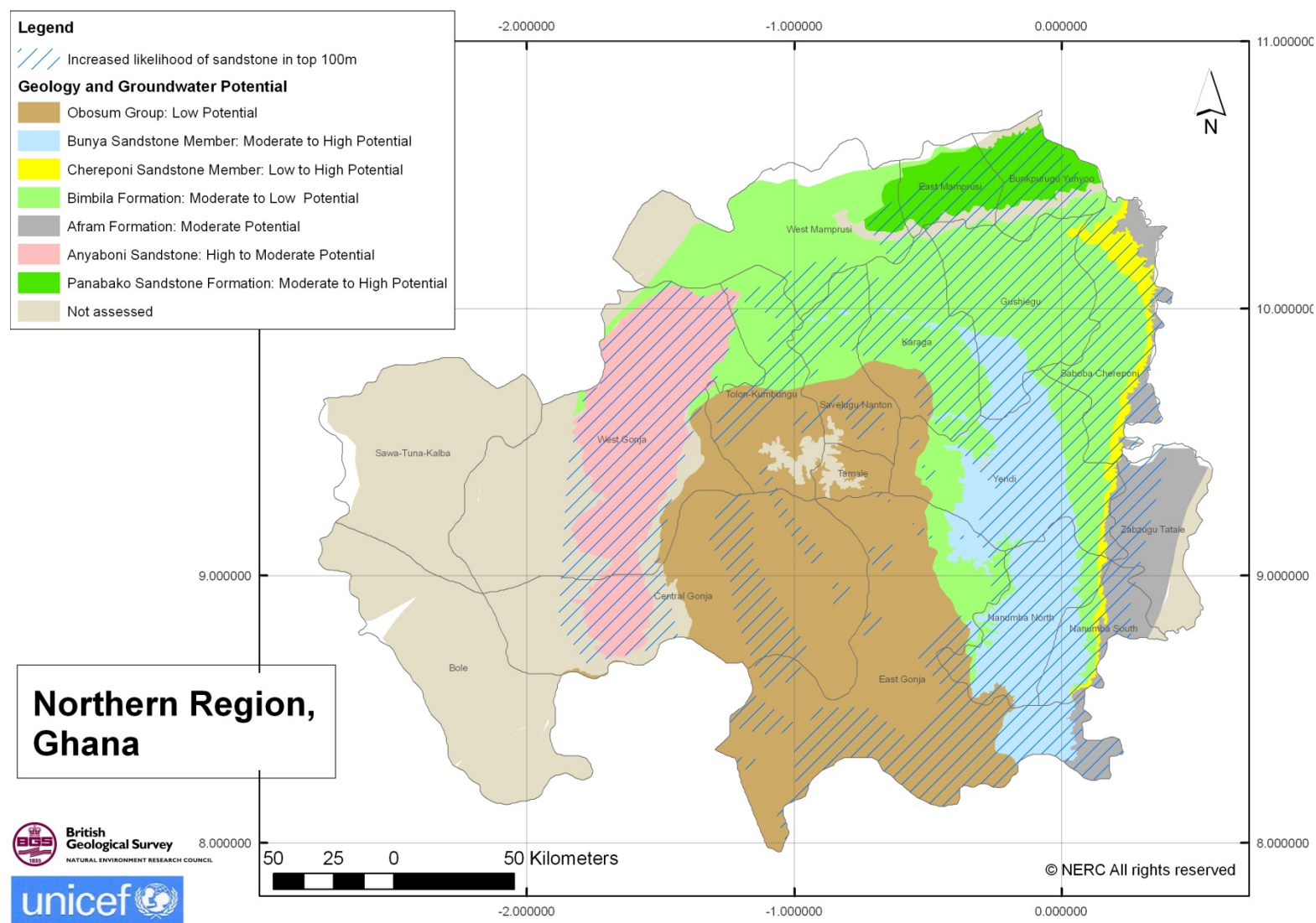


Table 4 Attribute table showing groundwater development potential in the main geological units of the Voltaian Basin rocks in the Northern Region

Geological Unit	Lithology	Weathered Zone	Main Groundwater Targets	Typical Groundwater Potential ¹	Typical success rate	Typical depths of successful boreholes	Natural groundwater quality	Recharge Potential
Obosum Group (un-differentiated)	Dominantly mudstones and siltstones with subordinate sandstones	Highly weathered to <5m. Clay layer below laterite is thinner below low lying areas than higher ground. Slightly weathered to 30-60m	<ul style="list-style-type: none"> Weathered fracture zones, especially in siltstones, to 30-60m Thin fracture zones in rare sandstones, to 80-100m 	Low	20-25%	30-80m	Typically Na/K-HCO ₃ to Na/K-Cl type. SEC generally moderate & occasionally very high. Variable F from low to high	In mudstones: little infiltration through clay; low acceptance potential. In rare sandstones, higher infiltration and acceptance potential
Bunya Sandstone Member (Oti-Pendjari Group)	Dominantly grey-green, medium grained feldspathic sandstones	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	<ul style="list-style-type: none"> Thin fracture zones; frequency decreases with depth 	Moderate to High	40-60%	30-70m	Typically Na/K-HCO ₃ type. SEC generally low, occasionally moderate. Variable F from low to high	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential
Chereponi Sandstone Member (Oti-Pendjari Group)	Alternating grey-green, medium grained sandstones and siltstones	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	<ul style="list-style-type: none"> Thin fracture zones, especially in sandstones; frequency decreases with depth 	Low to High	40-50%	20-70m	Generally low, occasionally high SEC. Generally low F	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential
Bimbila Formation	Dominantly grey to green, weakly micaceous and siltstones with thin beds of green-grey sandstones	Highly weathered <5m. Clay layer below laterite is thinner below low lying areas than higher ground. Slightly weathered to 30m, occasionally 60m	<ul style="list-style-type: none"> Thin zones at lithological boundaries from green-grey mudstone to chocolate - brown siltstone) Thin weathered fracture zones, especially in siltstones and rare sandstones. Frequency decreases with depth but significant inflows to 90m and occasional inflows below 100m 	Moderate to Low	40-55%	20-80m	Typically Na/K-HCO ₃ or no dominant type. SEC occasionally very high. F generally above WHO standard & occasionally very high	In mudstones: little infiltration through clay; low acceptance potential. In sandstones, higher infiltration and acceptance potential
Afram Formation	Dominantly grey-green micaceous mudstones and siltstones, with rare limestone and sandstone	<5 m. Clay layer below laterite is thinner below low lying areas than higher ground. Slightly weathered to 30m, occasionally 60m	<ul style="list-style-type: none"> Weathered fracture zones, especially in siltstones and rare sandstones, to 30-60m 	Moderate	40-55%	30-70m	SEC generally moderate. F generally high and occasionally very high.	Little infiltration through clay; low acceptance potential.
Anyaboni Sandstone (Kwahu Group)	Medium to fine grained, grey to red feldspathic sandstone	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	<ul style="list-style-type: none"> Thin fracture zones. Frequency decreases with depth but can find significant inflows to 100m and occasional inflows below 100m 	High to Moderate	>70%	40-60m	Generally low SEC and low F	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential
Panaboko Sandstone Formation (Kwahu Group)	Grey, weathering to yellow & pink, medium grained quartzose sandstone	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	<ul style="list-style-type: none"> Weathered fracture zones to 20-30m Thin to 0.5m thick fracture zones below this. Frequency decreases with depth but occasional inflows below 100m 	Moderate to High	40-60%	30-70m	Generally low SEC and low F	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential

Box 1 Associated notes for map and attribute table

These notes are designed to accompany the groundwater potential map and attribute table, to explain some of the terms given in the map and table, and to support groundwater development practitioners when planning and carrying out borehole siting work.

¹**Groundwater potential** is an overall function of groundwater storage, yield and residence time (length of time groundwater remains in the geological unit, i.e. the rate of throughflow).

The qualitative values given in the table correspond in general terms to:

Low: <15 l/min

Moderate: 15-80 l/min

High: >80 l/min

² **Success rate** refers to the percentage of boreholes yielding more than 10 l/min, the nominal minimum yield for a hand pump.

³SEC – specific electrical conductivity of water

Geophysical techniques: applicable to all the geological formations, but careful field procedure is needed and results must be interpreted in relation to the known geology and hydrogeology, and the scientific basis and limitations of each technique. This needs a good knowledge of typical resistivity and conductivity values for key geological units in their weathered and unweathered states; and a good understanding of potential groundwater targets. Ideally, more than one method should be used and the results compared to identify features that coincide in each result, to increase confidence.

EM34. Rapidly covers ground; non-invasive. 20m coil penetrates to ~15-30m, and indicates thickness of weathered zone. 40m coil penetrates to ~30-60m, and can indicate base of thick weathered zones, bedrock lithology, and the presence of large vertical fracture zones below the weathered zone. When interpreting, look for the base of large anomalies in the 40m coil (deep) results.

2D resistivity profiling: Rapidly covers ground. Indicates bedrock lithology and thickness of weathered zone to a maximum of ~60m in centre of profile. Invasive; can be difficult to get current into dry ground, and depth of penetration decreases rapidly away from centre of profile. Data noise is common in dry ground and can hide deep geological features; when interpreting, look for large features which are more likely to be real.

VES: Can confirm thickness of weathered zone and bedrock lithology, e.g. over features identified by EM34 or 2D profiling. Invasive; can be difficult to get current into dry ground. The Schlumberger array is simpler to carry out and interpret than the Dipole-Dipole array. Whichever array is used, continuing to wider electrode spacings (e.g. AB/2 >=100m) gives deeper penetration; and the correct model must be used to process the data. Interpret the resulting curve in relation to the most appropriate conceptual model for the known geology at the site.

6 Summary and assessment of current geophysical borehole siting and development practices observed

6.1 GEOPHYSICAL BOREHOLE SITING

6.1.1 Summary

Observations of current geophysical practice have indicated that there is a lack of understanding of the physical meaning behind geophysical siting techniques among some groundwater practitioners. In consequence, some geophysical techniques are being carried out wrongly and others are not being used to their full potential. Even where techniques are carried out correctly, there is often poor interpretation of the geophysical data, because of the lack of understanding of their physical meaning.

In a broader sense this indicates that effective technical scrutiny of practitioner procedures by internal and external agencies has been neglected. It also suggests that the level of adequate geophysical training of geophysical practitioners in the Northern Region is limited. It is possible that many of the practitioners using geophysical techniques have been given superficial training in how to carry out the techniques, but not taught the full detail of the science behind them. The geophysical community may have become isolated and may need to progress the training of younger scientists on appropriate programmes of study outside the Northern Region, or even outside Ghana.

6.1.2 Overview

Three main geophysical methods are currently used in the Northern Region by consultants working within the IWASH programme:

1. Resistivity: a procedure using dipole-dipole electrode arrays that is a combination of a Vertical Electrical Sounding (VES) and depth profiling (Section 6.1.3.2)
2. EM34: profiling (Section 6.1.3.4)
3. Resistivity: 2D profiling (Section 6.1.4)

A fourth method, resistivity VES using a Schlumberger array, was used by consultants working on the HAP project (CSIR 2009), but has not otherwise been widely used in the Northern Region (Section 6.1.3.3).

Little or no large scale geophysical surveying is done as part of groundwater development in the Northern Region. Instead, each potential drilling site is largely treated in isolation. The procedure for selecting locations for geophysical surveys is variable, but in many cases seems to involve only limited use of geological maps, identification of regional lineations that may be water-bearing features, or other pre-survey desk studies. It seems to be largely based on surface observations and community information collected during a pre-survey site visit.

Overall, there is little consensus on what groundwater targets the geophysical techniques are trying to identify, and at what depths these are found. It is particularly critical that despite the large amount of site-specific geophysical information that has been gathered during groundwater work, there has been no development of potentially significant summary knowledge, such as linking typical geophysical signatures to geological formation or lithology. This isolated use of site-specific information represents a failure to develop a background understanding that is critical to improving successful borehole siting. Even the small amount of overview interpretation of existing geophysical information undertaken during this BGS project proved very revealing.

Although it is generally believed among groundwater practitioners that the main groundwater targets in the Northern Region are fractures below the weathered zone, it is not widely recognised that most of the geophysical techniques used cannot identify such fractures. During the training, BGS stressed that even if carried out and analysed correctly, resistivity methods **cannot** reveal the presence of the kinds of narrow (sub)-vertical fractures at depth below the weathered zone. Only EM34, if carried out and interpreted correctly, can indicate the presence of such fractures.

There is little understanding of the true depth of penetration of the geophysical methods used, and how this relates to the typical depths of groundwater targets. The main geophysical procedures currently carried out persistently **only assess the shallow zone from 0 to approximately 30m depth**. Across most of the Northern Region, groundwater inflows due to weathering and/or fracturing are concentrated in the zone between approximately 30 and 70m (Sections 4 and 5; CSIR 2009). This means that the **majority of the geophysical assessments carried out during the HAP and IWASH programmes provided no primary guidance in relation to effective borehole siting**.

Current procedures used and an assessment of the three geophysical methods used in the Northern Region are discussed in more detail below.

6.1.3 Resistivity: Vertical Electrical Sounding (VES) and variants

The main geophysical procedure currently used to help site boreholes by most consultants is a version of a dipole-dipole array (see Section 6.1.3.2).

The standard procedure for most consultants is to select two or three sites for resistivity soundings at each potential drilling location. As described above, the typical procedure for selecting sites for resistivity soundings is not thought to include a detailed desk study with reference to wider geological and/or hydrogeological features.

6.1.3.1 GENERAL FIELD PROCEDURE AND DATA COLLECTION ISSUES

The ABEM terrameter system, which is the most commonly used equipment at present in the Northern Region, is largely very reliable and effective, but certain issues relating to its use in the Northern Region are worthy of note:

- The combined electrical connections within the system make it difficult to get electrical current into the ground, particularly when the ground is dry. There are a number of electrical connections within the system, and at each connection between the control box and the ground it is possible to lose current, so that the ultimate current entering the ground can be very low.
- The operators apparently do not always connect the wires carefully to the control box, which can make connection problems worse. The ends of the wires need to be clear and clean. The wire connection knobs on the control box should be unscrewed, the wires passed through the correct holes, and the screws tightened, to provide the best connection.
- Some of the wires used are old and have been broken and re-attached, with bare wire left showing at mended junctions. If these sections of bare wire touch the ground during the survey, as happened when participants were demonstrating their standard procedure in the field, then electrical coupling can occur, with current entering the ground at uncontrolled locations, which can cause data errors.

6.1.3.2 DIPOLE-DIPOLE

Based on examination of consultant data and reports and on observations of apparently standard procedures during the training course, the BGS concluded that a significant technical error seems to be present in many of the resistivity surveys carried out within the IWASH programme. This error is related both to the design of the field survey and to the subsequent analysis of field data.

An apparently ‘standard’ field procedure associated with a ‘standard’ data acquisition sheet is routinely used by all the IWASH consultants, and is called dipole-dipole. In geophysics, dipole-dipole resistivity is a valid technique that can be used correctly in several ways depending on the layout of the electrodes (sensors) used to obtain data in the field. One way is to obtain a Vertical Electrical Sounding (VES) which gives information on the change in geology with depth at a single location. A second way, called profiling, is to collect data related to a single depth range at a number of individual locations along a profile.

However, the procedure used by many consultants in the Northern Region appears, based on evidence from the ‘standard’ data acquisition sheets and observed field procedure during the training course, to be **a combination of VES and profiling**. Despite considerable experience in geophysical techniques around the world, the **BGS team are not aware of this version of the dipole-dipole method being used currently anywhere else**, although we know examples of it being used prior to the 1990s before computer software analysis methods for geophysics were developed.

The data collected during the combination dipole-dipole procedure in the IWASH programme seem to be interpreted using a simple plot of field data, with no modelling, as if the data related to a single vertical sounding at a fixed location – which is not the case given the observed field procedure. In reality, the collected data relate to a combination of a number of vertical soundings at different locations along a profile. The resulting data plots observed, as provided by the IWASH consultants, are distinct in that many have a saw-tooth appearance. Under standard circumstances (outside the Northern Region), these results would be regarded by geophysicists as **non-valid**, because they are unphysical (i.e., unrelated to the actual physical structure of the ground) geophysical responses.

The IWASH consultant reports, as well as discussions with participants during the workshop and training, indicate that the information from these plots is used to directly identify fracture zones at particular depths. **This is not a valid physical interpretation of these data**. Even if carried out, modelled and interpreted correctly, VES resistivity procedures cannot identify fractures.

The BGS team **are not aware of any suitable computer/software model for the correct analysis of field data from the combined VES/profiling dipole-dipole procedure** which appears to be standard for many of the consultants. A model for analysing dipole-dipole VES data is available in a free software package for interpreting geophysical data, IPI2win, **but this is not designed to analyse the combined VES/profiling procedure** being used in the Northern Region.

During a series of frank discussions in the workshop and training, it was noted that the use of this version (a combined VES/profiling procedure) of the dipole-dipole technique in Ghana can be traced back over 30 years. Since the procedure has become embedded in the Northern Region (and possibly elsewhere in Ghana), the BGS proposition – that the way it is carried out and interpreted is flawed – is understandably difficult for practitioners to accept, and it is recognised that some of the participants in the training course did not accept the BGS conclusions on the use of this version of the dipole-dipole procedure.

6.1.3.3 SCHLUMBERGER VES

Resistivity VES using a Schlumberger array was used by the HAP consultants. From the available reports and data, it appeared to be used and interpreted rigorously. For example, field values that appeared unreasonable were rejected and the sounding repeated at the same spot several times as deemed necessary to achieve conformity. The measured VES data were analyzed using 'RESIST' computer software (CSIR 2009).

Interpretation of the VES results was made in relation to observed resistivity values from known geological formations elsewhere, and the observed hydrogeology of these formations. By doing this, the HAP project began to develop a systematic body of knowledge related to the hydrogeological meaning behind geophysical data. For example, in areas underlain by granite or pure sandstone, the selection of drilling sites was based on the modelled thickness of overburden (with low to moderate formation resistivity) and the depth to bedrock, as thick weathered zones had been observed to yield appreciable quantities of water, and the transition zone to unweathered bedrock had also been observed to be a groundwater target. Geophysical criteria developed for identifying sandstone and granite areas are illustrated in Table 4. By contrast, as previous studies had shown that low bedrock resistivity occurs in areas of mudstone and siltstone, and was associated with dry or marginal boreholes, areas underlain by medium to high bedrock resistivity values were preferred as target drilling points, while bedrock resistivity values lower than 50 Ohm-m were avoided (CSIR 2009).

However, the limited number of boreholes drilled during the HAP project, coupled with the fact that most of the HAP monitoring boreholes were sited on granite or sandstone, with only three boreholes on mudstone and siltstone, meant that no understanding began to be built up to help interpret geophysical results from mudstone and siltstone areas. This kind of information will be critical in helping to ensure future borehole success.

Parameters	VES Selection Criteria	Groundwater potential		
		High	Medium	Low
Thickness of regolith, h_r (m)	≥ 15	$h_r \geq 15$	$h_r \geq 10$	$h_r \leq 5$
Regolith resistivity, ρ_r (Ohm-m)	≥ 20	$20 \leq \rho_r \leq 200$	$200 \leq \rho_r \leq 600$	$\rho_r \geq 600$
Bedrock resistivity ρ_b (Ohm-m)	≤ 600	$P_b \leq 600$	$600 \leq \rho_r \leq 1,000$	$\rho_b \geq 1,000$

Table 5 Criteria for ranking VES points for drilling on sandstone and granite (from CSIR 2009)

The Schlumberger method does not appear to be used by any of the consultants working in the Northern Region who attended the training course. During the training course, the HAP VES work, which did use the Schlumberger method, was only discussed briefly as an example of good practice.

6.1.3.4 EM34

One or two consultants also use EM34 equipment to run one or more profiles across a potential drilling location. The results of the EM34 survey(s) are used to identify sub-surface features which are investigated in more detail by VES.

The standard survey run is at 20m coil separation only. The wider standard (in international usage) coil separation of 40m is not used. The results appear to be interpreted mainly in terms of the potential presence of vertical to sub-vertical fracture zones.

Field procedures for running the surveys at 20m coil separation appear to be generally good, although there is potential for measurement errors relating to external sources of noise (e.g. electrical currents from other geophysical surveys being run at the same time), or to the coils become non-planar during measurements.

It is not widely recognised that at 20m coil separation, an EM34 survey can only give a maximum of 30m penetration into the ground, and that the bulk of the response, even from the horizontal coil response, is from above 15 to 20m. This is above the typical zone of groundwater inflow believed to occur across the Northern Region. It is also probably within the most highly weathered zone, which means that the response of any underlying features may be masked by the response of the weathered zone – so that, for example, the true response of the unweathered bedrock, and therefore potentially important lithological information, are missed; or (sub)-vertical fracture zones in the underlying less-weathered bedrock are missed.

Using a coil separation of 40m can give a maximum depth of penetration of 60m, with the bulk of the response from the horizontal coil down to 30 to 40m. This is often below the most highly weathered zone and so is more likely to be able to detect potential (sub)-vertical fracture zones that may be water-bearing, as well as the true response of the unweathered bedrock, making it harder to assess the lithology at depth.

Additionally, running the 40m survey over the same profile as the 20m survey provides a useful check on the 20m data, which can confirm the presence of important features, or highlight any measurement errors in the 20m data.

6.1.4 2D Resistivity Profiling

As well as VES surveys, 2D resistivity profiling using Lund equipment is carried out on some sites by or for WRI and international consultants, for example on the HAP and NORST projects. This system can achieve 60m penetration, although the maximum depth of penetration is only gained in the centre of the profile, and reduces significantly towards each end. The equipment may be considered relatively expensive but the cost is not excessive compared with other equivalent field geophysical equipment. The Lund system used is based on the ABEM terrameter, with the addition of an electrode switching system and multiple (e.g. >48) electrodes. As an invasive procedure it suffers from the same problem as with all resistivity methods in getting enough current into dry ground to make good measurements.

The data collection and modelling process is computerised and produces electronic cross sections. The model needs the correct input of field parameters, for example the electrode spacing. Because of problems with generating enough current, there can be high levels of noise in the cross sections, which can mask real geological features.

6.2 BOREHOLE DRILLING AND TESTING PROCEDURES

6.2.1 Drilling, data collection, borehole construction and borehole development

General observations on the drilling and borehole development process are:

- The experience of many drilling supervisors involved in groundwater development programmes in the Northern Region is inadequate for the difficult hydrogeological environment
- Drilling supervisors often lack control over the drilling teams
- Current geological sample collection is not done rigorously enough, and in particular, samples are not collected often enough

- Drilling practice is designed to achieve rapid penetration and maximise the speed of drilling, not to optimise the collection of geological samples
- Dust generated during drilling is a health hazard for operators and drill crew
- Current drilling practice could result in low yielding holes being wrongly identified as dry, and abandoned
- Good borehole development to optimise borehole yields is not widely practiced

6.2.1.1 DRILLING

All recent borehole development programmes in the Northern Region have used similar drilling systems: air-flush rotary using drag or rock-roller bits through the upper weathered zone, and a down the hole hammer bit through the underlying unweathered rock. Typical borehole diameters vary according to programme: IWASH boreholes are generally drilled at 200 mm through the weathered zone and 165 mm through unweathered rock. There is a depth limit of 100m for production boreholes, and 60m for test boreholes. In the HAP monitoring borehole programme, boreholes were drilled at 250 to 300 mm through the upper part of the weathered zone, and 180 to 200 mm from here to the base of the borehole. The depths of boreholes drilled in the HAP programme were between 80 and 166m.

6.2.1.2 COLLECTING DATA DURING DRILLING

Collecting data during drilling is difficult given the geological environment of the Northern Region. Changes in lithology with depth are subtle and often difficult to identify, and therefore if lithological logging of chip samples from boreholes is not done carefully and with great detail, useful geological information is lost. It is almost impossible to identify the presence of potentially water-bearing fractures from the chip samples that are the only geological data source available.

During the HAP programme, drill cuttings (i.e. geological samples) were collected and logged at 1m intervals and at any other lithological changes during drilling. However, based on the lithological logs provided by most of the IWASH consultants – for both successful and unsuccessful boreholes – it appears that this level of detail in sample collection and logging is not matched. The IWASH lithological logs typically do not contain sufficient detail to allow for some of these subtle changes to be identified. For example, there is not always a description of rock colour; and the logs often summarise lithologies over large depth intervals even when different lithologies occur – e.g. a 12m interval described in a log as ‘siltstone, shale intercalation’, or a 22m interval described as ‘reddish sandstone with shales’. As it is recognised that lithological boundaries such as between siltstones, shales and sandstones can be useful groundwater targets, this is an important loss of information, and mitigates against lesson learning.

The difficulty in accurately identifying groundwater target indicators such as lithological changes in a borehole – even identifying sandstone layers within a dominantly mudstone and/or siltstone sequence – is illustrated by comparing the lithological logs and the interpretation of the downhole geophysical logs for the HAP monitoring boreholes. There are often large discrepancies between the two logs. This appears to have led to the incorrect emplacement of borehole casing and screen in some of the HAP boreholes, with casing emplaced against zones where groundwater inflows were identified, which is highly likely to have reduced groundwater flow into the borehole.

6.2.1.3 BOREHOLE CONSTRUCTION

Most of the boreholes in the Northern Region appear to be constructed to a similar design. IWASH boreholes are constructed to a standard Community Water and Sanitation Agency (CWSA) design, which requires successful boreholes to be lined throughout with 125mm

diameter PVC casing and screen. A formation stabiliser of gravel is typically used to infill the annulus around the screen and casing. The HAP monitoring boreholes were also constructed with PVC casing and screen, with a nominal inner diameter of 126mm, and screen size varied from 0.75 to 2.0mm depending on the grain size of the aquifer material. A formation stabiliser is used throughout the screened section, and the top of the borehole is infilled with cement slurry to prevent direct surface water infiltration.

Screen is meant to be emplaced against the depths where groundwater inflows have been identified, but as has been observed, in a number of cases the location of screened intervals shows little relation to recorded water strike depths, or to any other indicators of groundwater flow zones. If screen is not placed adjacent to water inflow zones, any inflow to the borehole will rely on the transmission of groundwater through the annular space around the screen and casing, which is filled with gravel as a formation stabiliser. This will not lead to efficient borehole operation.

6.2.1.4 BOREHOLE REPORTING

The borehole information recorded and provided on borehole logs, particularly from the IWASH programme, is variable. In some cases, borehole coordinates are not provided on the log form, so that the borehole cannot be accurately located from the log. The rest (or static) water level is not always recorded. Hydrogeological information such as estimated airlift yields and potential fracture zones are not always recorded clearly. As discussed above, lithological logs are generally not very detailed.

6.2.1.5 BOREHOLE DEVELOPMENT

In general in the HAP, IWASH and previous programmes such as the EU project, standard borehole development appears to involve air lifting and sometimes air surging for up to three hours, or sooner if surged water runs clear before this time.

6.2.1.6 TEST PUMPING

The standard design for test pumping boreholes designated for installation with a hand pump is a six hour constant rate (constant discharge) test, nominally at a rate between 0.5 and 0.75 of the airlift yield of the borehole as estimated during drilling, followed by measuring recovery of borehole water levels for three hours. The theoretical minimum pumping rate for a hand pump is 13.5 l/min, but in practise a lower rate of 10 l/min is often used as the minimum yield needed to sustain a hand pump.

For apparently higher yielding boreholes intended for installation with a mechanised pump, the typical test design is to carry out a step test with at least three steps to determine the correct discharge rate for the constant rate test, which is carried out for 12 hours, followed by monitoring recovery for a further 24 hours.

6.3 DATA MANAGEMENT

Overall management of data and information relating to groundwater development in the Northern Region has traditionally been relatively poor. There has been little centralised collation of data and information produced during groundwater development activities. Centralising relevant data and information is vital if hydrogeological understanding is to be improved through regional interpretation; and to provide a resource for all groundwater practitioners working in the Northern Region to support their activities. For example, if a consultancy moving into a new area can obtain information about previously drilled boreholes in that area (both dry and successful), and related hydrogeological information, such as geophysical interpretations, they will be more able to carry out informed and effective borehole siting and development.

During Phase 1 of this project, much effort was put into identifying what groundwater related data were available and getting copies of these. Even outputs from the HAP project were not always easy to identify and source, and as has been noted, some outputs – such as a metadatabase of previous hydrogeological studies related to the Northern Region – did not seem to be widely known about, or available, in the region. The situation was even more difficult with information from the IWASH programme, and much of this had to be sourced from the individual consultancies which carried out the work. Within the consultancies, information was available in a variety of formats, but generally as data in spreadsheets and Word documents, sometimes raw data and sometimes interpreted. Some data were only easily available as printed documents, which to be made widely available had to be scanned and saved as pdf files.

There is currently much focus within CWSA in the Northern Region on populating their water supply and sanitation management database: Direct Monitoring and Evaluation System (DIMES). This is a national Microsoft Access database that is maintained at regional level, with a full-time CWSA employee in the Northern Region to support its development maintain it. It has an easy to use front-end to facilitate data entry and data retrieval in the form of summary reports on various parameters, such as the number of functional hand pump-equipped boreholes per district. It is updated periodically throughout the year based on information provided at district level. It can include relatively detailed data on individual boreholes, such as location, depth, lithological and construction logs, aquifer type, and test pumping results – although of course the detail and quality of the information provided to CWSA for entry to the database can vary hugely. The aim is to eventually link the database directly to maps so that information can be examined spatially.

The DIMES database doesn't, however, store information on geophysical surveys, and there appears to be no other central repository for geophysical data and information. This means there is no opportunity to consolidate, effectively interpret on a regional scale, and therefore learn from ongoing groundwater development work, and is a serious limitation on the development of hydrogeological understanding.

7 Recommendations for future groundwater development practices by practitioners

7.1 GENERAL

The groundwater development problems in the Northern Region **will not be solved overnight**, and a long-term plan will be needed to overcome them. The problems are complex and multi-faceted; grounded in real hydrogeological issues related to the prevalence of low productivity and low storage aquifers across the region, and compounded by a history of relative isolation, which has led to a lack of skills in some areas on the part of groundwater development practitioners.

It is important to **look at the bigger picture when siting boreholes**. There appears to be a tendency to treat each borehole to be drilled largely in isolation, without using evidence from other groundwater investigations in nearby areas, or similar hydrogeological areas elsewhere. Geophysical surveys at each new borehole site seem to be interpreted largely independently, without reference to the results of other surveys nearby and/or on similar geology, and without comparing the geophysical results to geological evidence from previously drilled boreholes. There is limited wider understanding to enable practitioners to interpret the hydrogeological meaning behind geophysical data. The HAP project began to develop this kind of systematic body of knowledge, but much more needs to be done to extend and deepen this understanding using geophysical data and (hydro)geological interpretations from ongoing borehole development.

It is also important to develop a **more detailed understanding of the regional and local hydrogeology**: what the detailed lithology of each geological unit is; what the groundwater targets are in each unit and at what depths; what the geophysical signature of each geological unit and groundwater target is. This understanding has to be built up over time and with a regional overview.

7.2 SITING BOREHOLES: RECONNAISSANCE DESK AND FIELD SURVEYS

The importance of reconnaissance – both desk studies and field reconnaissance – cannot be overstated. It is the basis of good siting, allowing practitioners to bring in useful evidence from all relevant sources to help improve their decision making. All available information should be used to increase confidence in identifying possible groundwater targets, whether these are weathered zones, fracture zones or lithological boundaries.

Some of the most useful sources of information during a desk study are:

- Geology and/or groundwater potential maps that indicate likely geological controls on groundwater potential and/or directly show aquifer productivity.
- Satellite, air photo or airborne geophysics data that may indicate the presence of lineations which could be water-bearing.
- Results of previous hydrogeological investigations in the same area, such as yields from existing boreholes; results from geophysical surveys to show typical resistivity and/or conductivity values from the local geology; and borehole geological logs from previous boreholes (even if dry) to help interpret the results of the geophysical surveys.

A field reconnaissance survey should concentrate on as large an area as possible – the whole of the village and surrounding area at least – and should include:

- Getting information on water occurrence from the community.
- Observing soil types and any changes across the area, which may indicate lithological changes in the rock below.
- Looking for direct evidence of the underlying geology, such as in dug pits or wells or in any rock outcrops.
- Looking for potential surface indicators of groundwater, such as particular vegetation types, or anthills. However, it is important to distinguish between indicators of shallow groundwater (which may be perched, possibly enough to supply a small shallow dug well) and of deep groundwater. The key groundwater flow horizons in Northern Region aquifers appear to be between 30 and 70m deep (Section 4). Few surface features can access water at this depth. It is also important to recognise that indicators which might be important on sandstones or basement rocks are often no use at all on mudstones. Sandstones are more freely draining, so that water disappears quickly in the dry season and vegetation can only survive where there are significant amounts of groundwater. However, the lower permeability of mudstones means they can hold onto very small amounts of groundwater for much longer, not letting it drain away; and although there is often not enough water to supply boreholes or even shallow wells, there is enough moisture in the ground for trees and other plants to survive.

7.3 GEOPHYSICS

Geophysics **does not tell us where groundwater is** – it cannot directly locate productive groundwater flow zones (i.e. groundwater targets). When used and analysed correctly, however, it can tell us something about the physical structure of the sub-surface, which can be interpreted in terms of the known types and locations of potential groundwater targets. Any changes in resistivity or conductivity observed must be **modelled and/or interpreted in terms of a broad and deep understanding of the local and regional geology and hydrogeology**. Key to interpreting site geology from geophysical results is a good knowledge of typical geophysical responses (resistivity and/or conductivity values) from similar geological units, in their weathered and unweathered states, across the region. Key to interpreting hydrogeology from geophysical results is a good understanding of what and where the groundwater targets are in each of these geological units.

If geophysics is to be useful in helping to find groundwater, the consultants using geophysics in the Northern Region need to **look deeper** using their current techniques; to **analyse the results correctly**; and to **interpret them in relation to the geology and hydrogeology**. Currently, the way geophysical methods are being used by consultants only provides geological information down to about 30m depth; and in many cases (i.e. because of incorrect analysis of results from the dipole-dipole combined procedure) does not appear to provide correct information at all.

Using the small changes recommended in this report, the current geophysical equipment could provide a relatively robust picture of the geological sequence to about 60m depth – i.e. throughout the main zone of groundwater flow in the region.

To **maximise the amount of information provided**, ideally at least two geophysical methods should be used in tandem. For example, a robust procedure would be to run one or more EM34 profiles along lines identified from the pre-site survey as being of hydrogeological interest (e.g. perpendicular to regional lineations); identify features that are potential groundwater targets from the EM34 results, and follow by running VES over these features.

Careful field procedure is needed to ensure good data are collected:

- Resistivity:
 - Equipment should be properly maintained, in particular the cables.
 - Care should be taken to ensure as good connections as possible are maintained. This is difficult given the number of connections in the system (between the terrameter control box, cables, etc) and particularly so when equipment is old (such as the cables), but is critical in order to optimise good data collection.
- EM34:
 - For each profile, surveys should be run using both 20m and 40m coil separations, to give depths of penetration up to 60m and to provide a check on potential data error
 - Surveyors should be aware of potential sources of data error, e.g. current from other geophysical surveys being run at the same time.
 - Care should be taken to keep the coils co-planar during measurements.
 - Surveyors should be aware of potential measurement errors: if measured values change quickly (e.g. by more than 15 milliSiemens/metre over 1 – 2 stations), the readings should be repeated to check they reflect real features or are errors.

Regarding **VES**, it is the experience of the BGS team, from working in many parts of the world, that **the Schlumberger array is easier and more robust** to carry out in the field and to interpret accurately, and that it is more widely supported by standard geophysical literature and analysis models and software. Resistivity VES using a Schlumberger array was used by the HAP consultants. It is noted that the maximum depth of penetration of a Schlumberger VES is related to the separation distance of the maximum outer (current) electrode (referred to as AB/2). A rule of thumb used by most geophysicists is that the depth of penetration is between one quarter and one half of the AB/2 maximum separation. In less resistive (i.e. more conductive) formations, the potential depth of penetration is less than in more resistive (i.e. less conductive) formations. In other words, at an outer (current) electrode separation of 100m, the results from the VES relate to a depth into the ground of about 25m (e.g. in weathered basement or soft mudstone) to about 50m (e.g. in unweathered basement or dry sandstone).

During the HAP project a set of criteria was also developed for ranking the layered models derived from the VES data from sandstones and granites (Table 4). This is a table providing resistivity responses (values and ranges) for all the lithologies encountered in the HAP project. It provides a good starting point for developing a more detailed dataset of **typical resistivity and conductivity responses for all the geological units** in the Northern Region, both in their unweathered and weathered states. Note that the HAP table does not include criteria for selecting sites for drilling on mudstone and siltstone formations: these were apparently avoided by the HAP project. More data therefore needs to be collected from ongoing groundwater development activities, by collecting good geophysical data and comparing it to the geological logs for boreholes drilled at the surveyed sites. In particular, more detail is needed on the range in geophysical responses related to mudstone and siltstone units, e.g. the Obosum Group and Bimbila Formation, and to specific local lithologies within these (i.e., mudstone, siltstone, sandstone, or various combinations of these).

The BGS team are unaware of a model for interpreting the **combined VES/profiling dipole-dipole technique** that is currently used by many of the consultants. It is our opinion that the current method of interpreting the resultant data (i.e. plotting the field apparent resistivity values and directly relating them to depth) does not give physically meaningful results. During the training, a model for analysing dipole-dipole VES was identified within a free software package for interpreting geophysical data, IPI2win. However, the model behind this software is unlikely

to be applicable to the combined VES/profiling procedure being used by consultants – it is more likely to have been designed for one or other of a separate VES **or** profiling dipole-dipole method. Before it is used, therefore, its applicability should be carefully examined, and if the model behind it is not directly applicable to the current procedure, either this procedure should be amended or another VES array for which a suitable model is available should be used.

The **2D resistivity profiling system** allows for robust field procedure, and covers more ground more quickly than resistivity VES. However, it suffers from the same problems as VES in terms of getting current into dry ground, which can result in data noise. Additionally, the maximum depth of penetration is only gained in the centre of the profile, and reduces significantly towards each end. When interpreting the modelled resistivity cross sections, practitioners need to have a good understanding of the geophysical nature of the groundwater targets which are being searched for, such as typical resistivity values for sandstones which are a key target, and for mudstones which have low groundwater potential. Care should also be taken to ignore data noise and instead to look for large anomalies which are more likely to be real geological features. It is also useful to compare the 2D profile results with an EM34 survey over the same line, and look for features that coincide in both sets of data.

The currently available geophysical equipment in the Northern Region, if it is used appropriately and the results analysed correctly and interpreted within respect to the geology and hydrogeology, can provide results which are directly appropriate to supporting groundwater development in the Northern Region. **The introduction of more ‘state-of-the-art’ geophysical equipment would not, by itself, improve borehole siting success.** Geophysical equipment is only part of a package that also involves adequate procedures and the correct use of modelling and interpretation software, which are bound together with critical scientific and technical understanding. The key issues related to geophysical siting practices identified during this project lie more with the sometimes **inadequate procedures** used and the **lack of appropriate interpretation** of geophysical data – which both appear to be related to a **lack of suitable geophysical training and understanding** – than with inappropriate equipment. There appears to be a low level of scientific and technical understanding, so that geophysical training to modern undergraduate or MSc level would be required to underpin any developments in geophysical technology.

Having said this, EM34 is a particularly useful technique both used alone and in combination with VES, but only a few of the consultancies regularly use it. Wider use of EM34 profiling, if carried out adequately and interpreted correctly, could provide more information to support hydrogeological interpretations and therefore borehole siting decisions.

7.4 DRILLING, CONSTRUCTING, DEVELOPING AND TESTING BOREHOLES

In the Voltaian Basin of the Northern Region, with its poor groundwater development potential, where groundwater targets are difficult to detect with geophysical methods, every borehole drilled can provide potentially useful data to support future groundwater development. Careful data collection and lesson learning are therefore disproportionately important. Recording information is not done just to check on the drillers work: a knowledge of information such as water strike depth, the nature of the samples at that depth, the yield and the groundwater SEC (conductivity) are all highly useful bits of information that contribute to properly designed and successful boreholes. Because boreholes are constructed underground and the groundwater target zones cannot be seen at the surface, the evidence gained from drilling is vital in order to accurately locate and successfully exploit any water yielding zones.

To move towards developing a better understanding of the geology and hydrogeology of the Northern Region, better data should be collected during borehole drilling and testing, and these data need to be centralised, interpreted and used by practitioners to build a more detailed understanding of the types and depths of groundwater targets in the different geological units.

From observations of the drilling procedures used by Church of Christ during the training, which are reported as typical for all the IWASH consultants, the BGS team felt that drilling procedures were generally good, but that by making some small changes to procedures, qualitative improvements to information gathering could be gained.

Optimal data collection during drilling requires rigorous collection and recording enforced by the contract technical specifications. Drilling supervision is best undertaken by a knowledgeable hydrogeologist. The drilling supervisor, as the consultant's representative on site, is responsible for all data collection and recording and for borehole construction.

The key recommendations related to **drilling and data collection** are:

- It is important to have good control of the drilling crew, in order to ensure good quality data – e.g. geological samples and groundwater flow data – are collected. Collecting the best data may mean drilling slightly more slowly, which may require a cultural change among drilling contractors and borehole supervisors.
- Attempts to increase the speed of drill penetration (by excessive hydraulic pull down) can result in excessive dust production and drilling of a non-vertical borehole. In softer (e.g. mudstone, or weathered sandstone or siltstone) formations, it may be better to use air flush rotary with medium-toothed tricone (or rock roller) bits instead of the standard use of down the hole hammer bits. This will produce larger rock chip samples, reduce dust production, and may be a cheaper method of drilling.
- Rock chip samples should be collected every 1m. The supervisor should ensure that the driller tops each 1m and blows the borehole clear before re-starting, in order to clear the hole and allow the collection of an accurately-located depth sample.
- Chip samples should be washed to show their true colour, which is an important indicator of weathering as well as lithology, and therefore of the location of potential groundwater targets.
- Chip samples should be stored on site in a suitable manner, e.g. in sectioned sample boxes to allow easy and effective logging and recording, e.g. by photograph. An alternative to the standard sample boxes is to make 'photo logs' with a digital camera in sectioned, marked halved plastic pipes (Figure 16). These clearly show rock colour changes caused by weathering or lithological changes with depth; they can be stored digitally and are very useful for supporting written lithological logs.
- Particular care should be taken over chip sample description, or logging. Even if the exact identification of the **lithology** or rock type (e.g. sandstone or siltstone) is uncertain, the following parameters should be fully and consistently described for each interval (ideally each 1m) of the borehole: **colour** (defined using standard charts, e.g. Munsell colour charts), other **indications of degree or nature of weathering** (e.g. oxidation), and any **indications of fractures** (e.g. vein quartz/calcite). An example is shown in Figure 16.
- It is possible to preserve small sub-samples of chip samples in suitable containers (e.g. pill bottles), labelled by depth, borehole ID and location. This data could be very useful for future geological and/or hydrogeological investigations.
- Drilling penetration rates should ideally be recorded for each metre drilled, and additionally the depths of any changes in drilling rate or action should be noted and recorded. To accomplish this, each drill rod must be marked off in metre intervals from an established datum, which can be done using drilling grease or similar. The relationship of the depth below surface of the drill bit, the ground surface and/or any other datum used must be known at all times. Penetration is thus the time taken for each metre mark to

pass through the ground surface or other datum. Where metre marks on the drill string are masked by dust generated by drilling, ensure that suitable dust suppression measures are taken by the driller.

- If water is encountered, the depth of the first water strike should be recorded. The drill bit should then be pulled back and the borehole airlifted until the discharge rate stabilises, at which point the yield should be measured accurately and recorded. Drilling should then continue. The depth of any increase or decrease in yield should be recorded, and if any further significant water flows are struck, procedure of airlifting and measuring the borehole yield should be repeated as required.
- It is also useful to record key groundwater chemistry indicators during drilling. Measurements of water SEC (conductivity) and potentially pH and temperature should be taken at the same time as airlift yield measurements are done.
- Drilling deeper than approximately 70m in mudstones and siltstones is not likely to result in significant additional yields. Drilling below this to 100m in sandstones may produce significant additional yields, but drilling below 100m even in sandstones is likely to only produce small, occasional additional inflows. There is little evidence that drilling deeper than approximately 120m in sandstones is likely to produce significant additional yields.
- Apparently dry boreholes should be allowed to remain open overnight to ensure that any water inflows that may need to break through smeared borehole sides are recognised

Key recommendations related to **borehole construction** are:

- Borehole screen needs to be placed accurately to coincide with all potential groundwater flow zones. It is not efficient to place screen approximately, and hope that vertical flow will be induced in the formation stabilised. This may mean screening the whole length of a borehole, particularly if it intercepts wholly or mostly sandstone
- In mechanised boreholes it is useful to ensure that the completed borehole diameter is wide enough to allow for water level monitoring

Key recommendations related to **borehole development** are:

- Continue airlift development until water is fully clear
- For mechanised boreholes, also use pumps for development, before test pumping is carried out. If the borehole water level has risen following test pumping, the whole cycle of borehole development and testing should be repeated to ensure optimum development and borehole assessment

The key recommendations related to borehole **test pumping** are:

- Test pumping must only be done after proper borehole development. If there is any indication of rest water levels rising after test pumping, the whole cycle of development and testing should be repeated.
- Data gathered during the test pumping of IWASH boreholes should be analysed to provide more information on aquifer properties, such as transmissivity and specific capacity values for different geological formations.

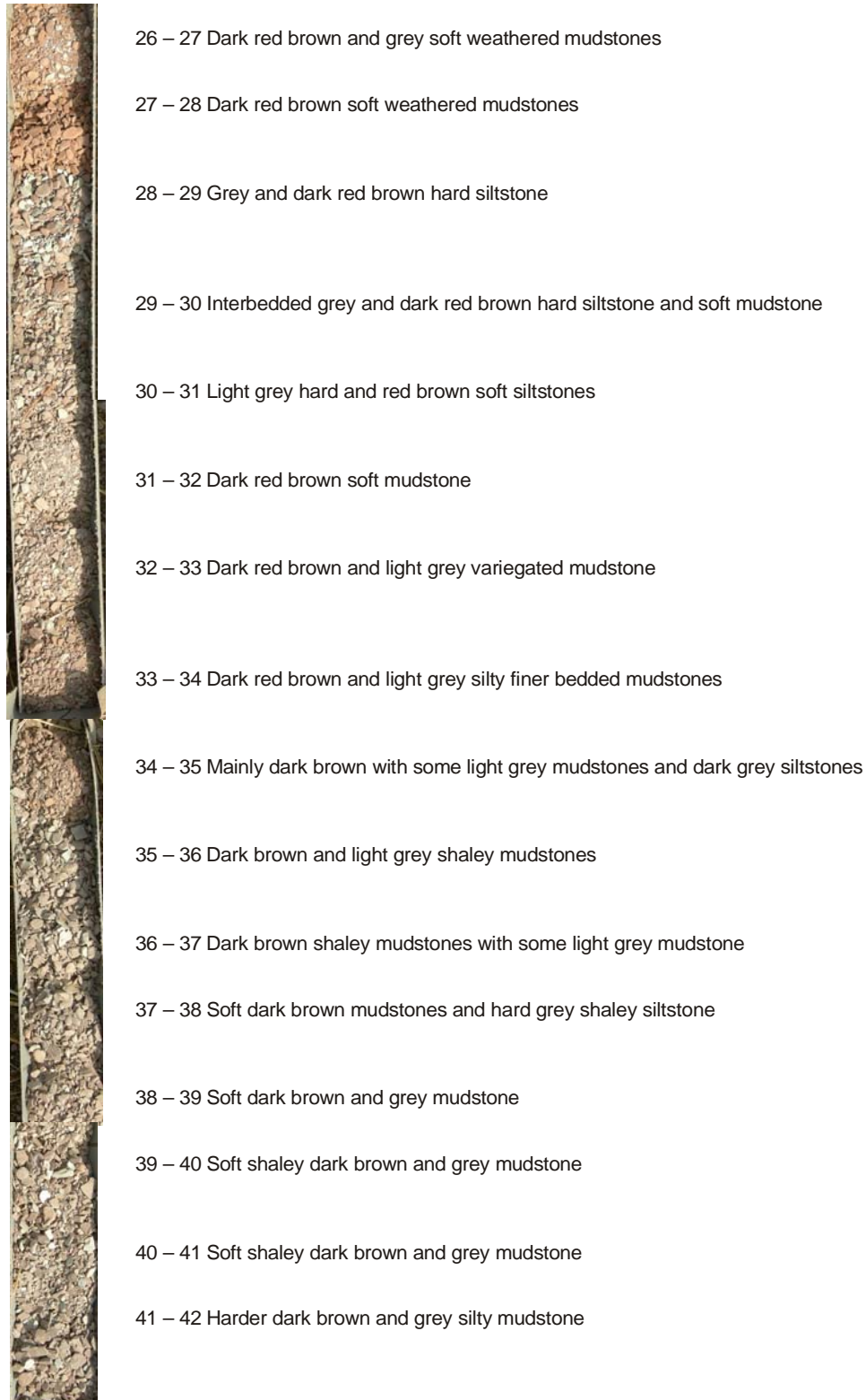


Figure 16 Example of a detailed ‘photo log’ for a section of a dry borehole drilled at Kpachaa village, Northern Region, during the training course. Numbers are depth below the ground surface in metres

7.5 DATA MANAGEMENT

In order to improve understanding of the regional hydrogeology, which is needed to inform local borehole siting decisions, there needs to be both central collation of geological and hydrogeological data and information from across the region, and interpretation of this information at a regional scale. Data and information collected during groundwater development projects is vital to the development of this improved understanding.

A central database such as the CWSA DIMES system is key to collating, managing and making data available. It needs to be as comprehensive as possible in including data from across the region; to include as much relevant information as possible on each borehole or other groundwater development site; and to be regularly updated.

However, even a detailed database like DIMES cannot hold all potentially relevant and useful information related to groundwater development. Two key areas where different data storage systems are likely to be needed are in storing geophysical survey data and detailed geological information.

If the analysed results of geophysical surveys and any geological or hydrogeological interpretations with regard to the local hydrogeology are stored and made available centrally, they can be used by practitioners to support new surveys and interpretations. For example, someone carrying out a geophysical siting survey on the Bimbila Formation could examine the results of previous surveys on the same formation – i.e. conductivity and/or resistivity values and patterns – along with lithological, water strike and yield information from boreholes drilled at the same sites, to indicate what they should look for in the results of the new geophysical survey to identify potential groundwater targets.

Another important requirement for improving understanding is a detailed interpretation of drilling information on each of the geological formations. Very detailed hydrogeological information from boreholes can only be produced by drilling and interpreting cored boreholes, but it is also possible to obtain very useful information from the boreholes drilled for groundwater abstraction, particularly if the small changes in data collection during drilling recommended in this report are made, so that subtle details in the complicated intercalated sedimentary sequences typical to the Northern Region are not overlooked during borehole logging. One way to move towards a better geological overview may be to deposit digital copies of improved borehole logs with the Geological Survey of Ghana, who have the expertise and regional understanding to interpret them. For example, consultants could provide a scanned version of their hand-written field log alongside a photograph of the chip samples from the field ('photo log' – Figure 16) and a digital copy of the summary log from the project report. Even if information from only a small percentage of new boreholes drilled was deposited in this way, it would significantly increase the amount of geological information available for study and interpretation in the future.

8 Conclusions: key issues and recommendations

This project has involved many different activities, touched on a large number of hydrogeological techniques and practices, and raised numerous issues relevant to groundwater development in the Northern Region of Ghana. The issues range from those related to wider groundwater development policy, contractual aspects and the professional development of hydrogeologists and related experts, to technical and practical issues related to best practice in borehole siting, drilling and development by practitioners on the ground. This section attempts to summarise the key issues and recommendations arising from the project.

An assessment of current technical practices is given in Section 6; recommendations for alternative technical practices were made in Section 7. Most of these will not be repeated in this concluding section, rather, we will highlight the main overriding issues from the review of existing data and practices and by discussions with groundwater practitioners in the workshop and training. A roadmap for future research is also given.

8.1 GENERAL

- The Northern Region is a very difficult area in which to find and develop groundwater resources. It should be accepted that borehole success rates here will always be lower than in most other areas. Particularly in the most difficult areas dominated by mudstones, more resources – time and money – need to be focussed on careful siting of boreholes in order to maximise potential success, including detailed desk reconnaissance surveys and the effective use and interpretation of geophysical siting methods.
- Fractures in sandstones, to depths generally not more than 100m, are the most important groundwater target in the Northern Region. Drilling below 100m in sandstones occasionally produces small additional yields, but there is little evidence that drilling deeper than approximately 120m in sandstones produces significant additional yields. Only small amounts of groundwater are typically found in fractures in siltstones, and groundwater is rarely found in mudstones, even where fractured. Drilling deeper than approximately 70m in mudstones and siltstones is not likely to result in significant additional yields.
- There is no magic bullet for success. There is no single technique that will find groundwater in the Voltaian Basin in the Northern Region. Improving success in this very difficult area requires the effective implementation of a combination of many different approaches. Groundwater supply practitioners will need a better understanding of where and how groundwater occurs in the rocks (the groundwater targets); how to try and identify these targets using geological, geophysical and other surveying techniques; and how to develop groundwater effectively and sustainably once it is found. All this will rely on careful collection, analysis and interpretation of field data, and the central collation and interpretation of these data to develop a better regional understanding, which in turn should be used by practitioners to better inform groundwater development.
- In areas of particularly low success, such as areas underlain by unfractured mudstone where there has been continued failure to drill successful boreholes, other water supply options should be considered, such as piping in water from higher potential areas at distance, treating surface water, or rainwater harvesting.
- Groundwater practitioners in the Northern Region, especially those working in the private sector, appear to be to varying degrees isolated from the wider hydrogeological community. A consequence of this seems to be a lack of deeper understanding of some of

the groundwater development techniques being used, in particular geophysics. With limited opportunities for sharing experience with other professionals elsewhere in Ghana, let alone further afield, the practitioners aren't able to increase their understanding and skills.

8.2 CURRENT PRACTICES AND RECOMMENDATIONS

- There is a lack of understanding of the physical meaning behind geophysical siting techniques among some groundwater practitioners. It is possible that many of the practitioners using geophysical techniques have been given superficial training in how to carry out the techniques, but not taught the full detail of the science behind them. In consequence, some geophysical techniques are being carried out wrongly and others are not being used to their full potential. Even where techniques are carried out and data are analysed correctly, there is often poor interpretation of the geophysical data, because of the lack of understanding of their physical meaning. The bottom line is that most of the geophysical siting methods used within the IWASH programme have provided little, if any, useful information on the location of groundwater targets. If geophysical methods had not been used, it is likely that borehole success rates would have been largely the same.
- There seems to be particularly little opportunity for contact and sharing experience between universities and the private sector, although there is more interaction between government agencies, NGOs and private consultancies. Groundwater experts in universities typically have more opportunity to develop a deeper understanding of hydrogeology and to learn about new and/or alternative techniques. Promoting interaction between all groundwater practitioners would be a positive step towards improving knowledge and skills, particularly among more junior staff.
- There is a tendency to take a site-specific or local rather than a regional view, so that individual borehole sites are typically investigated in isolation, without reference to wider understanding of the geology, hydrogeology, or results from previous geophysical surveys and borehole logs in similar areas. Greater understanding of local groundwater potential can only come from a better understanding of the regional hydrogeology. More use should be made of resources such as geological and groundwater maps, databases of existing boreholes, and datasets of typical geophysical responses for the rocks in the region.
- There is a general feeling among practitioners that within contracts there is too much pressure to drill boreholes quickly and cheaply, which contributes to short-cuts in reconnaissance and geophysical surveys, as well as in detailed data collection during drilling and effective borehole development.
- The relevant hydrogeological information collected during groundwater development activities should be collated centrally, so that it is available for all practitioners to access in order to support their future activities, and for future research to further develop understanding of the nature and occurrence of groundwater in the region.
- An experienced hydrogeologist should be involved in a hands-on way throughout the process of siting and developing a borehole, to ensure expert hydrogeological input throughout the process and act as the link between the different parts of the process. The hydrogeologist should be involved not only in the reconnaissance survey, but in choosing the profiles and sites for geophysical surveys; in interpreting the results of geophysical surveys in terms of the known hydrogeology of the area; in choosing a drilling site; in closely supervising the drilling process and the collection of good data; in testing the borehole and assessing its potential and likely long term sustainability; and in feeding back the relevant data to the central data management system.

- It is reported that a number of boreholes show falling yields or even complete yield failure after a few years of use. Where this is not due to mechanical failure of the pump, there may be a number of explanations, including borehole siltation or blockage of borehole screen, as well as falling groundwater levels if groundwater storage is being reduced (see below). Particularly for high yielding, especially mechanised boreholes, it is worth investigating these possible factors using a downhole camera, before going to the trouble and expense of siting and drilling a replacement borehole.

8.3 WIDER RESEARCH ISSUES

- Two recommendations are made to take the current hydrogeological understanding of the Voltaian Basin sedimentary rocks to another level:
 - The recent new airborne geophysical data provides considerable scope for investigating controls on groundwater targets, including the possibility of using EM data to predict the presence of sandstones at shallow depth, and using reprocessed magnetic data to identify lineations which may be water bearing. However, more work is needed to investigate how useful these new datasets could be in reality to help improve borehole success. A research project to site, drill and test new boreholes on targets that were identified from the airborne geophysical data would start to show whether the airborne data could be used in this way.
 - A programme to drill and investigate in detail a series of targeted, deep, cored boreholes would provide direct information on the detail of lithological changes, weathering styles and depths, and the occurrence, distribution and nature of water-bearing fractures.
- There should be an investigation of boreholes that have declined in yield or failed after several years to investigate whether the failure is due to pump breakdown, borehole blockage or siltation, or falling groundwater levels as local groundwater storage is used up.

References

Referred to in this report:

- AFD. 2008. Rural Water and Sanitation Project in the Northern Region: Final Report: Volume 1: Final Project Report.
- Bannerman R R. 1990. Appraisal of hydrogeological conditions and analysis of boreholes in the Nanumba and Western Gonja Districts – Northern Region, Ghana: Assessment of groundwater potential for hand dug wells. Final Report for Rural Action NORRIP/GTZ.
- CIDA. 2009. Hydrogeological assessment of the Northern Regions of Ghana: Interim Report January 2006 – June 2008.
- CSIR. 2009. CIDA-HAP Geophysics Report. CSIR Water Research Institute.
- Ewusi A. 2006. Groundwater exploration and management using Geophysics: Northern Region of Ghana. PhD Thesis, Brandenburg Technical University of Cottbus
- Gill H E. 1969. A ground-water reconnaissance of the Republic of Ghana, with a description of geohydrologic provinces. *US Geological Survey Water Supply Paper* 1757-K.
- Jordan C J, Carney J N, Thomas C W and McDonnell P. 2009. Ghana Airborne Geophysics Project in the Volta and Keta Basin: BGS Final Report. British Geological Survey Commissioned Report CR/09/02.
- Junner N R and Hirst T. 1946. The Geology and Hydrogeology of the Voltaian Basin. *Gold Coast Geological Survey Memoir* **8**, 51p
- Kwei C A. 1997. Evaluation of groundwater potential in the Northern Region of Ghana. CIDA project, Comwasan Consult report, Ghana, March 1997, 66p
- MacDonald A M and Davies J. 2010. BGS Consultancy: UNICEF IWASH Project, Northern Ghana. Visit Report 25/10-5/11/2010. BGS Internal Report IR/10/
- MacDonald A M, Davies J, Calow R C and Chilton P J. 2005. Developing groundwater: a guide for rural water supply. Practical Action Publishing, Rugby
- Ofosu S. 2005. The Hydrogeology of the Voltaian Formation of the Northern Region of Ghana. M.Sc. Thesis. University of Reno, Nevada, U.S.A
- Pelig-Ba J B. 2004. Estimation of water balance in the Northern Region of Ghana. *Ghana Journal of Development Studies* **1** (2), 118-141.
- Sander P, Chesley M M, Minor TB. 1996. Groundwater assessment using remote sensing and GIS in a rural groundwater project in Ghana: lessons learned. *Hydrogeology Journal* **4** (3) 40-49
- Teeuw R M. 1995. Groundwater exploration using remote sensing and a low-cost geographical information system. *Hydrogeology Journal* **3** (3)
- Tod J. 1981. Ground water resources in the Northern Region of Ghana. NORRIP Sectoral Report

Other useful references not specifically referred to in this report:

- Acheampong S Y and Hess J W. 1998. Hydrogeologic and hydrochemical framework of the shallow groundwater system in the southern Voltaian Sedimentary Basin, Ghana. *Hydrogeology Journal* **6**, 527-537.
- Cobbing J E and Davies J. 2004. Understanding problems of low recharge and low yield in boreholes: an example from Ghana. In: *Proceedings of the International Conference on Water*

Resources of Arid and Semi-arid Regions of Africa (WRASRA), August 3-6 2004, Gaborone, Botswana.

Davies J and Cobbing J E. 2002. An assessment of the hydrogeology of the Afram Plains, Eastern Region, Ghana. *British Geological Survey Commissioned Report CR/02/137N*

Geological Survey Department of Ghana and the Bundesanstalt für Geowissenschaften und Rohstoffe, 2009. Geological Map of Ghana, scale: 1:1 000 000. For the Ghana National Geological Map Project

Hydrogeological Assessment Project of Northern Ghana (HAP II), 2010. Geo-logging and Diver Installation of 15 Newly-drilled Monitoring Boreholes. Geo-logging and Diver Installation Report. For CSIR Water Research Institute, Ghana.

MacDonald A M, Kemp S J and Davies J. 2005. Transmissivity variations in mudstones. *Ground Water* **43**, 259-269.

Sami K and Van Rooyen RC. 2009. Hydrogeological Map Explanation – Map Sheet 1001D (scale 1:100 000). CGS/BRGM/Geoman, Geological Survey Department of Ghana (GSD) report No. MSSP/2005/GSD/4

Sami K and Van Rooyen RC. 2009. Hydrogeological Map Explanation – Map Sheets 0701A/1, 0702B/2, 0801C/3 and 0802D/4 (scale 1:100 000). CGS/BRGM/Geoman, Geological Survey Department of Ghana (GSD) report No. MSSP/2005/GSD/7

Viljoen J, Agenbacht A, Shelembe R, Gyapong W And Al Hassan A. 2008. Hydrogeological Map of Ghana, Map Sheets 0701A/1, 0702B/2, 0801C/3 and 0802D/4 (scale 1:100 000). CGS/BRGM/Geoman, Geological Survey Department of Ghana (GSD)

Viljoen J, Reddering K, Thomas E, LeBere P and Gyapong W. 2009. Hydrogeological Map of Ghana, Map Sheet 1001D (scale 1:100 000). CGS/BRGM/Geoman, Geological Survey Department of Ghana (GSD)

Viljoen J, Reddering K, Thomas E, LeBere P and Gyapong W. 2009. Geochemical Synthesis Map of Ghana, Map Sheet 1001D (scale 1:100 000). CGS/BRGM/Geoman, Geological Survey Department of Ghana (GSD)

Water and Sanitation Monitoring Platform, 2010. A Directory of Ghana's Water and Sanitation Sector: Who does what, where and how? www.wsmp.org

Glossary

WRI: Water Research Institute, Ghana, a constituent institution of the CSIR

AFD: Agence Francaise de Developpement

CIDA: Canadian International Development Agency

CSIR: Council for Scientific and Industrial Research, Ghana

CWSA: Community Water and Sanitation Agency

HAP: Hydrogeological Assessment Project

IWASH: UNICEF and EC project towards Guinea work eradication through Water Supply, Sanitation and Hygiene in the Northern Region, Ghana

MSSP: Mining Sector Support Programme

WRC: Water Resources Commission of Ghana

Appendix 1 Workshop and Training Course, 7-17 February 2011, Tamale, Northern Region: Attendees and Feedback

1. List of organisations who were issued with invitations to attend the workshop and training

World Vision International

Church of Christ Rural Water Development

Terrex Limited

Watersites Limited

Prohydro Limited

Terrahydro Associates

Geological Survey Department

Water Research Institute

Community Water and Sanitation Agency

Bezalel Water and Agro Services

Unihydro Limited

Comwasan Consult

Optimum Geo Limited

Geohydrotrach Limited

Water Resources Commission

University of Ghana

University of Development Studies

University of Mines and Technology

Hydrocom Limited

Watersides Limited

T B L Resources

UNICEF

Water Vision Technology

DRP – Karaga

DRP – Central Gonja

Cephavick

KNUST - Kwame Nkrumah University of Science and Technology

2. Actual participants' attendance

Name	Organisation	7/2/ 11	8/2/ 11	9/2/ 11	10/2/ 11	11/2/ 11	12/2/ 11	14/2/ 11	15/2/ 11	16/2/ 11	17/2/ 11
Bukari Ali	KNUST/ Optimum Geo										
Sam Owusu	COMWASAN										
Kiemtore Samadou	Waterside (Gh)										
M Aninm Gyampo	UDS Novorongo Campus										
Musa Saeed Zango	UDS Novorongo Campus										
Joseph Kippo	UG Legon										
Isinguzo Henry	Terrahydro										
Timothy S Bawre	GSG/ Terrex										
Sumaila Mohammed Sherrif	Waterside (Gh)										
Daniel Boateng Amankwaah	CWSA A R										
Kassim Yakubu Alhassan	Karaga DA										
John G Aduakye	CWSA NR										
Samuel Anthonio	WRC / ACCRA										
Abdoul-Samed Aliou	Hydronomics										
B O Dochatagh	BGS										
Jeffrey Devies	BGS										
Charles Dargbey	TBL Resources										
James J Lempogo	Cephavick Ltd										
Eric Yaw Darko	CSIR - WRI										
Patrick Mainoo	CSIR - WRI										
Samuel Azagonor	Bezalel W A Services										
Jerry Akplome	Prohydro										
Ang-numbaala Kamwinang Una	UG Legon										
Micheal Dumulga	COC										
William Novidzro	Prohydro										
Patricia Gyamfi	CWSA-NR										
Samuel Edusei	WV -GRWP										
Sampson Tettey	WV -GRWP										
John Osman	Watersites Ltd										
Festus Barfi Fofie	Watersites Ltd										
D BEAMISH	BGS										
Mashood F Rahman	Central Gonja DA										
Emmanuel Atubuga	Water Vision Technology										
Osman Mumuni	Watersites Gh Ltd.										
Kabuka Banda	UNICEF										
Emmanuel Mensah	Geological Survey of Ghana										
Nathaniel Adams	COC										
Samuel Abanyie	WVT/ UDS										
Maxwell A. Abendiba	Araco Limited										
Francis A Okari	UG Legon										
Fideli Adongo	NORST- Gambaga										
Malechi Saibu	NORST - Yendi										
Samuel N Hervie	CWSA										

3. Feedback from participants

At the end of the workshop and training the participants were asked to provide feedback on their experience of the course. Twenty four questionnaires were returned. The following are the main free-text comments that the participants provided.

1. Comment on geophysics best practice as discussed during training
 - Combined EM and resistivity: Schlumberger AB/2 should have a wider spacing to investigate deeper
 - The use of EM profiling and sounding selected points
 - Note depth of probing need to be increased
 - More than one geophysical methods should be employed
 - The dipole-dipole was best used by the people in the region, but the facilitators suggested the use of Schlumberger
 - Use of the best model to analyse electrical methods but needs to increase the depth of exploration
 - Best method has not been arrived yet but there is a need to increase the depth of exploration
 - A further study to compare the 2 VES results will rather bring a conclusive decision
 - The training about this two still needs further clarification
 - The dipole-dipole sounding and Schlumberger can easily show your anomalies
 - The best method is combining one or two method or techniques rather than using only one
 - I think all the practices must be employed or used since getting water in the Voltaian is very difficult and 2D must be added to them
 - Combining both the dipole-dipole with EM profiling for interpretation
 - Combine both the dipole-dipole with the EM profiling method for interpretation
 - Schlumberger method being pushed above dipole-dipole. In my experience however, I find the dipole-dipole more appropriate to use than the Schlumberger method
 - Spend much time in the community to do ground truthing and extensive work
2. Mention one or two things you have learnt that will improve your work in groundwater exploration
 - Apply correct model in analysing geophysical data. Spend much time to do recce survey
 - Integration of GIS into groundwater investigation
 - The introduction of GIS will help and improve my skills in groundwater exploration
 - The use of GIS and MapWindow
 - Introduction to the use of MapWindow was reinforced
 - Learnt that the use of dipole-dipole is good and has being given result
 - GIS for data interpretation; need to increase depth of exploration
 - The need to increase the depth of geophysical explorations
 - GIS
 - Groundwater data management and water quality issues
 - Recent classification of the Northern Region geology
 - The use of deeper investigation of the ground to get information from deeper depth; the photo logging if the ground sections
 - The process in logging and identifying various materials (lithology) during drilling
 - Use of GIS
 - I have a good picture of the various geology and difficult to find water as well as how to identify and log drill cuttings
 - A very good and accurate study of the terrain before geophysical survey; combining one or more methods with models to get better idea and understanding to help improve success rates

- Very happy about the GIS. It would help me to know the area I am going to work in before going there
 - Geological logging techniques, especially assign photographing sample to the usual sample logged
 - Proper geological logging techniques especially adding photographing samples to the usual sample logging; water potential in the various geological units in the Voltaian Basin in the Northern Region
 - Learnt to use GIS in mapping and properly organising borehole data; learnt that groundwater monitoring must be done to know how the aquifer is functioning and whether it is being mined
 - About using the 2D and the EM34; borehole pumping test
 - Reconsider the use of EM and Schlumberger VES to complement dipole-dipole VES; it is important to inventorise and study existing boreholes in a community before entering the community; the use of the Lund 2D method looks interesting, and may be adopted to proceed the determination of VES sites
 - Groundwater monitoring and samples description
3. Mention issues that you will need training to further improve your work in groundwater exploration
- Correct and good interpretation of the 2D geophysical model; application of remote sensing in GIS to enhance groundwater map
 - Further geophysical training
 - Further training on softwares to back data collection
 - Appropriate geophysical method and interpretation of results
 - Understanding the hydrogeology of the Voltaian
 - Detailed geology of various locations will be necessary
 - The use of the Schlumberger method of geophysics
 - Aquifer delineation issues; GIS
 - Knowledge of the stratigraphy of the Northern Region (Voltaian formation)
 - GIS will need to be further considered as a means of improving planning for drilling projects
 - Borehole drilling / geophysical survey etc
 - The use of GIS
 - GIS and report interpretation
 - Geophysical investigation and the use of advance or improved techniques
 - GIS
 - Add local resource personnel
 - Proper interpretation of geophysical data and pumping test
 - Contractual issues in tendering for projects; geophysical survey methods
 - Need more training in the new methods available apart from the existing ones
 - The GIS data training and groundwater data management would have help if re-train again
 - Practical use of the various geophysical methods e.g. EM34, resistivity methods in groundwater exploration; use of GIS systems
 - More training on the GIS MapWindows software
4. Any other remarks/advice/suggestions
- Insightful training and wish that it is organise yearly for hydrogeologists and geophysicists
 - More funding for detailed geophysical work in groundwater exploration. Data collection during fieldwork should be carefully looked at. Equipment manuals should be well-read – know the conditions under which the equipment operates

- I will suggest that further studies will be made to help increase the success rate
- The workshop was well-planned. I suggest that detailed geology of Ghana should be incorporated into the programme in future
- That further training be provided in order to improve the success rate
- A good workshop. Funds should be made for exploratory boreholes to offer opportunity to study the Voltaian on a more comprehensive level
- Another workshop focussed on using all the geophysical methods to try to interpret the drilling report will further help drawing better conclusions
- Make more research on how to groundwater all the communities in Northern Ghana
- I wish I had participated in all sessions especially sessions on geophysics
- The program or workshop was great and educative
- There was no lecture on borehole construction. I expect the facilitators to come out with a siting method that can improve our success rate and train participants on how to use these methods. I am also disappointed that much was said about the 2D method
- If all participants could stay at one place to enable them to discuss issues after the facilitators end the day, and also the participants could be in groups to tackle issues being discussed during facilitating
- Training very useful and helpful. Such training exercises or workshop that can bring all players in the water sector or rural water sector should be organised at least quarterly. This is to enable persons in the sector share experiences
- A very good workshop and career enhancing program. More of these should be organised. Thankyou
- Am happy to learn about the GIS but I need further training of it
- Analyses should be made to compare borehole construction success between Schlumberger VES and dipole-dipole VES. My conviction is that the Schlumberger VES is not too helpful in the Voltaian, since it does not pinpoint the fractures, etc, which are more likely to be the water-bearing zones in these rocks. I have not obtained any new siting techniques to help me improve my siting ability in the Voltaian.

5. Field work in groundwater exploration

a. Reconnaissance

- Not much time was spent to do recce
- Not sufficient time allocated for that
- Proper terrain evaluation through very good geological map and base map combined possibly with aerial photos; calibration of already existing data with new ones on the field; studies of meteorological and groundwater potential map of terrain under study
- I don't think we explore the area enough before selecting an area for drilling/geophysics
- Reconnaissance survey was properly executed
- Was done fairly well, but after the profiling lines has been selected. Moreover, the recce survey concentrated in the northwestern sector of the community (where incidentally four dry holes had previously been drilled)
- Fairly good
- Good
- Not enough
- Good
- OK
- OK
- OK
- Need more research
- Adequate
- Very well
- OK
- This was OK

b. Geophysical Survey

- Not much work was done
- Inadequate
- Two days was woefully inadequate
- Not enough assessment was used
- Not much could be achieved
- Need more time in making geophysical survey
- Adequate
- Very well
- Proper terrain evaluation and survey; Schlumberger, dipole-dipole, 2D and EM34 (hence was educative and worth learning)
- We could have practised all the methods available here before selecting the drilling point, e.g. carrying out the various sounding process/methods, compare the results before deciding where to drill
- Overdependent on 2D and EM methods and very little time was available for extensive VES, especially with dipole-dipole
- Insufficient background data before entry into community; use of EM34 and Lund 2D resistivity survey demonstrated. One Schlumberger VES only and an incomplete dipole-dipole VES. Sites identified for VES on the 2D profile were not sounded. Site selected for drilling based on EM profile only. Inadequate!
- Interpretation not adequate
- Good • OK
- Fair • OK
- OK

c. Drilling processes

- Good but need to improve on sample chips collection – at least 1m intervals
- Air rotary drilling; sampling of geological samples for at least 1m interval; proper logging of sample data taken
- Everything with the drilling process was good especially the sample collection and logging
- The selection of the drilling point was not agreed upon. There were arguments about the point to be drilled. I think that is what led to the dry results recorded
- Had good lesson from logging but disappointed on dry drilling
- Drilling process was very good
- Rig in use efficient, operators were willing to make necessary stops for samples collection
- It was very OK • OK
- Good • OK
- Good • Adequate
- Unsuccessful • Excellent
- Good • OK
- OK