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ASSESSMENT OF GROUNDWATER MONITORING PROCEDURES AND NETWORK DESIGN

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prepared by

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ACRONYMS AND ABBREVIATIONS

DLS	Department of Livestock Services
DSA	Deep sandstone aquifer
DWR	Department of Water Resources
Eh	Redox potential
GBA	Greater Banjul Area
IWRM	Integrated Water Resources Management
mbgl	Meters below ground level
mg/l	Milligram per litre
Mm^3	Million cubic meters
NAWEC	National Water and Electricity Company Ltd.
NWSRP	National Water Sector Reform Project
SSA	Shallow sand aquifer
TDS	Total dissolved solids
ToR	Terms of Reference
TSS	Total suspended solids
VWSS	Village water supply system
WHO	World Health Organization
μS/cm	Micro-Simens per centimeter

1. BACKGROUND

As The Gambia depends mostly on groundwater sources to satisfy its water needs, several studies have been executed. The most important are listed below:

- Groundwater Resources Study by Howard Humphreys Ltd., 1978.
- Groundwater Resources of the Gambia by the Ministry of Water Resources funded by UNDP, 1983.
- Groundwater Survey Studies by Howard Humphreys Ltd. & S. Ceesay, 1987.
- Groundwater Survey of the Gambia by Scott Wilson Kirkpatrick, 1993.

It is worth noting that the latter also included a salinity risk mapping for The Gambia.

From these studies as well as investigations carried out in neighbouring Senegal there are sufficient documentation on the two main sources of groundwater within the Senegambia sub-region, namely the shallow sand aquifer (SSA) and deep sandstone aquifer (DSA).

Shallow sand aquifer

The SSA system is geologically of Mio-Pliocene age and located at depths between 15 and 120 meters below ground level (mbgl). The SSA is composed of unconsolidated sand with textures ranging from fine to coarse sand but the majority of the aquifer is characterised by medium to coarse sand.

This aquifer system is exploited throughout The Gambia and much of Senegal. Within The Gambia, the SSA is subdivided into an upper phreatic aquifer and a lower semi-confined aquifer. These two units are separated by a clay-silt aquitard with a thickness of 15 to 30 m that still allows hydraulic connection – though limited – between the two units. Recharge of the SSA is primarily from infiltration of rainwater within The Gambia, although some lateral flow also occurs from neighbouring areas in Senegal. All groundwater utilized in The Gambia is abstracted from the shallow sand aquifer partly through numerous dug wells tapping water from the upper phreatic part of the SSA and partly from boreholes sunk in the lower semi-confined part of the aquifer.

Deep sandstone aquifer

The DSA system comprises mainly Maastrichtian (Late Cretaceous epoch) sedimentary deposits, and separated by clays and marls depths between 120 m to 250 m but there is some crossover with Paleocene deposits. Paleocene sandstones occur at average depths of 250 to 300 mbgl. The aquifer is recharged through lateral flow over long distances from the southern part of Senegal at an estimated rate of 1.75 Mm^3/year (Howard Humphreys Ltd. and S. Ceesay, 1987). The general direction of the groundwater flow lines is depicted in Figure 1.

The DSA is currently not exploited in The Gambia, but in neighbouring Senegal it is an important source of water at various locations.

Contrary to previous conceptual groundwater flow hypotheses, which assumed a continuous flow towards the Atlantic Ocean, the more recent conceptual understanding as shown in Figure 1 advocates that the DSA flow regime includes three independent zones, with different hydraulic characteristics, namely:

- In the **Eastern Zone**, the groundwater flows follow a generally centripetal pattern, and recharge mainly occurs from the south and south-eastern edges of the basin, and less pronounced along the upper course of the Senegal River. It is hypothesized that the dominant pathway of groundwater drainage in the Eastern Zone occurs by vertical ascension through the upper part of the aquifer system, also referred to as the Continental Terminal. This hypothesis is sustained by quantitative estimates of actual recharge of the aquifer combined with a range of possible evaporation rates from the deep unsaturated zone in the Ferlo (ref. Figure 1).
- Being "hydraulically blocked" by the geological structure of the **Central Zone** with its stagnant saline waters, the **Western Zone** is structurally isolated from the rest of the Maastrichtian aquifer. A vertical recharge directly generated by infiltration of rainfall is offset by current groundwater exploitation, which at various locations exceeds the recharge, and by the natural equilibrium with the sea level.

Figure 1: Conceptual flow model of the Maastrichtian Aquifer System in Senegal[1]

Groundwater quality

The parameters and specific values quoted in this section is retrieved from the Department of Water Resources water quality database.

From Table 1 it can be seen that in general there is an increasing mineralization of the water in the Deep Sandstone Aquifer in an east to west direction. This implies that good quality (potable) water in the DSA is expected only in the eastern part of the country, where the reservoir (aquifer storage volume) is estimated to hold 80,000 Mm^3 of a total of about 650,000 Mm^3.

[1] *COWI / Polyconsult / SGPRE, 2001. Hydrogeological characteristics in the Maastrichtian aquifer system, presented at the International Symposium on Aquifer Systems Management, 30 May-1 June 2006, Dijon, France.*

In particular, three deep boreholes sunk into the DSA at strategic locations in The Gambia in the late 1980'ies show conductivity (TDS) increasing westwards from above 300 mg/l at Garowal to around 1,000 mg/l at Sankwia, and further approaching 2,000 mg/l at Banjul. The chloride content is also low in the east (less than 20 mg/l) increasing westwards to above 600 mg/l. Likewise, fluoride content increases from 0.4 mg/l in the east to above 5 mg/l in the west.

Table 1: Water quality of the deep sandstone and shallow sand aquifers

Parameter	WHO drinking water standards		Deep Sandstone Aquifer			Shallow Sand Aquifer - Gambia (mg/l)
	Highest desirable (mg/l)	Max. permissible (mg/l)	Garowal (mg/l)	Sankiwa (mg/l)	Banjul (mg/l)	
TDS	500	1,500	322	955	1,766	20 – 90
Calcium	75	200	34	6	6	4 – 15
Magnesium	30	150	20	3	5	0.2 – 4
Chloride	200	600	17	355	616	2 – 25
Sulphate	200	400	28	42	101	1.6 – 15
Nitrate	45	45	0.1	0.2	0.1	0 – 50
Fluoride	0.6	0.8	0.4	1.8	5.3	0 – 0.1

With reference to Table 1, it is evident that the quality of the water of the Shallow Sand Aquifer is well suited for potable use. In addition to the parameters shown in the table, it can be mentioned that pH values in the SSA are on the low side in some areas varying from 4.0 to 6.7.

The low pH is related to low mineral content and buffer capacity (low HCO_3 and Ca^{2+} ions) resulting in high dissolved CO_2 concentrations. In existing treatment works in the Greater Banjul Area this is raised by aeration for removal of free CO_2 gas or by lime dosing.

High iron (Fe) content is encountered in a number of places typically in the range between 2.5 mg/l to 4 mg/l. In some areas like Bansang, the groundwater has high iron and Total Suspended Solids (TSS) content, which is removed by aeration and filtration. High iron content is also encountered at Sibanor, Bullock, and Sintet in the Western Division, and Jali, Pakaliba, Dumbutu, Dongoroba, Bureng and Kwinella in Lower Division.

The nitrate (NO_3) content is high 5-50 mg/l in many places of the upper phreatic aquifer as sampled in the dug wells and increases with population density indicating pollution. In some cases values as high as 200 mg/l have been observed. The values, however, are generally below World Health Organization (WHO) standard of 45 mg/l. In the lower semi-confined aquifer, the nitrate is found to be below 10 mg/l. Fluoride content is well within WHO standards in the SSA groundwater.

The electrical conductivity, and hence the total dissolved solids, have been measured to be within the WHO standards in the range of 50 to 400 μS/cm at 25°C. However, the electrical conductivity are generally higher 500 to 900 μS/cm near the coast line and close to the saline River Gambia and the swamps, and in exceptional case in the east around Fatoto. The groundwater in the well fields in the northern part of Greater Banjul Area shows electrical conductivity values below 100 µS/cm.

In conclusion, on a country-wide basis it can be stated that the Shallow Sand Aquifer holds groundwater with a quality in its natural state well suited for potable use, whereas the Deep Sandstone Aquifer looks less attractive for domestic water supply in the central and western parts of the country.

2. PAST MONITORNG ACTIVITIES AND RESULTS

Groundwater monitoring is essential for effective water resources management. The information that is gathered through monitoring provides key data and knowledge to enable sustainable use and long term planning in relation to groundwater and help to guard against over-extraction, and to ensure that reserves do not become further 'stressed' or drop below sustainable levels.

The groundwater monitoring that was carried out in 1993-99 on 47 observation boreholes was done with manual water level meters. The problems associated with this method are its proneness to human error and parallax during measurement.

Some physical and chemical water parameters such as temperature, pH, sodium and redox potential (Eh) were measured with Hanna® pocket meter kits. Water samples drawn from the surface were obtained with a bailer to carry out these tests. Since purging of boreholes was not carried out, the bail samples were not necessarily water actually taken from the aquifer proper, but from storage, which makes its representatively questionable. Measurements were carried out on monthly basis for a period of six years, but there were no internal and external controls, and no interpretative analysis was carried out of data collected.

Groundwater level data from these 1993-1999 monitoring activities are recorded and available in excel files. These water level time series show normal seasonal fluctuations reflecting recharge from rainfall and groundwater discharge. The annual water level fluctuations range between 20 and 200 cm. However the long term trend cannot be assessed due to short term data series.

Groundwater levels also vary across the country. Water table depths vary spatially as follows: Greater Banjul Area (10 to 15mbgl), Foni area (6 to 20 mbgl), Niumi–Jokadu (10 to 20 mbgl), Kerewan and Kaur (15 to 20 mbgl), Mansakonko (on average, 20 mbgl), Kuntaur (on average, 15mbgl), Janjangbureh (on average, 10 mbgl) and Basse (10 to 13 mbgl). As a general rule, water tables close to the coast and along the banks of the River Gambia and its tributaries are shallow. Depths increase northwards, towards the Senegal border, to between 30 to 45 mbgl, and southwards the average depth of the water table is around 20 mbgl indicating the influence of the coast and river on the groundwater tables.

The 'topography' of groundwater levels is dominated by *mounds* and *sinks*. Mounds are found in Kombo (GBA) and Niumi (Kerewan), and sinks in Mansakonko, Kuntaur and Basse-Ftatoto. Centrifugal flow from these mounts occurs in all directions. In contrast, flow converges towards groundwater sinks.

3. ASSESSMENT OF EXISTING MONITORNG NETWORK

In **Annex 1** the result of the inspection of the groundwater monitoring network is presented in form of an inventory of existing functional and dysfunctional monitoring boreholes. In total 53 sites are included (12 boreholes constructed in the 1970'ies and 29 boreholes constructed in the 1980'ies, 6 sites combining 2 piezometers each to monitor the upper phreatic aquifer and the lower semi-confined aquifer at the same location constructed in 1993, and 5 boreholes constructed in 2007-08).

All 47 existing boreholes in the monitoring network were inspected as part of the present Study, and evaluated in terms of functionality and suitability for continued use in a re-designed monitoring network. Annex 1 also provides a brief assessment of each site, and the reasons for recommending its continued presence or exclusion from a future monitoring network. The map in **Annex 2** shows the location of the existing functional and dysfunctional observation boreholes.

A summary overview is given in Table 2, and it can be seen that the **National Water and Electricity Company Ltd.** (NAWEC) has established and owns nearly half of the observation boreholes in the network. However, today NAWEC is not collecting data on water level or other variables from these, perhaps – it can be argued – because the main interest is in groundwater abstraction and no legal framework is in place to enforce such a monitoring.

Table 2: Overview of existing observation boreholes and their affiliation

Monitoring boreholes established by	Number
NAWEC	28
Department of Livestock Services	12
Department of Water Resources	1
Village Water Supply Systems	2 x 6
Total	53

Out of the 28 NAWEC observation boreholes, 5 are very close to abstraction boreholes with a separation distances ranging from approximately 6 m at Latrikunda BH5 to 15 m at Salagi Forest OB8, which disqualifies them from incorporation in a re-designed monitoring network due to their close proximity to abstraction boreholes. 4 other boreholes in the range of 23 m to 35 m to abstraction boreholes will be incorporated into the future monitoring network. 4 other boreholes are backfilled with rubbish and abandoned which automatically excludes them from a future monitoring network. Additionally, one other borehole, Wellingara EX4, cannot be traced on the ground[2]

During the period January 2007 to April 2008, NAWEC added 7 observation boreholes to its inventory, although NAWEC has not been continuously monitoring these sites. Interestingly, two of these boreholes are equipped with water divers and one equipped with a conductivity diver as also highlighted Annex 1. Figure 2 shows (a) the well head

[2] *There has been a pronounced change in land use over the past couple of decades and encroachment in 'back wood" areas, where the boreholes were originally located.*

of one of the abandoned observation boreholes, and (b) one of the intended monitoring boreholes equipped conductivity diver.

(a)

(b)

Figure 2: Borehole head at (a) Mariama Kunda OB2 and (b) Brikama O6A (with diver)

Some NAWEC observation boreholes are constructed with 103 mm PVC casing and screens, and the others with 175 mm PVC casings and screens with slot sizes of 0.5 mm to 0.75 mm over 18 to 30 m sections of specific boreholes[3]. Other NAWEC observation borehole designs are in line with best practices and in conformity with the Department of Water Resources design and technical specification standards. The slots size for the screens and gravel pack material is in the range of 0.5 mm to 0.75 mm and 1 to 2 mm respectively.

In Table 2 it can also be seen that the existing monitoring network includes 12 boreholes originally drilled for cattle-watering by the **Department of Livestock Services** (DLS) and 6 piezometers associated with **Village Water Supply Systems** (VWSS). The DLS boreholes are constructed with 150 mm of PVC casing and screen, 12 m of slotted screen that is double-wrapped with a 1 mm geotextile mesh/netting material. The general idea behind for using these DLS boreholes which were abandon was to collect data on groundwater level fluctuation for descriptive analysis.

The DLS borehole designs do not conform to the Department of Water Resources (DWR) design standard given the absence of gravel pack replaced ostensibly by geotextile wrapping. It is recommended, therefore, that these boreholes are excluded from a re-designed monitoring network. Beyond design issues, it has been confirmed that 5 DLS boreholes some time back were vandalized.

The 6 piezometers (VWSS) are each made up of 2x50 mm diameter plastic PVC material, including 6 m length of slotted screen, double wrapped with a 1 mm geotextile mesh of mosquito netting and placed in a sand filter pack. The design and technical standards of the DWR was not adhered to and for this reason it is also recommended to omit them from the re-designed network. The purpose of these installations was to observe the seasonal groundwater level fluctuation both in phreatic and shallow sand aquifer as well as the influence of abstraction on both of them.

From the present survey of the existing monitoring boreholes, it is concluded that to a large extent the existing network does not meet the requirements for the boreholes to be included in a new monitoring programme designed to capture various groundwater

[3] *Water level depths in observation boreholes lie between 50 m and 90 m.*

'parameters' and occurrences, i.e. short-term, localized over-pumping situations, long-term water quality and water table levels etc. In fact, as further described in Section 5 below, only 20 of the existing observation boreholes are recommended to be included in the new monitoring network.

4. OBJECTIVES OF NEW MONITORNG NETWORK

Monitoring of groundwater levels is crucial for proper planning, development, and management of groundwater resources. Changes in water levels reflect changes in groundwater storage and thus the amount of water available. Water level changes are generally a response to rainfall, evapotranspiration, abstractions and natural drainage. During the dry season, the groundwater table is normally lowered since there is no recharge from rainfall, and losses through evapotranspiration and natural drainage occur. Changes over a longer period of several years would be due to changes in abstraction patterns or impact of climate changes.

It goes without saying that monitoring boreholes should be judiciously located and the borehole should be in good condition, and the water level measurements should always be taken from a fixed (reference) point with known position above sea level, for example from the top of the casing.

Management objectives underlying monitoring networks have gradually changed from general state descriptions a few decades ago, to quite specific problem-oriented information today. The placement of monitoring wells is based on knowledge of (a) the position of a well field (to monitor the impact of the major abstraction points), and (b) knowledge of the different aquifers. It is only if there is no knowledge of the two, (a) and (b), that a statistic approach will be used.

Since the potable water supply relies nearly entirely on groundwater abstracted from the shallow sand aquifer underlying the whole country, it is recommended that the 'new' network of observation boreholes also should serve the purpose of capturing changes in water quality characteristics due either to natural causes, pollution or overexploitation.

The 'new' monitoring network should be designed aimed at addressing the following aquifer and groundwater aspects:

- Short/long-term lowering of the groundwater levels due to intensified groundwater exploitation and introduction of higher yielding pumping regimes (increased pumping rates and/or shorter distances between production boreholes).
- Long-term trends in the static groundwater levels country-wide to capture possible impacts of climate change affecting the rate of infiltration (aquifer replenishment) due to reduction in rainfall and increase in evapotranspiration.
- Deteriorating water quality due to location of the boreholes, e.g. appearance of brackish water close to banks of the river system (determination of a safe saltwater buffer zone).
- Helping to better define the groundwater flow regime, and hence supporting generation of hydrogeological data for groundwater modelling analyses – and later on strategic and planning exercises.

In addition to contributing to the above monitoring objectives, it is also important that the monitoring network and the individual observation boreholes should be established with the following considerations in mind:

- adequate distance between observation and abstraction boreholes should be maintained;
- appropriate borehole design, construction and completion (purging) should be adhered to;
- harmonization of field equipment should be a guiding rule;
- taking into account requirements for trans-boundary basin management and existing regional collection systems such as HYCOS; and
- clear operational, data handling and storage protocols should be established.

It must be emphasised that even with a well thought through 'design' and proper established groundwater monitoring system, the ultimate success of course will rely on how well it is utilized and the collected data processed, analysed, understood and acted upon. In other words, means and resources to operate and maintain the monitoring activities must be ensured by DWR, and staff trained in the required technical disciplines.

5. DESIGN OF NEW NETWORK

Taking into consideration the various criteria and aspects outlined in the preceding section, a new groundwater and hydrogeological monitoring network is proposed, which combines a number of the old observation boreholes and new ones to be constructed.

Of the existing observation boreholes the 12 old DLS boreholes and the 6 pairs (= 12) piezometers[4] drilled under VWSS programme have been taken out from the monitoring network for non-compliance with the set rules as described above. Furthermore, the casing and screens of the 12 piezometers do not meet the design and technical requirements of the DWR and therefore cannot accommodate into the new monitoring network.

If NAWEC's 5 recent boreholes are taken into consideration, the total number of observation boreholes under the authority of NAWEC is 28. 10 of these are dropped from a future network (ref. Annex 1). In this category, 5 boreholes are very close to the abstraction boreholes (<15 m), 4 of them have been backfilled with rubbish, and one cannot be traced after much searching[5].

The remaining 18 NAWEC observation boreholes will be incorporated in the groundwater level and water quality monitoring network depending on borehole development (purging) outcomes and pumping test results.

Table 3: Propose observation boreholes and divisional location

No.	Site name	Division
1	Tannene	West Coast Region
2	Somita	West Coast Region
3	Mayork	West Coast Region
4	Kwinella	Lower River Region
5	Karantaba	Lower River Region
6	Pakaliba	Lower River Region
7	Denton Boiram	Central River Region
8	Yoro Beri Kunda	Central River Region

[4] *One in the semi-confined aquifer and the other in the phreatic aquifer.*
[5] *Residents in the area do not know of its whereabouts, and NAWEC field staff has no record of its location.*

9	Santanto Bubu	Central River Region
10	Kerr Modi Hali	Central River Region
11	Kerr Sait Mariam	Central River Region
12	Tabanani	Central River Region
13	Ndungu Kebbeh	North Bank Region
14	Gunjur	North Bank Region
15	Farafanni	North Bank Region
16	Ballingara	North Bank Region
17	Yorobawol	Upper River Region
18	Brifu	Upper River Region
19	Mansajang	Upper River Region
20	Kantel Kunda	Upper River Region

In conclusion, the monitoring network is recommended to be made up of 18 of the existing observation boreholes and added to these proposed number of 20 new boreholes to be drilled as tabulated in Table 3 above. That means the proposed groundwater monitoring scheme will be based on 38 observation boreholes in total. The four (4) boreholes of the existing 18 observation boreholes will entirely be used to check the impact of the bulk abstractions and hence as a local management tool for the closest abstraction boreholes. The rest of the observation network will use for water resource management both in terms of quality and quantity, long-term water table trends etc.

The map in **Annex 3** shows the proposed configuration of the new monitoring network for the country. The selection of locations is based on flow pattern, and abstraction areas and as well for future recharge estimates for the country. The filled circles (●) in the map depict the locations of existing observation boreholes and the filled triangles (▲) indicate the location of recommended new monitoring boreholes. Geophysical soundings will be carried out at the geographical localities for the new boreholes to determine the optimal siting. The more detailed map in **Annex 6** shows the location map of 18 NAWEC observation boreholes which are to be incorporated in the new monitoring network.

It can be noted in Annex 3 that the new observation boreholes are almost at equidistant from closest neighbour in view to capture the incoming flow from Senegal and to better estimate recharge. Since the aquifer systems are interconnected between the two countries it is therefore essential to capture the incoming flow as well as to monitor water quality. This configuration will establish a monitoring network representing the entire country. The increased density in some areas and spatial configuration are envisioned to provide intensive monitoring in areas with heavy abstraction load and for groundwater level interpolation issues.

6. MONITORING EQUIPMENT AND PROCEDURES

Against the background and ‘lessons learnt’ from the earlier abandoned monitoring activities (ref. Section 2 above), it is recommend to introduce new technologies and procedures for future groundwater monitoring (water table observations and water quality). The aim must be to make data collection easier and more robust, and at the same time improve accuracy and reliability of the data collected. Furthermore, incoming data should also as much as possible be ‘readymade’ for smooth integration into the planned Water Resources Management Information System (WRMIS).

Equipment

The equipment recommended to be procured for installation as part of the new groundwater monitoring system for retrieval of data and processing is given in Table 4. Further details are presented in Annex 5.

Table 4: Equipment specifications for groundwater monitoring

Item	Description	Quantity
1	Mini-Diver Type **DI 501** Measuring range 10mH2O •typ. accuracy** ± 0.05% •resolution 0.25 cmH2O	38
2	Mini-Diver Type **DI 502** Measuring range 20mH2O •typ. accuracy** ± 0.1% •resolution 0.40 cmH2O	3
3	Mini-Diver Type **DI 505** Measuring range 50mH2O •typ. accuracy** ± 0.25% •resolution 1.0 cmH2O	1
4	Steel wire (fitted and packed for the 42 divers)	42
5	Communication package (USB read-out unit, CD with manual and software for communication)	1
6	Water level dippers – 50 length PLS 50	2
7	Water level dippers – 100m length PLS 100	1
8	Ruggedized laptop for field data collection	1
9	Bladder pump (Grundfos Redi-Flo2), compressor, control unit and free standing reel(Groundwater sampling)	1
10	Generator (rated AC output 4.0 KVA)	1
11	Hand-set barometer pressure measurement in digital format	1

Procedures

The operational procedures and routines to be followed to carry out the activities under the new monitoring programme will be prepared and put into a manual format for all the future monitoring boreholes. The data to be generated will be water level time series and water quality, and their frequency for data collection will be determined but usually quarterly will be good enough since natural water quality doesn’t change much as well as with less industries that can generate pollution.

Since pollution is not a major issue in the country, the physical, chemical and micro-biology properties of water will be sampled and measured on quarterly or half-year basis to be decided. This procedure will be dilated in a manual format for usage by the monitoring team and laboratory in Abuko of the DWR.

7. PREPARATION FOR GROUNDWATER MODELLING

As part of the groundwater assessment study activities, groundwater modelling will also be carried out in a few selected areas, which experience water stress and/or water quality problems. The aim is to apply groundwater modelling for water balance calculations as a tool for groundwater management in terms of safe yield estimations, groundwater recharge zoning and detection of trends in water quality. Hence, the areas for groundwater modelling are suggested to be where major abstractions are taking place within the NAWEC water supply zones in the Greater Banjul Area (GBA) and also where groundwater exploitation for commercial agricultural activities takes place.

The abstraction boreholes under NAWEC are located in the shallow sand aquifer, and an indication of the water stress in various parts of GBA is the fact that some hand-dug wells in the vicinity of production boreholes are drying up earlier than usual – or even permanently – in the absence of re-deepening. Undoubtedly, GBA is a sensitive and vulnerable area concerning the balance between groundwater exploitation and natural aquifer recharge. This is where population growth in the country is highest and urbanisation is impacting infiltration rates – and possible pollution impacts. It must also be realized that it may already be impossible to move people away from the zones of high natural infiltration. In Nema Kunkuo within the GBA, an agricultural production unit owned by Radville Farm will be included in the groundwater model set-up.

Another area proposed for inclusion in the groundwater modelling applications is the sprawling agricultural production zone in Kafuta some 25 km southeast of GBA owned by the Kharafi Group. In this zone intense groundwater exploitation is taking place in an area where in fact the hydrogeological information is quite scarce.

After careful assessment in the quest to identify the most appropriate modelling tool to suit the Gambian aquifer conditions, it has been decided to acquire one of the commercially available versions of the widely used ModFlow software products, i.e. the Visual ModFlow Flex (VMOD Flex) version.

The modelling tool will be calibrated and applied in the above identified priority areas. It is anticipated that the drilling campaign to establish the new monitoring boreholes and the accompanying pumping tests in the selected areas eventually will produce a first batch of new aquifer data and other information to carry out proper runs of the groundwater modelling tool. The water balance and recharge assessments of the selected areas will be computed using the groundwater model.

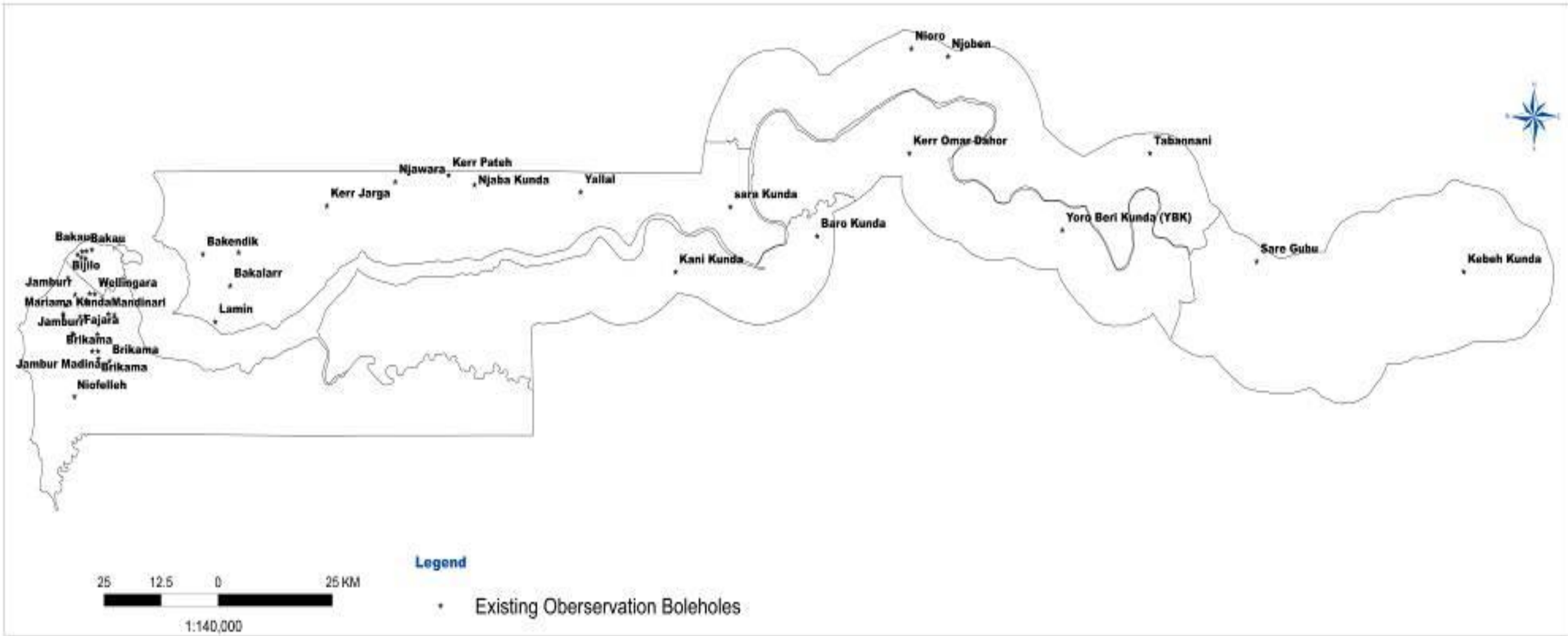
The map in **Annex 4** shows the rough demarcation of the selected areas to be included in the groundwater model applications – a more detailed demarcation will be made a part of the modelling. Eventually, the information and results emanating from these activities will also be used to facilitate an updating of the National Hydrogeological Map (1987).

ANNEX 1: Inventory of existing observation boreholes

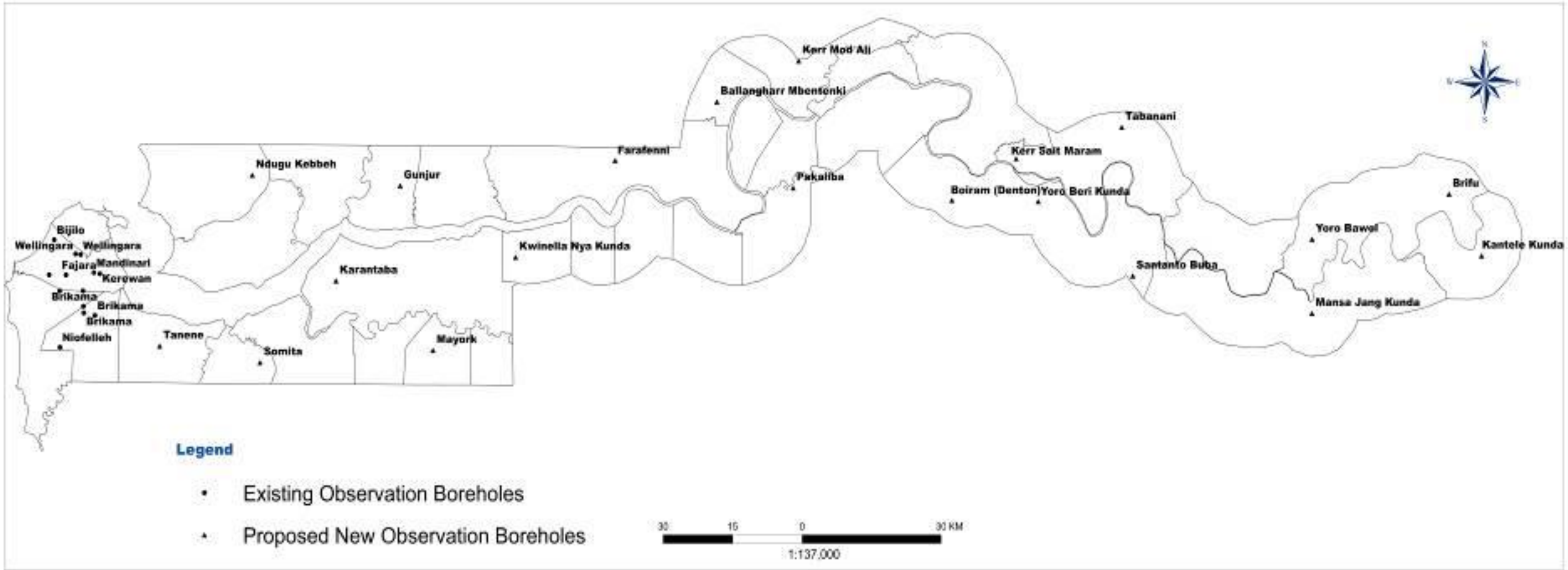
Site Name	Id	Measuring point	N	W	Suitability Assessment/Remarks
Bakendik	POB1 SOB2	0.26 m 0.4002 m	13 27 34.1	16 27 03.7	Rejected due to small diameter and design
Lamin	POB1 SOB2	0.35 m 0.35 m	13 20 59.9	16 25 36.6	Rejected due to small diameter and design
Sara Kunda	POB1 SOB2	0.51 m 0.51 m	13 32 09.1	15 24 45.4	Rejected due to small diameter and design
Kerr Jarga	POB1 SOB2	0.2062 m 0.2062 m	13 32 15.7	16 12 25.2	Rejected due to small diameter and design
Njawara	POB1 SOB2	0.36 m 0.4007 m	13 34 35.3	16 04 20.8	Rejected due to small diameter and design
Kerr Pateh	POB1 SOB2	0.26 m 0.4002 m	13 35 13.9	15 58 02.5	Rejected due to small diameter and design
Kebbeh Kunda	POL09L	0.643 m	13 36 3.5	13 58 11.1	Rejected due to poor design
Nioro	POL22L	0.472 m	13 47 31.5	15 03 22.2	Rejected due to poor design
Sare Gubu	POL12L	0.40 m	13 26 51.7	14 22 34.6	Rejected due to poor design
Njoben	POL21L	0.42 m	13 46 45.9	14 59 02.9	Rejected due to poor design
Tabannani	POL20L	0.405 m	13 37 30.1	14 35 10.6	Rejected due to poor design
Kerr Omar Dahor	POL16L	0.421 m	13 37 21.0	15 03 36.4	Rejected due to poor design
Barro Kunda	POL17L	0.555 m	13 29 19.2	15 14 30	Rejected due to poor design
Kani Kunda	POL19L	0.505 m	13 25 49.8	15 31 14.6	Rejected due to poor design
Yallal	POL25L	0.399 m	13 33 35.5	15 42 26.7	Rejected due to poor design
Njaba Kunda	POL26L	0.411 m	13 34 16.2	15 54 59.2	Rejected due to poor design
Bakalarr	POL27L	0.308 m	13 24 30.1	16 23 50.1	Rejected due to poor design
Fass Omar Sahor	FASS	1.02 m	13 27 44.1	16 22 50.4	Rejected due to poor design
Yoro Beri Kunda	POL11L		13 29 54.0	14 45 32.7	Rejected due to poor design
Latrikunda	BH5	1.79 m	13 27 10.5	16 40 56.7	Rejected due to close proximity of the production borehole. Separation distance is 5.75m.
Bakau	TB10	1.80 m	13 27 59.9	16 40 11.2	Rejected due to its backfill with rubbish
Bakau	BH6	1.92 m	13 27 51.5	16 40 49.8	Rejected due to it close proximity of the production borehole. Separation distance is 6 m.
Fajara	1A		13 27 50	16 41 20	Rejected due to it close proximity of the production borehole. Separation distance is 8 m.

Kotu Stream	TB11	0.114 m	13 27 32.4	16 41 51.7	Rejected due to rubbish backfill.
Kotu Quary	TB13	1.453 m	13 27 14.3	16 41 27.2	Rejected due to rubbish backfill.
Fajara	TB8	1.82 m	13 27 57.9	16 41 33.8	Incorporated in network. Inside a private residence.
Bijilo	OB6	0.468 m	13 25 14.9	16 43 00	Incorporated in network. Inside a private residence.
Brufut	OB7	0.525 m	13 23 44.4	16 44 36	Incorporated in network. Inside a private residence.
Mariama Kunda	OB2	O.465 m	13 21 30.0	16 43 35	Incorporated in network. Inside a private residence.
Jambur	OB3	0.563 m	13 19 46.5	16 42 18	Incorporated in network. Inside a private residence.
Jambur	JO2	0.736 m	13 19 50.1	16 42 26.7	Incorporated in network. Separation distance is 35 m.
Salagi Forest	OB8	0.542 m	13 22 36.4	16 43 15.3	Rejected due to close proximity of the production borehole Separation distance is 15 m.
Sukuta	EX2	0.54 m	13 23 37.5	16 42 10.9	Rejected due to close proximity of the production borehole Separation distance is 15 m.
Wellingara	EX1	0.48 m	13 23 41.7	16 39 50.7	Incorporated in network. Inside a private residence.
Wellingara	EX5	0.56 m	13 23 45.4	16 40 26.7	Incorporated in network. Inside a private residence.
Senchu Sore	OB1	0.573 m	13 23 5.1	16 40 47	Incorporated in network. Separation distance is 23 m.
Wellingara	EX4	0.60 m	13 23 0.2	16 40 55	Rejected because it cannot be traced on the ground.
Old Yundum	EX3	0.827 m	13 21 33	16 40 56.9	Rejected due to backfill of sand and rubbish
Baffoloto	OB4	0.616 m	13 19 48	16 39 31.6	Incorporated in network. Inside a private residence.
Kerewan	OB5	0.47 m	13 21 38.9	16 37 31.5	Incorporated in network. Inside a private residence.
Brikama	OB1	0.50 m	13 17.446	16 39.411	Incorporated in network. Inside Brikama water treatment plant
Mandinari	OB3	0.47 m	13 21.765	16 38.236	Incorporated in network.. Fenced off by NAWEC.
Brikama	O6A	0.56 m	13 18.153	16 39.471	Incorporated in network. Fence off by NAWEC. Equipped with a diver DL501-10 m snG0242
Brikama	O4	0.58 m	13 17.177	16 38.088	Incorporated in network. Fenced off by NAWEC. Equipped with a conductivity diver D1261 10 m/80mS/cm
Niofelleh	05	0.68 m	13 13.743	16 42.238	Incorporated in network. Fenced off by NAWEC. Equipped with a diver DL501-10 m snG0269
Jambur Madina	JO3	0.76 m	13 18.158	16 40.144	Incorporated in network. Separation distance is 32.40 m.
Mariama Kunda	JO1	0.75 m	13 21.784	16 43.565	Incorporated in network. Separation distance is 34.50 m.

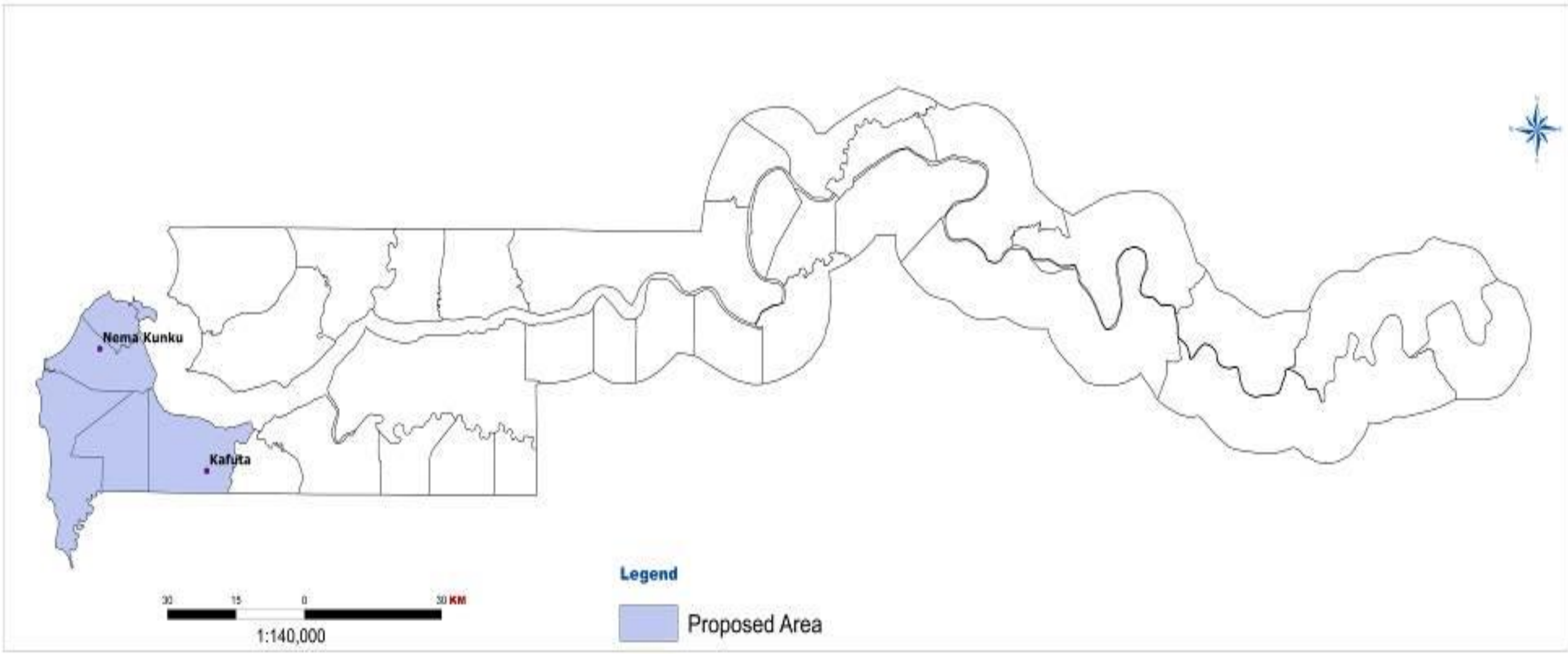
ANNEX 2: Location map of existing observation boreholes



ANNEX 3: Location map of new groundwater monitoring network



ANNEX 4: Selected areas for groundwater model application



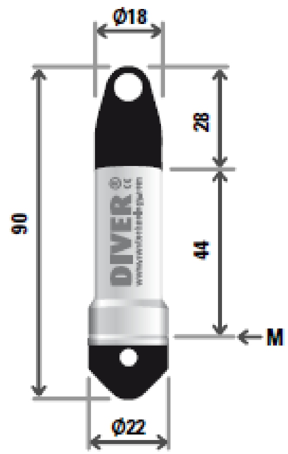
ANNEX 5: Groundwater monitoring equipment specifications

Mini-Diver

The Diver, from *Schlumberger Water Services*, is the smallest instrument in the world for automatic measurement and registration of groundwater levels and groundwater temperatures. The Diver fits in the palm of your hand and is remarkably light. With its length of only 90 mm (135 mm for the CTD-Diver) and a diameter of 22 mm (18 mm for the MicroDiver), the Diver can be used in virtually any monitoring well.

The mini-diver is depicted to the right .

Measuring frequency: 0.5 sec up to 99 hours (fixed only)
Memory capacity: 24,000 measurements (non-volatile)
Material housing: stainless steel 316L
Material pressure sensor: ceramic (Al_2O_3)
Temperature range : -20 °C up to 80 °C
• accuracy: ± 0.1 °C (OT)
• resolution: 0.01 °C
• compensated range : 0 °C up to 40 °C
Battery life : 8-10 years (dependent on use)
Dimensions : Ø 22 mm x 90 mm
Weight : 70 grams
Type 501/502/505
Measuring range 10m/20m/50mH2O
• typ. accuracy** ± 0.05/0.01/0.025%
• resolution 0.25/0.40/1.00 cmH2O



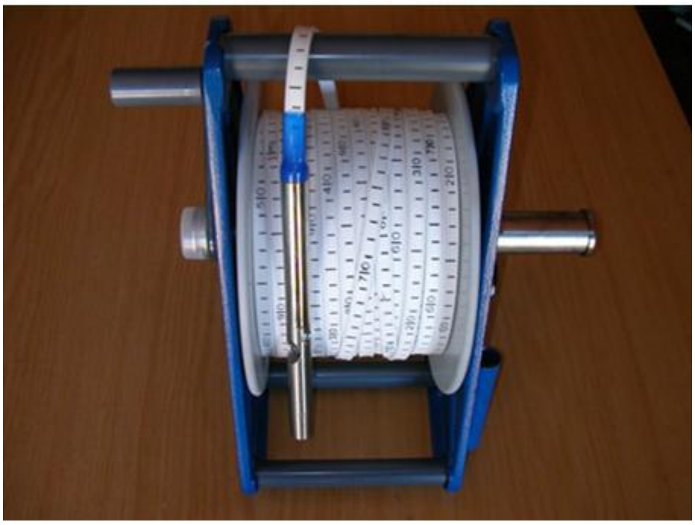
M = membrane
Dimensions are expressed in mm.

Water Level Meter

The special features for a manual water level meter/dip meter are:

Accurate: Markings each 1/100 ft. or millimeter
Traceable to national standards
Sensitivity adjustable to conductivity
Probes avoid false readings in cascading water

Reliable: Permanent laser markings
Non-stretch PVDF tape with stainless steel conductors



Water level dipper

Long Life: Rugged, corrosion proof components
Strong, flexible tapes
Easy to splice and repair

Types of indicator: with visual and audible signal
Others: complete with a carrying bag

Ruggedized laptop for field data collection

Typical specifications for ruggedized computers are:

- Processor Intel Core Duo ULV SU9600 (1.6GHz, 800 MHz FSB, 3 MB L2 Cache)
- Genuine Windows 7 Professional 32-bit Operating System
- Displays 12.1" WXGA DLV outdoor-readable with capacitive multi-touch (1280 x 800)
- Memory: Dual Channel DDR3 1066MHz (1 GB down + 1 slot)
- Up to 5 GB DDR3 1066 MHz
- 500 GB Solid State Drive
- Standard sealed keyboard or backlit rubber sealed keyboard
- Capacitive multi-touch screen with dual-touch input and digitizer pen
- 10/100/1000 gigabit Ethernet network interface adaptor
- Wireless LAN: (Varies by country)
- Bluetooth
- Power: 6-cell 42W/Hr Li-Ion Primary Battery
- Optional vehicle docking systems
- Chassis that can stand up to drops, spills, vibration and temperature extremes.

Ruggedized laptop
Manufacturer's Website: http://www.dell.com

Bladder pump for groundwater sampling

The bladder pump is used for sampling inorganics/hydrocarbons. It operates to a maximum depth of 110 m. It is powered by compressed air. The Grundfos Redi-Flo2 is also very robust and quite suitable for this kind of condition such as borehole purging. Typical specifications for bladder pumps are:

- The bladder ensures that drive air or gas does not contact the sample, thus avoiding degassing or contamination of the sample.
- Bladder pumps are rugged and long lasting. Teflon bladders are ideal for dedication, while less expensive polyethylene bladders could be used if bladders are to be changed after each use. Bladders and intake filters should easily be replaced in the field in just a few minutes. No special tools required.
- The bladder pump should be excellent for either regular flow or low flow sampling, the stainless steel pumps lifts from depths up to 110 m below ground level. The PVC Bladder Pump operates up to 110 m below ground level.
- Packers can be used to further reduce purge volumes and to speed sampling times.
- Stainless Steel (1" / 25 mm diameter) or low cost PVC (1.66" / 42 mm diameter)
- Pumps should operate effectively at almost any angle and can be placed under landfills, tailings, storage tanks or contaminant plumes.
- Bladders are not damaged by operation in sediment laden water, or in dry pumping conditions.

Bladder pump

Portable generator

Typical specifications for a portable generator are:

- Rated AC output 4.0 KVA
- Fuel tank capacity 25.0 litres
- Dry weight : 45kg
- Voltmeter and backlight: The Voltmeter enables measurement of the high output performance of the generator. The Backlight voltmeter allows one to check the generator output even in the dark.
- Fuel gauge and oil Alert: Oil alert system stops the engine automatically when oil level is too low. Large fuel gauge allows one to check fuel level at a glance.
- Air Cleaner: Large-size air cleaner ensures excellent air intake efficiency for optimum engine power output.
- Protective Frame: Sturdy frame with upper guard pipes protects the machine, while making it easier to transport.

Portable generator for powering bladder pump

ANNEX 6: Location of the 18 monitoring boreholes within GBA