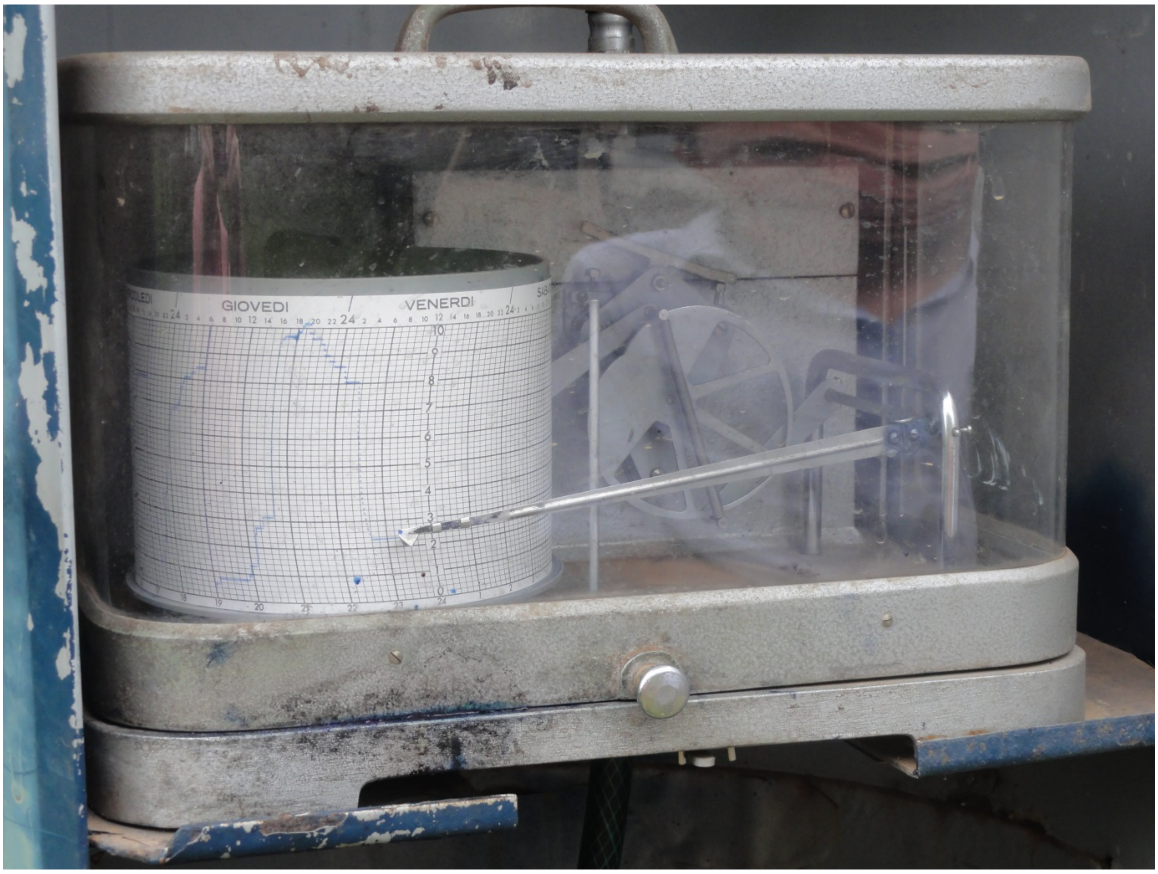
Republic of Sierra Leone

Ministry of Water Resources

Data and hydrological understanding generated in the Water Security project

Volume 3 of a three volume set

March 2015



An automatic raingauge at the Bumbuna Dam Site

The three volumes produced through the Sierra Leone Water Security Project (Box 2) were drafted by a team drawn from the Ministry of Water Resources and Adam Smith International. The team members were (in alphabetical order) Richard Carter, St John Day (Lead Author), Peter Dumble, Mohammed Juana, Ishmail Kamara and Abubakarr Mansaray. The three volumes have benefitted from additional comments from members of the Ministry of Water Resources and Bumbuna Watershed Management Authority, as well as inputs from local Government. This volume should be cited as ***Ministry of Water Resources (2015) Data and hydrological understanding generated in the Water Security project. Volume 3 of 3. Government of Sierra Leone.*** It may be downloaded in electronic form from www.salonewatersecurity.com. The other two volumes are: *Volume 1 Strategy for Water Security Planning* and *Volume 2 Water resources monitoring in Sierra Leone*. For further information contact Mohammed Juana (msejuana@yahoo.co.uk), cc'ing Richard Carter (richard@richard-carter.org), St John Day (stjohn.day@adamsmithinternational.com), and Peter Dumble (Peter.Dumble@PDHydrogeology.com).

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Go to www.SaloneWaterSecurity.com

Abbreviations

AfDB	African Development Bank
ASI	Adam Smith International
ASL	Above sea level
BOD	Biochemical oxygen demand
BWMA	Bumbuna Watershed Management Authority
d/s	Downstream
DFID	Department for International Development
DO	Dissolved oxygen
EC	Electrical conductivity
Fe	Iron
GEF	Global Environment Facility
GoSL	Government of Sierra Leone
IFAD	International Fund for Agricultural Development
MEWR	Ministry of Energy and Water Resources
MW	Megawatts
pH	A measure of acidity
SLEPA	Sierra Leone Environmental Protection Agency
SLL	Leone (currency)
TSS	Total suspended solids
u/s	Upstream
UKMO	UK Meteorological Office
UNDP	United Nations Development Programme
UNICEF	United Nations Children's Fund
UNIDO	United Nations Industrial Development Organisation
WASH	Water, Sanitation and Hygiene
WMO	World Meteorological Organisation
WSP	Water and Sanitation Program (World Bank)

Definitions

Community-based	Referring to activities undertaken by, or with the participation of, local communities.
Data, information and knowledge	Data are raw numbers derived from measurement or regular monitoring. When data is processed and interpreted, it becomes information. When that information is assimilated and used by individuals and organisations, it becomes knowledge.
Groundwater	Groundwater refers to water below ground, held in saturated bodies of rock or earth material. It can provide water to wells and boreholes. If the water table intersects the earth's surface, groundwater discharges naturally as spring flow and river base flow.
Hydrology	Hydrology is the study, measurement and understanding of surface water flows. Groundwater hydrology is the corresponding study of underground water.
Hydrometeorology	The study, measurement and understanding of surface and groundwater hydrology, together with the meteorology on which water resources depend.
Improved / unimproved water source	Improved water sources are those which are engineered and protected in such a way as to provide safe water, ie water free of, or low in, disease-causing pathogens. Unimproved sources are unprotected from faecal contamination and so pose a risk to human health.
Meteorology	Meteorology is the study, measurement and understanding of weather.
National monitoring networks	Networks of rain gauges, river flow stations and groundwater data points designed to inform a nation of the spatial and temporal distribution of its water resources.
Water resources	Water resources are the streams, rivers, surface water bodies and groundwater stores which by their natural discharges support wetland ecosystems, and which can be exploited for water supply for many purposes.
Water security	Water security means different things to different water users. However, the common feature for all is the assurance of sufficient quantity and quality of water for all the uses to which water is put. This, combined with low risk from water-related hazards (floods and droughts) constitutes water security.
Water security planning	Water security planning is a structured participative process involving risk assessment, focused monitoring and action planning. It is an extension of the more narrowly focused approach known as water safety planning.
Water supply	Water supply is the act of harnessing, engineering and managing the delivery of water to water users, for domestic, agricultural and industrial (including electricity generation) uses.

Ministerial Foreword

Sound monitoring and management of water resources are essential in all countries which are striving to achieve water security for their people and economies. Data collected from monitoring has to be analysed and understood before it can be used. This document represents an important contribution to creating that hydrological understanding in Sierra Leone.

Prior to our nation's destructive civil war (1991-2002), Sierra Leone had extensive hydrometeorological monitoring networks and published annual water resources yearbooks. In the years that followed virtually no water resources management activities have taken place. We want to address this oversight by (re-)establishing systems for monitoring and managing water resources, strengthening our institutions and helping to promote sound stewardship of water and land resources at local, national and transboundary levels.

With increased understanding of water quality and quantity, coupled with the introduction of new legislation and the formation of a new regulating agency, we have the possibility to develop our water resources in a safe and sustainable manner. The time and cost involved in introducing water security measures will be far outweighed by the social, economic and environmental damage that will be experienced if we do not act now.

The more our population grows and industries working in Sierra Leone expand, the greater the impacts on our water and land resources. We must also overcome the difficulties of water security planning by coordinating and guiding the growing number of donors and implementing agencies that plan to undertake some form of water resources monitoring and management activities. Everyone agrees the challenge is to build institutional capability so that we can ensure water availability is consistent with growing demand. In particular we need to understand collective water demands on dry season river flows. If we can become better at building on models of success, ensure that good ideas don't get lost and adopt them more quickly and efficiently across the country, then we can build national and transboundary water security plans from local level initiatives.

I am committed to achieving the ambitions contained within this strategy document, as I believe they can be a catalyst for the change Sierra Leone needs to make. We are all increasingly aware of the importance of sound stewardship of water and land resources. But we will only achieve our ambitions through clear commitment and leadership from Government, working alongside our international donors, industry, communities, water utilities and implementing partners.

I would like to thank everyone who has contributed to this document, especially those who have been directly involved in the Sierra Leone Water Security Project, who have taken the time to share learning and evidence generated from this project.

Honourable Minister Momodu Maligi III
Ministry of Water Resources, Sierra Leone

Executive Summary

Although Sierra Leone is a well-watered country, the pressures on the quantity and quality of its water resources are growing daily. Small-scale abstractions for rural and small town water supply, as well as large-scale requirements for hydro-electric power production, mining, irrigated agriculture and urban water supply all compete for a finite quantity of water. Discharges or effluents from all these uses and users threaten to pollute aquifers and watercourses, affecting other downstream users. As population grows and the economy matures, these pressures will only increase. Measures taken now can mitigate some of the risks to Sierra Leone's precious water resources.

Some of these measures have been piloted in the Sierra Leone Water Security Project, a two-part programme funded by DFID through its WASH Facility, facilitating collaboration between the Ministry of Water Resources, the Ministry of Energy (specifically the Bumbuna Watershed Management Authority) and specialist consultants from Adam Smith International. This programme has been working since October 2012 to test out different aspects of water security planning, and to develop guidance for practitioners, scientists and policy-makers.

This document is Volume 3 of 3, and sets out analyses of the data collected so far in the Water Security Project and compares this to historical data sources. Volume 1 provides strategic and policy-level guidance to Government, while in Volume 2 practical guidance is given on the monitoring of water resources.

This Volume begins by identifying the river basins of Sierra Leone and setting out the types of hydro-meteorological data gathered by this project both from historical sources and from a pilot monitoring network established in the mid-Rokel-Seli River basin involving monitoring at a total of 33 sites. It then goes on to explain in detail how this new data compares to historical records and to interpret data in ways that have relevance to the management of water resources in the river basin. The final sections draw out conclusions and recommendations based on the experience of gathering data from community, government and other stakeholder organisations working together, and how this may be used to inform current plans to re-establish national monitoring networks in Sierra Leone.

A major challenge in operating any monitoring system is in building skills and expertise not only in using equipment and standardising methodology when collecting data, but also in collating, cleaning, and ensuring data is of high quality and can be understood, accessed and used by others for management purposes – ie to deliver a public service.

The pilot monitoring network established in this project incorporates 16 sites where groundwater levels are recorded every 15 minutes; 26 sites with rain gauges where rainfall is recorded at least daily; 4 surface water sites with weirs installed to measure small stream flows; and a number of existing monitoring sites along the Rokel-Seli River where data has been made available by other organisations for this project, including river flow measurements.

This Volume draws on the experience of the Water Security Project in taking the data collected from the pilot monitoring network in the Rokel-Seli river basin, presenting this in written and digital formats for access by others and drawing some preliminary conclusions based on data collected during 2013 representing almost a full hydrological year.

Sound management of water resources depends, among other things, on good information – information about the quantity, quality, seasonality and behaviour of weather, surface water flows and groundwater. Such information can only come from **monitoring** to produce good quality data, intelligent **analysis** of those data, and complete and clear **communication** of the key issues to educated and well-informed decision-makers.

Box 1 Sierra Leone's river basins

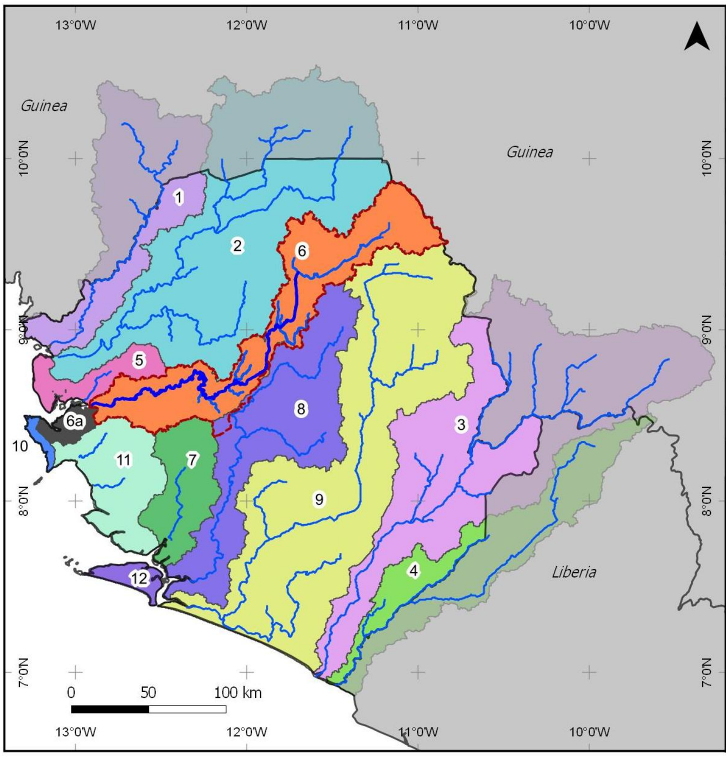
Between ten and thirteen main river basins and water resource areas (WRAs) have been identified in Sierra Leone following those shown in a 1988 map in Ndohamina and Kabia 2004. Map 1 is updated from the 1988 map using the same numbering system but with boundaries generated by USGS HydroSHEDS (http://hydrosheds.cr.usgs.gov/index.php). This map provides a more accurate representation of boundaries between basins than previously available and includes the full extent of those which cross international borders into neighbouring Guinea and Liberia. There is a 2% difference in the total HydroSHEDS river basin areas compared to the officially published country area for Sierra Leone of 71,740 km^2. This is due to different methods of calculation.

USGS HydroSHEDS catchment boundaries are generated automatically and should be considered to be first order approximations. Boundaries are computed from 15 arc second (~450 m) Shuttle Radar Topography Mission data (SRTM). Although SRTM data is currently the best digital elevation data available for Sierra Leone, the automated methods, together with vegetation artefacts and other noise sources in elevation data can lead to errors in boundary positions. In order to improve the accuracy of the Rokel-Seli catchment boundary, the HydroSHEDS generated boundary was validated and corrected using contours derived from the more detailed SRTM DEM 3 second data (~90 m). Further validation and correction was then undertaken against other data sources such as Bing and Landsat satellite images. The revised boundary is shown in red in Map 1 and is in fact slightly larger than the HydroSHEDS calculated basin area. It is this area that is used in the maps and other details of this report.

Ultimately all Sierra Leone catchments should be validated in this manner. Improved validation is now possible following the release in October 2014 of SRTM 1 arc second (~30 m) elevation data.

Maps

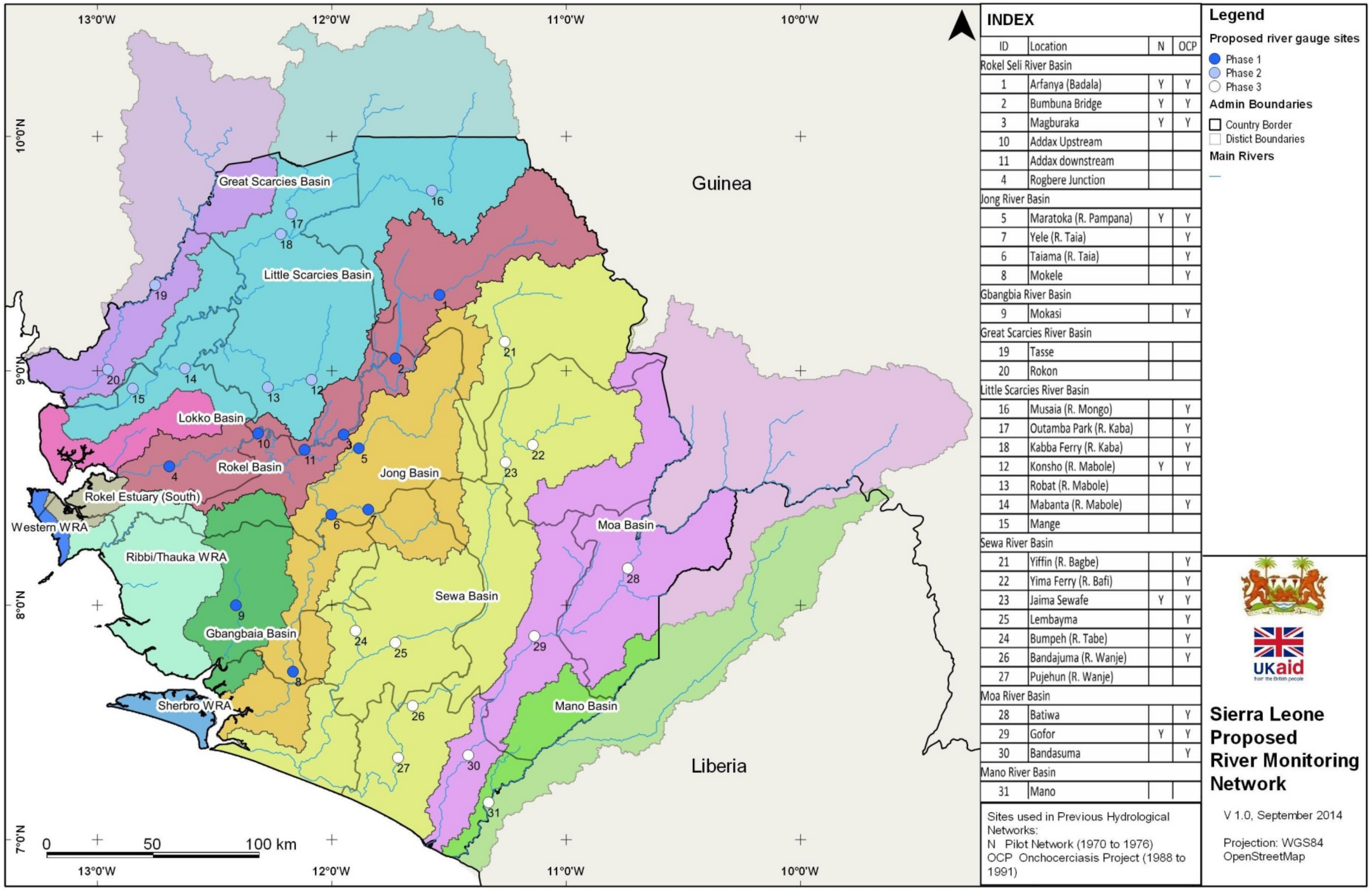
Map 1 Sierra Leone river basins



Basin	Name	Country Area	Total Area
B 1	Great Scarcies Basin	2979	8303
B 2	Little Scarcies Basin	13383	18955
B 3	Moa Basin	9583	19835
B 4	Mano Basin	1959	7776
B 5	Lokko Basin	1565	1565
B 6	Rokel Basin	8236	8236
B 6a	Rokel Estuary (South)	579	579
B 7	Gbangbaia Basin	3121	3121
B 8	Jong Basin	8288	8288
B 9	Sewa Basin	19022	19022
B 10	Western WRA	223	223
B 11	Ribbi/Thauka WRA	3670	3670
B 12	Sherbro WRA	612	612
	Totals	**73220**	**100185**

Notes:
* Source HydroSHED catchment boundaries http://hydrosheds.cr.usgs.gov/index.php
* Rokel basin area has been modified after manually digitising the Rokel boundary (Red line)
* All areas are in square kilometres
* WRA - Water Resources Area
* "Country Area" is basin area inside Sierra Leone
* "Total Area" is total basin area
* Basin 6a is part of the Rokel River management area shown in GOSL documents. It is subdivided here for clarity

Map 2 Sierra Leone river basins and proposed river monitoring network, 2014

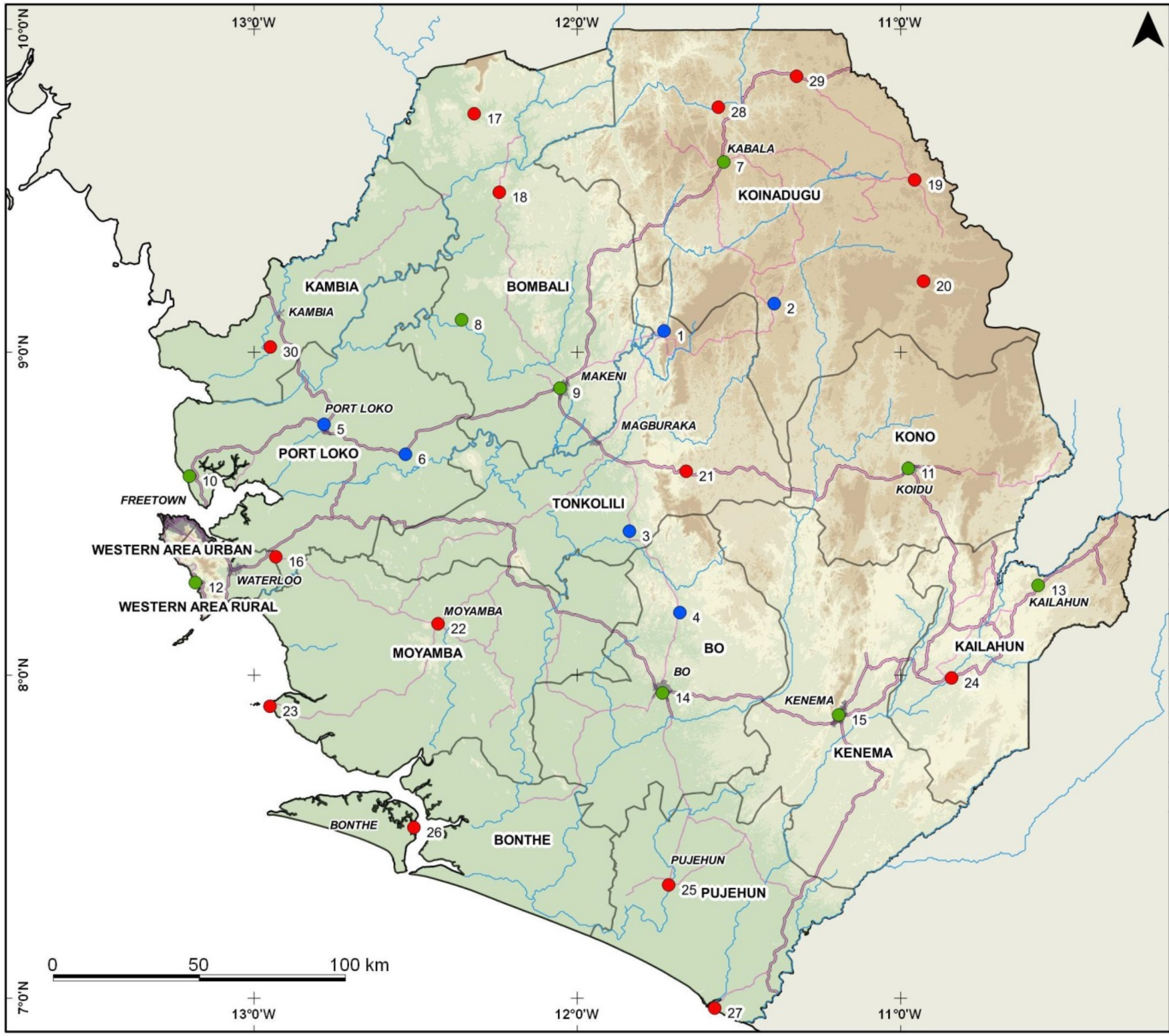


INDEX

ID	Location	N	OCP
Rokel Seli River Basin			
1	Arfanya (Badala)	Y	Y
2	Bumbuna Bridge	Y	Y
3	Magburaka	Y	Y
10	Addax Upstream		
11	Addax downstream		
4	Rogbere Junction		
Jong River Basin			
5	Maratoka (R. Pampana)	Y	Y
7	Yele (R. Taia)		Y
6	Taiama (R. Taia)		Y
8	Mokele		Y
Gbangbia River Basin			
9	Mokasi		Y
Great Scarcies River Basin			
19	Tasse		
20	Rokon		
Little Scarcies River Basin			
16	Musaia (R. Mongo)		Y
17	Outamba Park (R. Kaba)		Y
18	Kabba Ferry (R. Kaba)		Y
12	Konsho (R. Mabole)	Y	Y
13	Robat (R. Mabole)		
14	Mabanta (R. Mabole)		Y
15	Mange		
Sewa River Basin			
21	Yiffin (R. Bagbe)		Y
22	Yima Ferry (R. Bafi)		Y
23	Jaima Sewafe	Y	Y
25	Lembayma		Y
24	Bumpeh (R. Tabe)		Y
26	Bandajuma (R. Wanje)		Y
27	Pujehun (R. Wanje)		
Moa River Basin			
28	Batiwa		Y
29	Gofor	Y	Y
30	Bandasuma		Y
Mano River Basin			
31	Mano		

For details and locations of historical river gauging stations, see Volume 1, Appendix C.

Map 3 Sierra Leone topography and proposed meteorological monitoring network (2014)



ID	Nearest Town	a	b
1	Bumbuna		
2	Alikalia	AC	
3	Yele	R	
4	Dambara		
5	Port Loko	C	Y
6	Lunsar		
7	Kabala	S	Y
8	Mateboi		
9	Makeni	C*	Y
10	Lungi	S*	Y
11	Koidu-Sefadu	R	
12	York (No 2 River)	C	Y
13	Kailahun	C	Y
14	Bo	S*	Y
15	Kenema	C	Y
16	Newton	C	Y
17	Yana		
18	Kamakwie	AC	
19	Bendugu	AC	
20	Kurubonia		
21	Makali	C	
22	Moyamba	AC	Y
23	Shenge	R	
24	Daru	S*	Y
25	Pujehun	C	Y
26	Bonthe	S	Y
27	Sulima	R	Y
28	Musaia	C	Y
29	Falaba		
30	Rokupr	C	Y

(a) Sites which have been used in the past
* Site in current use by SL Met Department
S Synoptic Station
C Climate Station
AC Agro-Climate Station
R Rainfall Station

(b) Sites used in Gregory, 1965, Rainfall over Sierra Leone. University of Liverpool. 58pp

Legend

Proposed Meteorological sites (UK Met Office)
- Located on basis of proximity to water and HEP stations
- Sites included in SLMD basic AWS network
- Sites located for evenness of coverage across whole country

Admin Boundaries
- District Boundaries
- District Towns
- Country border

Roads
- main
- secondary

Main Rivers

Elevation (m)
- 100-200
- 200-300
- 300-400
- 400-500
- 500-600
- 600+

UKaid from the British people

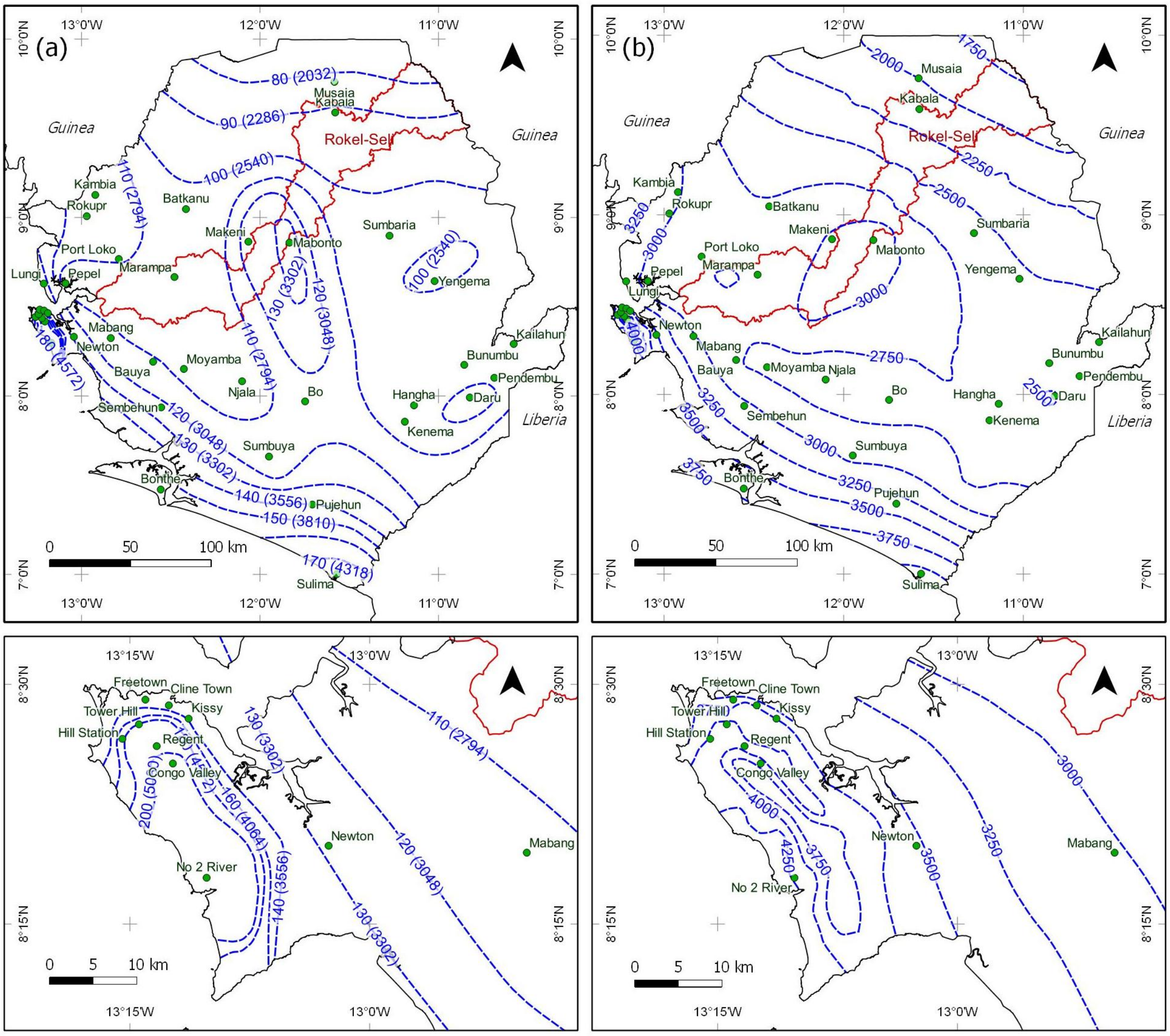
Sierra Leone Proposed Meteorological Monitoring Network

V 1.0, September 2014

Projection: WGS84
SRTM Topography
OpenStreetMap

For details and locations of historical Meteorological and Rainfall stations, see Volume 1, Appendix B.

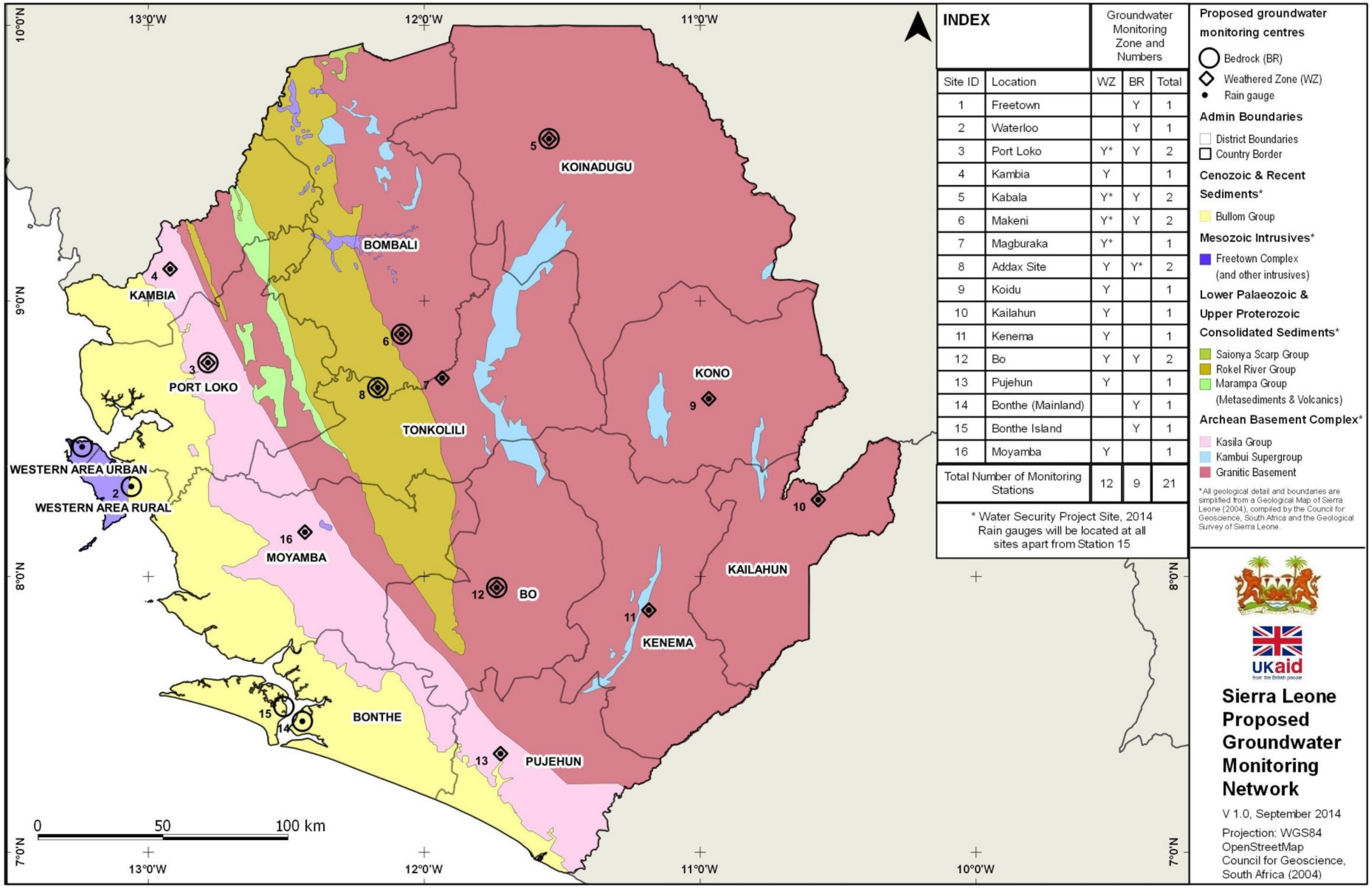
Map 4 Sierra Leone mean annual rainfall



Mean annual rainfall 1941 to 1960
Source: Gregory, 1965, Fig 30
Rainfall values in inches (mm in brackets)
Locations of Historical rainfall stations labelled

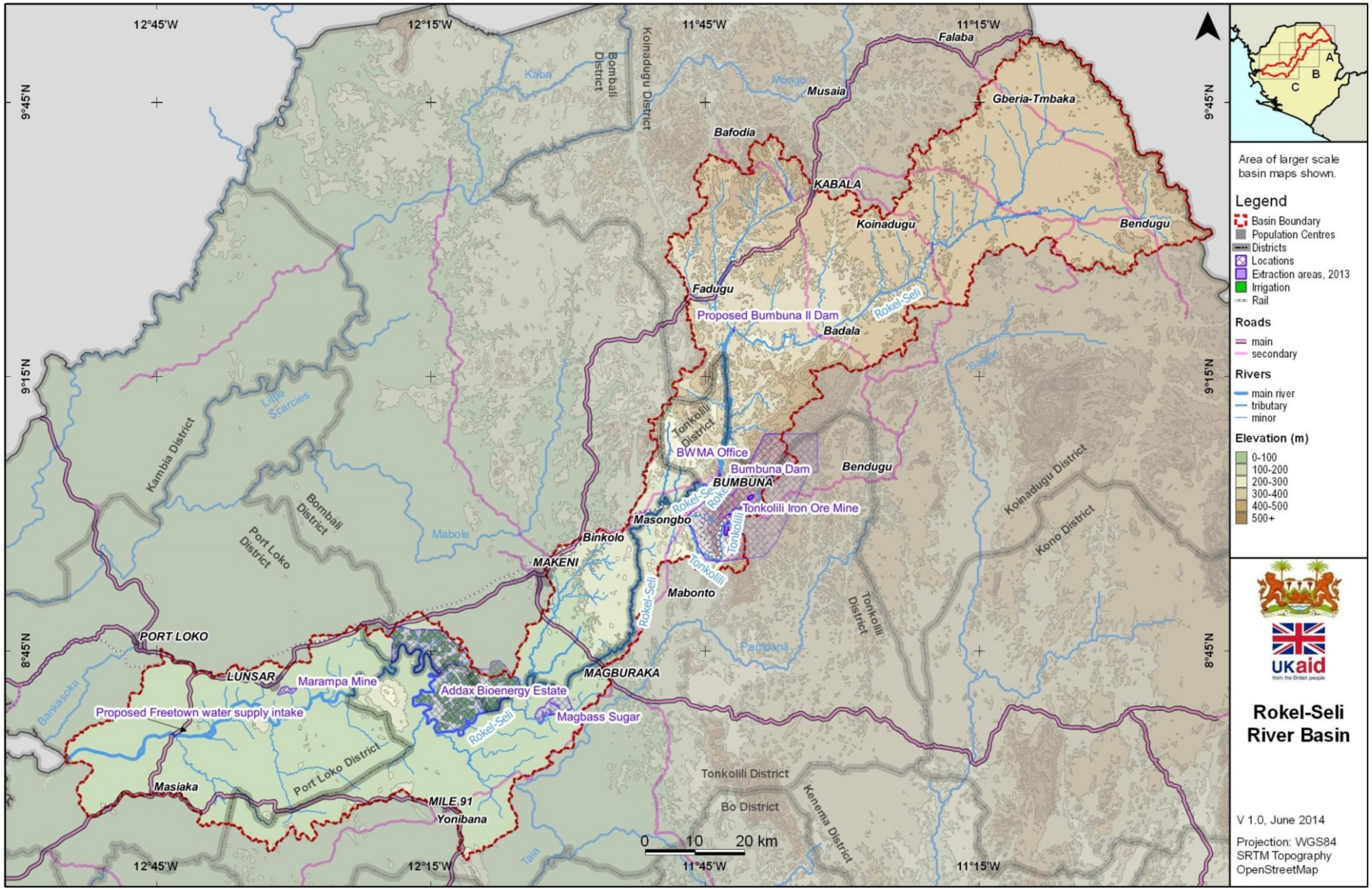
Mean annual rainfall 1950 to 2000
Source: WorldClim raster data (http://www.worldclim.org/)
Contoured using Inverse Distance Weighting
Rainfall values mm
Locations of Historical rainfall stations labelled

Map 5 Sierra Leone geology and proposed groundwater monitoring network (2014)

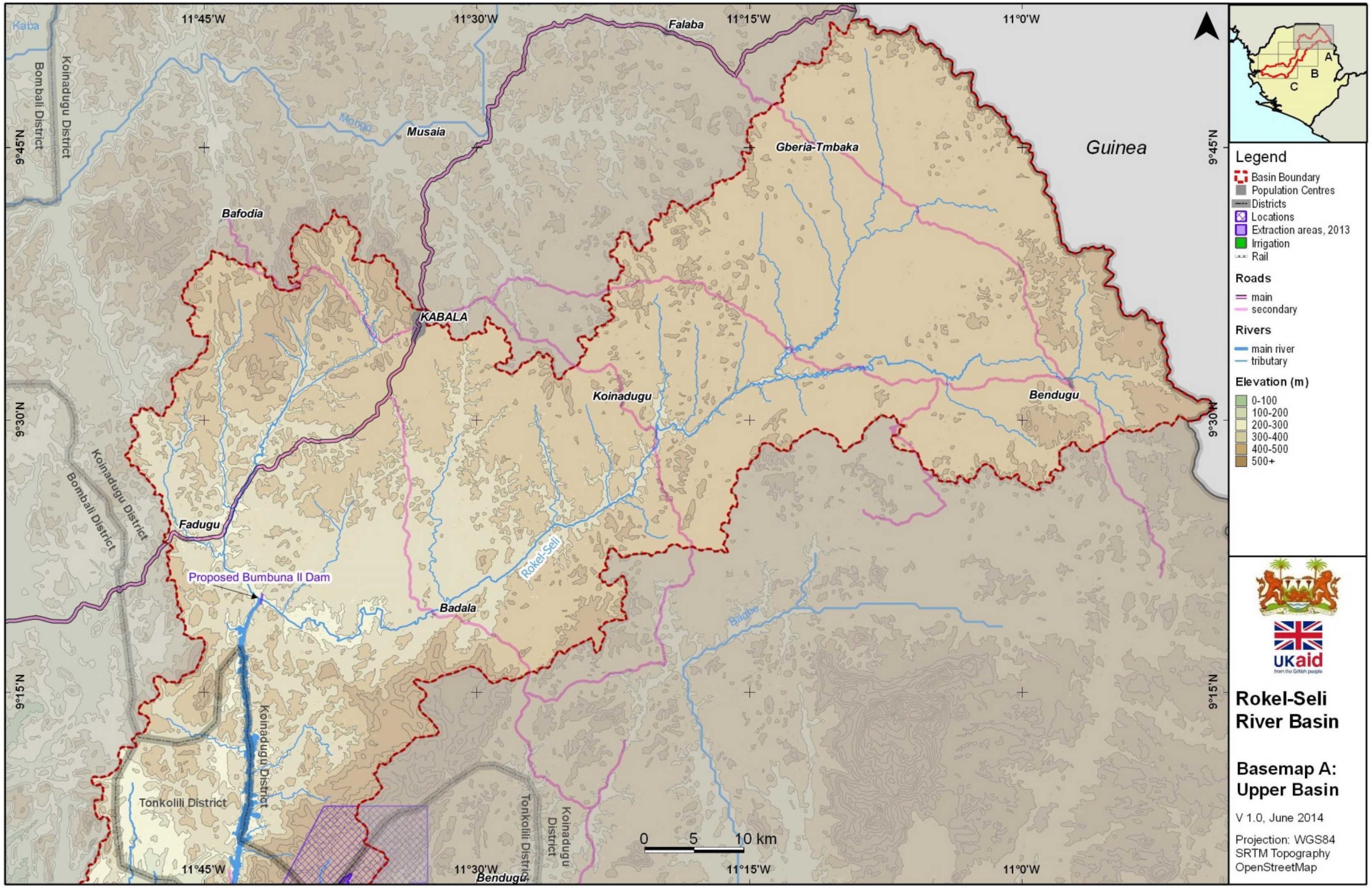


For a photographic reproduction of a more detailed Map from the Geological Survey of Sierra Leone (2004) go to Koidu Holdings web site (*http://www.koiduholdings.com/images/kkp_geology_fig1_large.jpg*)

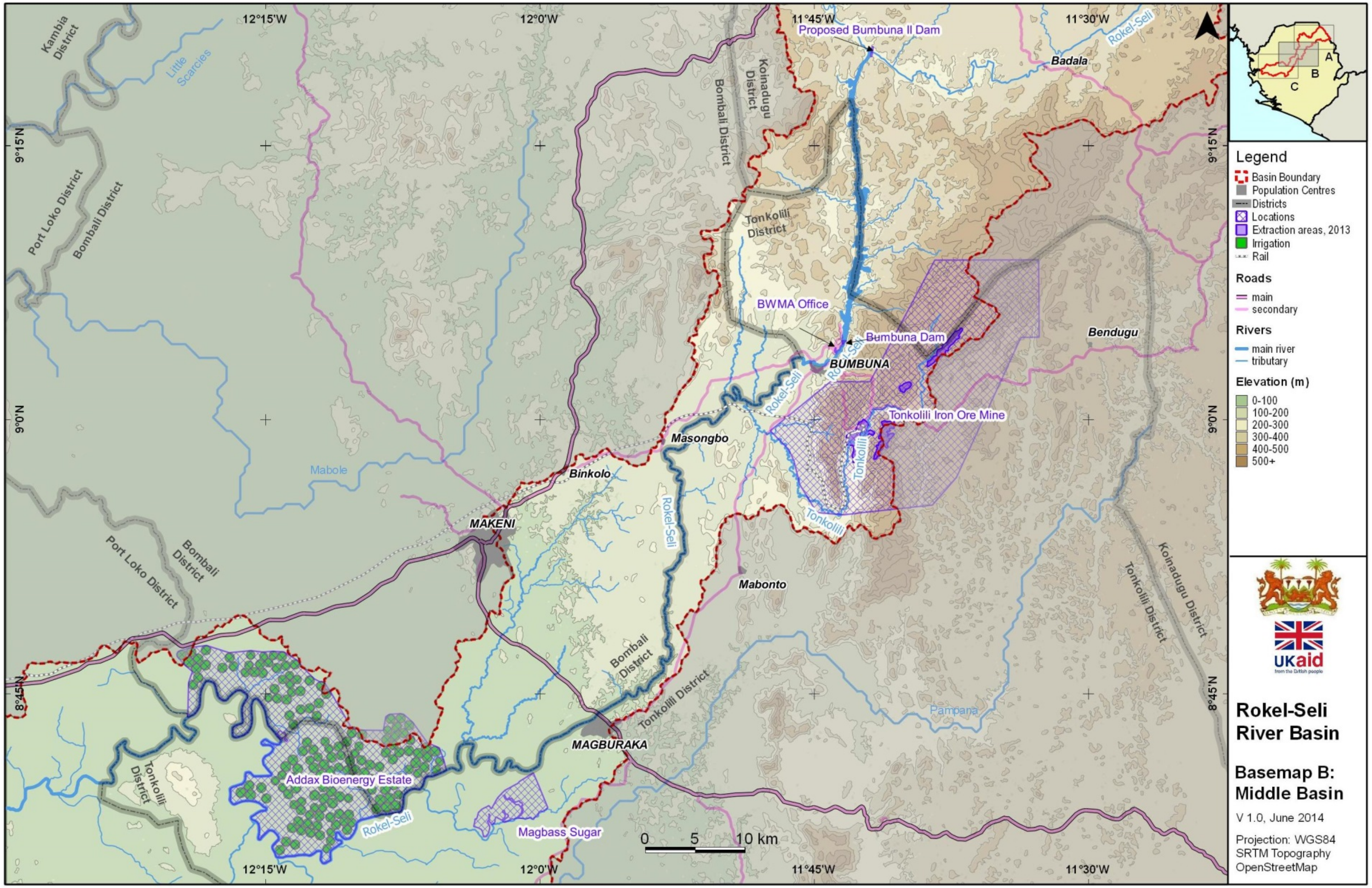
Map 6 Rokel-Seli River Basin



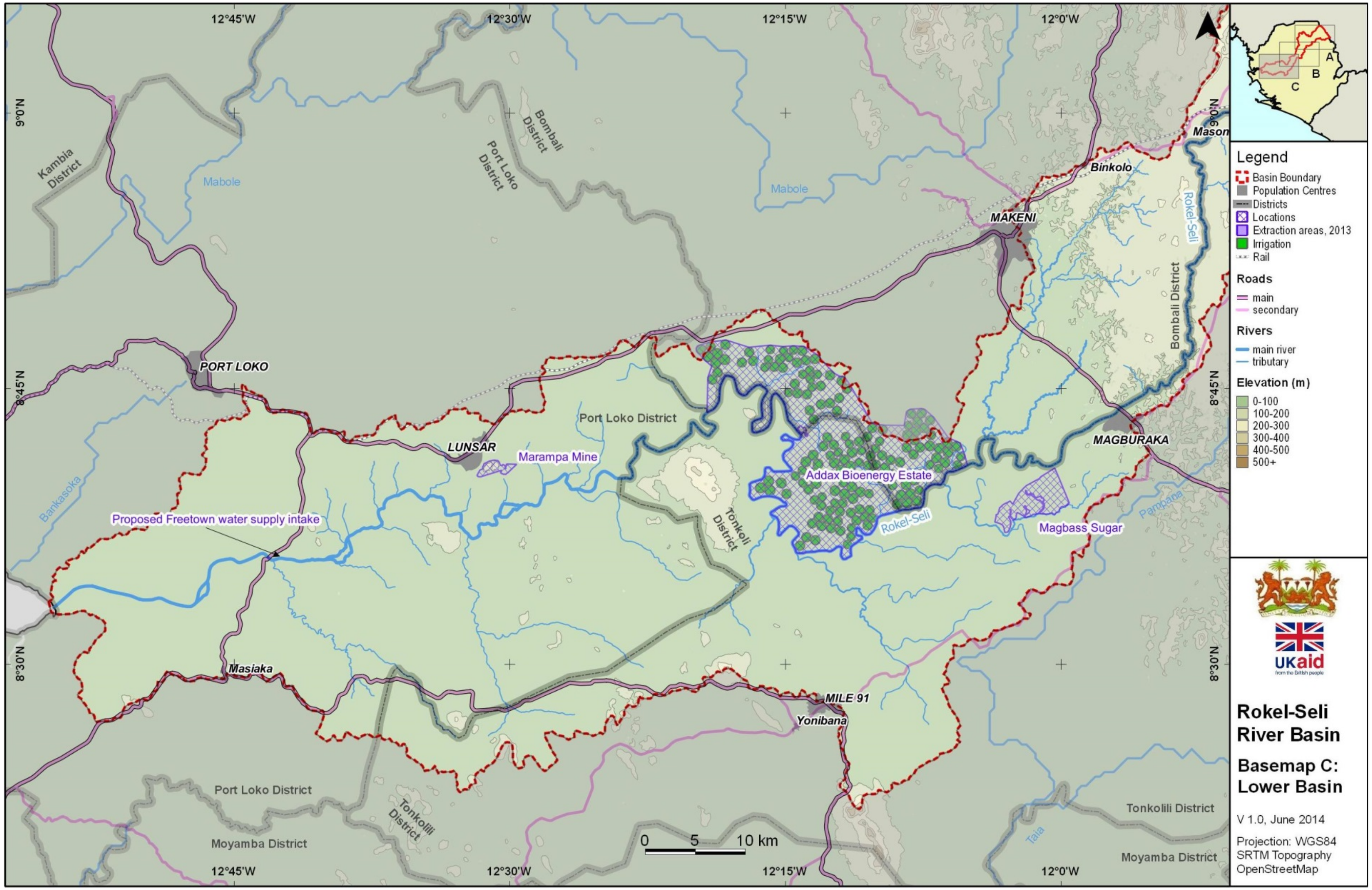
Map 7 Rokel-Seli River Basin – Upper Basin



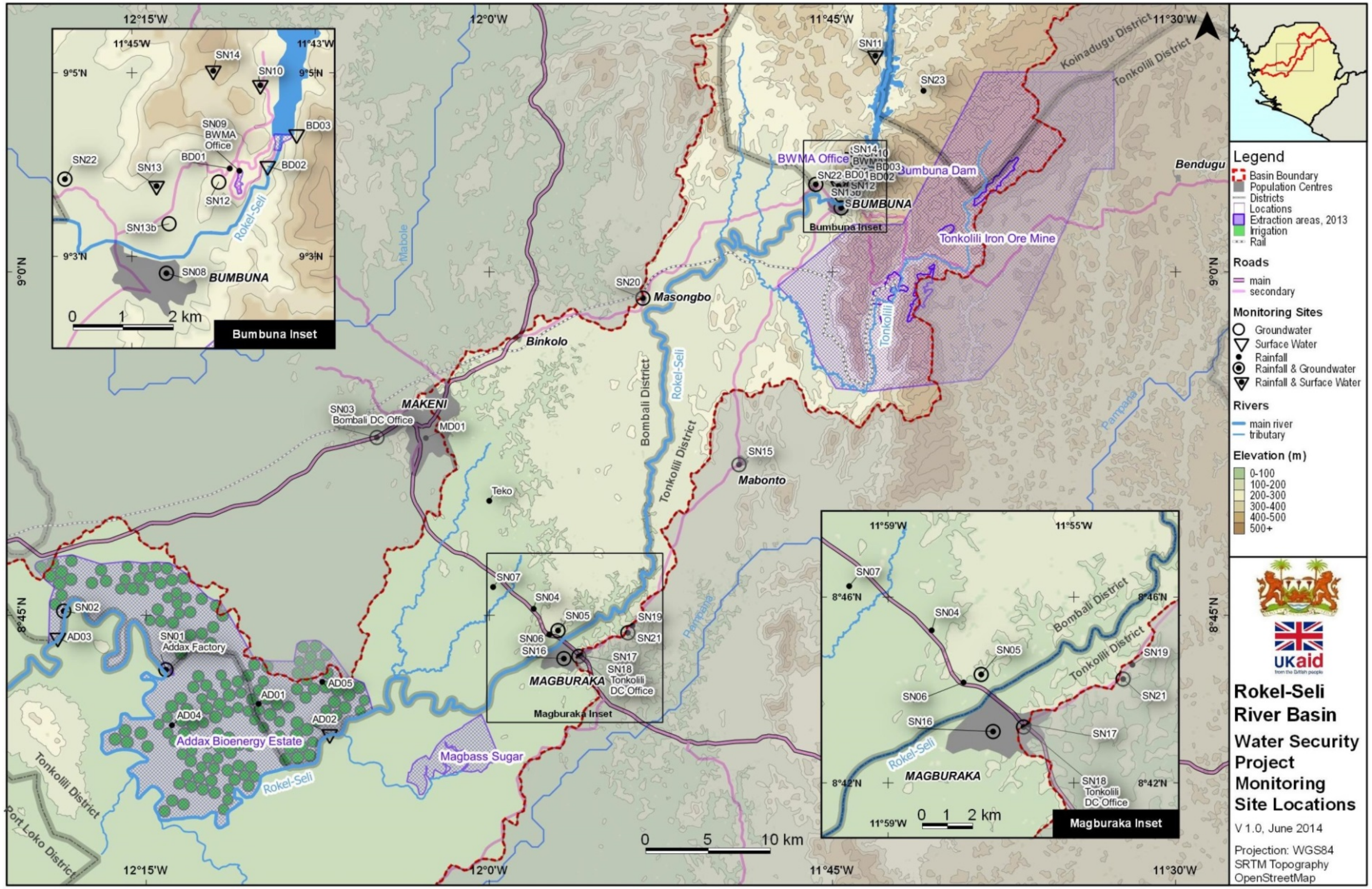
Map 8 Rokel-Seli River Basin –Middle Basin



Map 9 Rokel-Seli River Basin –Lower Basin



Map 10 Rokel-Seli River Basin – Pilot Area and Water Security Project Monitoring Sites



Box 2 The Sierra Leone Water Security Project

The Sierra Leone Water Security Project consists of two work streams, both funded by DFID through its national WASH Facility. The two work streams together facilitate collaboration on water security between the Ministry of Water Resources, the Ministry of Energy (specifically the Bumbuna Watershed Management Authority), a team of specialist consultants from Adam Smith International, and a large number of local and national stakeholders. The two work streams began in late 2012 and early 2013, and are due to complete their initial phases in early to mid-2014. The two work streams are considered jointly in these Volumes.

The Water Security Project has the overall aim of '*putting in place the foundations for water security in Sierra Leone*'. Water security means different things to different water users. However, the common feature for all is the assurance of sufficient quantity and quality of water for all the uses to which water is put. This, combined with low risk from water-related hazards (floods and droughts) constitutes water security.

The Water Security Project has been working in the middle reaches of the Rokel-Seli River Basin, the largest and arguably one of the most strategic river basins in Sierra Leone. The Rokel-Seli River Basin contains a microcosm of the water management and water security issues which occur in Sierra Leone. Large-scale hydroelectric power production, mining, urban water supply and irrigated agriculture compete for surface water, while rural and small town populations depend heavily on spring flows, small streams, wells and boreholes for their domestic water supply.

Overall, the Water Security Project has been addressing the following main issues:

- how to begin to re-establish water resources monitoring in Sierra Leone;
- how to most usefully analyse, interpret and present hydrometeorological data;
- how to involve all stakeholders in decision-making over water management;
- how to guide Government as it considers its policies and procedures for national-scale water resources management.

Three Volumes of interim findings and guidance from the Water Security Project are presented:

- Volume 1 consists of strategic guidance to national Government.
- Volume 2 presents practical guidance on water resources monitoring.
- Volume 3 sets out analyses of our own and other water resources data.

Box 3 The Rokel-Seli River Basin, Sierra Leone

The Rokel-Seli River Basin rises in the highlands of the Sierra Leone – Guinea border, in the north-east of Sierra Leone, at an elevation of about 900masl. It runs a total distance of about 390km, discharging into the Atlantic Ocean north of Freetown. The basin area is estimated as 8,236km^2. The mean annual river flow at Bumbuna (measured over the period 1971-78) was 112.9m^3/s or 3,560Mm^3/a. The flow is highly seasonal with mean monthly discharge in September of 330.5m^3/s and in March only 6.1m^3/s.

The Bumbuna hydroelectric power dam is located 2.5km upstream of the Bumbuna falls. It was commissioned in November 2009, although construction had originally commenced in the 1990s. Construction was abandoned in 1997 when the dam was 85% complete, as a consequence of the war. The dam has been operational since 2009. It is a run-of-river scheme, having relatively little reservoir storage despite its 88m high dam and 30km long reservoir. The power plant is rated at 50MW (through two turbines), but it has rarely operated at this level to date. A second dam, Bumbuna II, is under detailed design at the time of writing. It is to be located 28km upstream of Bumbuna I at Yiben, and it will significantly add to the power output of the Rokel-Seli River.

Other major water users / potential polluters in the upper basin include the iron ore mine operated by African Minerals at Tonkolili – ramping up to full production by 2014 – and the Magbass irrigation scheme – developed in the 1980s.

Further down the basin Addax Bioenergy abstracts water from the Rokel-Seli River for irrigation of sugar cane, while a number of other mining concessions exist too (including Marampa, near Lunsar, operated by London Mining since 2011).

There are current plans / intentions to extend Freetown's water supply, based on abstraction from the Rokel-Seli River at Makeni Ferry Bridge about 24km upstream of Freetown.

The Rokel-Seli River Basin flows through parts of Koinadugu, Tonkolili, Bombali and Port Loko Districts. Within these districts, rural and small town water supply is needed for domestic use, and the demands for clean water are likely to go on increasing as population grows.

In short, the Rokel-Seli River Basin is a microcosm of all the competing demands for water from rural and urban domestic users, industry, energy and agriculture, together with the risks of water pollution which accompany all these uses. In the absence of well-informed decision-making, water security in the Rokel-Seli River Basin, as elsewhere in Sierra Leone, is at risk.

Introduction

This document is one of three Volumes prepared at the end of the first phase of the Sierra Leone Water Security Project. The purpose of this document is to **present** monitoring data collected during this project and from historical sources, to provide **clear references** for public access to these data, to critically **review** data and to describe how it can be **interpreted** to understand hydrological issues.

The document is expected to be of interest and use both to practitioners who are directly involved in the monitoring of water resources, and also those responsible for policy, strategy and 'the bigger picture' of water resources management in Sierra Leone.

Data sources and monitoring networks

The Rokel-Seli basin, its extent, geographic and major stakeholder activities are identified in Map 1, Boxes 1 to 3 and in Maps 6 to 10.

This chapter presents and describes the sources of hydrological data identified and collected since the start of the Water Security Project in October 2012. This includes data from the pilot monitoring network established in the middle part of the Rokel-Seli basin (Map 10, Annexes A, B and C) and a compilation of historical hydrometeorological data gathered from other sources (Annexes E to I). Table 1 summarises the sources of data compiled for this report.

Digital raw data sets and other supporting information are available to download from the web via www.SaloneWaterSecurity.org

Historical networks and data sources

Most rainfall and river gauging sites were either destroyed or abandoned during the civil war and records lost or displaced at that time. However, it became apparent during the course of his project that there are sources of historical hydrological and meteorological data for Sierra Leone but these are not readily accessible. Some of this data is being gradually rediscovered during the course of this project. Those relevant to the Rokel-Seli pilot area are listed in Table 1 and have been collated and referenced in Annexes E to I. These data form an invaluable historical baseline, essential when providing comment on climatic and hydrological trends for the country. The data presented are by no means comprehensive and it is anticipated that other historical data will be uncovered as institutional capacity increases.

River gauging data sources

The distribution of historical river gauging sites in Sierra Leone in use in the 1970s is presented in Volume 1, Annex C, including 4 locations on the Rokel-Seli river at Badala, Bumbuna, Magburaka and Marampa. Of these, data for Bumbuna is presented as Appendix I. Data for Badala is in the process of being digitised. It is understood that a total of 24 river gauging stations have been in use in the past, but data for these is yet to be located.

Table 1 Historical data sources

Data Type	Item	Period	Data Presented	Source Reference
Rainfall	Daily rainfall, Makeni	Jan 1975 – Dec 2012	Annex D	Sierra Leone Met Department station, Makeni (pers comm)
	Monthly rainfall data, Makeni, Kabala, Teko	Jan 1921 to Nov 1978	Annex D, E, F	Nippon Koei UK 2005.
	Rainfall analyses for 38 rainfall stations, Sierra Leone	1941 – 1960	Map 4a, Annex G	Gregory 1965

	Daily rainfall at Bumbuna Dam Site	Jan 2007 – Dec 2012	Annex H	Bumbuna Dam Site data records (pers comm)
River Flow	Monthly Mean River Flow at Bumbuna	Jun 1970 – Apr 1979	Annex I	Bumbuna Dam Site data records (pers comm)
	30 minute / 15 minute River flow at Bumbuna Dam downstream weir	Apr 2010 to Dec 2012	Annex C	Bumbuna Dam Site data records (pers comm) / Project monitoring since Aug 2013
Lake Level	2-hourly water levels in Bumbuna Dam reservoir	Jan 2009 – Aug 2012	Annex C	Bumbuna Dam Site data records (pers comm)
Groundwater	Summary data for over 350 boreholes in Sierra Leone (spreadsheet)	Undated	Chapter 4	Dr Mustapha Thomas University of Sierra Leone, Fourah Bay (pers comm).
	Register of wells and boreholes, Sierra Leone	2012	Chapter 4	MEWR / WSP 2012, Water point mapping survey.

Rainfall data sources

A summary of the history of the development and decline of the meteorological and rainfall station network in Sierra Leone is provided in Volume 1, Appendix B. 118 stations are identified spanning the period 1910 to 1991. Grid references are not given for most of these sites. Over time, the Sierra Leone Meteorological Service (now Department) gathered data from 7 synoptic stations and 42 climate stations (Table B1, Volume 1, Appendix B) for which grid references are given for all but 3 sites. From these historical sites, 41 stations have continuous records greater than 10 years in length. Fifteen stations have records extending over 30 years.

In 2013, the Sierra Leone Meteorological Department indicated that only 4 stations were in operation (Makeni, Bo, Bonthe and Lungi Airport). Historical data is not readily available from any sources in Sierra Leone and little if any has been digitised.

Spatially averaged rainfall time series data are available on websites such as www.cru.uea.ac.uk (Climate Research Unit at the University of East Anglia) and www.worldclim.org, though little if any raw data from Sierra Leone is included in these models.

Groundwater data sources

There are many organisations (government, academic and NGOs) which are actively involved with groundwater development programmes in Sierra Leone. Within these there is a wealth of expertise and knowledge relating to the hydrogeology and groundwater resources of Sierra Leone. There are however very few raw data records which are published in a readily accessible format for others to use. More work is required to improve sharing of data. Dr Mustapha Thomas at the University of Sierra Leone (Fourah Bay) has provided a spreadsheet listing over 350 boreholes which includes incomplete details of locations, depths, water levels and well yields. Some statistics are derived from these data for this report, though the data itself are not reproduced. Dr Thomas himself recognises more work is needed with the data to build into a reliable database.

Other hydrogeological data sources are more general in nature and include published papers and governmental reports (eg Adekile 2013, Akiwumi 1987, MEWR undated). Web-based sources include GIS maps and related publications at continental or global scale showing interpolated depth to groundwater level, productivity, recharge and storage properties, (eg http://www.bgs.ac.uk/research/groundwater/international/africanGroundwater/maps.html). None of these are based on any data derived from within Sierra Leone and in the absence of ground truth, should be used cautiously.

A national water point mapping survey of water sources in Sierra Leone undertaken by the Water and Sanitation Programme (WSP) of the World Bank was carried out in 2012 (MEWR 2012). This work identified 28,850 improved water points including around 18,000 hand dug wells and 2000 boreholes from which data such as location, seasonality, pump and well condition can be derived.

The Rokel-Seli pilot monitoring site network

Between October 2012 and July 2013 twenty four monitoring sites (SN01 to SN23, SN13b), were established in the Rokel-Seli middle basin area with additional hydrological data collected from nine monitoring sites operated by other organisations in the same area (Table 2, Map 10). Available details for each site, including photographs, are provided in Annexes B and C and examples of a data record included as Figures 1 and 2.

Monitoring has focused on establishing measurements of rainfall, groundwater level and surface water flows. Monitoring was carried out using equipment and resources which were relatively inexpensive, portable and capable of being deployed and operated locally by trained Government of Sierra Leone staff working alongside local communities. Training, mentoring and technical guidance was provided by external consultants.

Monitoring sites are representative of a variety of stakeholder groups (Annex A) and include 11 schools, 6 village communities, 2 site investigation boreholes (drilled by Joule Africa near to Bumbuna Dam), and 7 sites within the Addax Bioenergy estate. A further 7 sites are controlled by various government organisations including Tonkolili District Council, Bombali District Council, Bumbuna Watershed Management Authority (BWMA), the Sierra Leone Meteorological Department (Makeni) and Bumbuna Dam. Data at Bumbuna Dam are gathered on behalf of the Ministry of Energy by consultants or contractors.

Each site has been allocated a site reference number identified in Table 1 (e.g. SN01, BD02) and these are used to reference specific locations in maps and subsequent text.

Table 2 Register of monitoring sites

For further detail including GPS grid references, see Annexes A and B.

District	Site Reference Number[1]	Monitoring Site	# Approx Ground Elevation (m ASL)	Primary Monitoring or Water Source Type	Monitoring Measurements			
					Rainfall	Water Level (using Loggers)	Baromtric Pressure (using loggers)	Stream Flow
Bombali	SN01	Addax - Environmental Office	61	Borehole (monitoring)	√R	√L	√B	
Bombali	SN02	Addax - Lungi Nursery	68[2]	Borehole (water supply)	√A	√L		
Bombali	SN03	Makeni - Bombali DC Office	85	Hand dug well with electric pump	√R	√L	√B	
Bombali	SN04	Mayagba - Chester Heath Memorial Secondary Technical School	89[2]	Rain gauge only	√R			
Bombali	SN05	Mayawlaw - Primary School	98	Hand dug well / No pump	√R	√L	√B	
Bombali	SN06	Mayawlaw - SDA Secondary School	94[2]	Rain gauge only	√R			
Bombali	SN07	Rosinth - WCSL Primary School	77[2]	Rain gauge only	√R			
Tonkolili	SN08	Bumbuna - Boyo Memorial Baptist Schools	129[2]	Hand dug well with handpump	√R	√L	√B	
Tonkolili	SN09	BWMA Office	247[2]	Barometric Pressure Station	√R		√BB	
Tonkolili	SN10	Kadala Spring	281[2]	Surface Water (Unprotected Spring)				(√L 45°)
Tonkolili	SN11	Kakutan Spring	275	Surface Water (Unprotected Spring)	√R			√L 60°
Tonkolili	SN12	Kamathor 1 (Joule Africa Borehole 4)	231	Borehole (monitoring)		√L		
Tonkolili	SN13	Kamathor 2 Stream	142	Surface Water (Unprotected Stream)	√R		√B	√L 45°
Tonkolili	SN13b	Kamathor 2 (Joule Africa Borehole 8)	118	Borehole (monitoring)		√L		
Tonkolili	SN14	Kasokira Stream	402	Surface Water (Unprotected Stream)	√R		√B	√L 60°
Tonkolili	SN15	Mabonto - TDC Primary & Secondary Schools	117[2]	Hand dug well with handpump	√R	√L		
Tonkolili	SN16	Magburaka - Boys Secondary School	100	Hand dug well with handpump	√R	√L	√B	
Tonkolili	SN17	Magburaka - National Commercial Secondary School	103[2]	Rain gauge only	√R			
Tonkolili	SN18	Magburaka - Tonkolili DC (WSD Office)	104[2]	Hand dug well with handpump	√R	√L		
Tonkolili	SN19	Maraka - SLMB Primary School	92[2]	Rain gauge only	√R			
Bombali	SN20	Masongbo	120	Hand dug well with handpump	√R	√L	√B	
Tonkolili	SN21	Mathora - RC Primary School	98[2]	Hand dug well with handpump	√R	√L		
Tonkolili	SN22	Kathombo - RC Primary School	147[2]	Hand dug well with handpump	√R	√L		
Koinadugu	SN23	Waia	311	Rain Gauge	√R			
Bombali	AD01	Addax - Automatic Weather Station	60	Rain Gauge	√A			
Bombali	AD02	Addax - Rokel River (Upstream Gauging Site)	60	Rokel River				√
Bombali	AD03	Addax - Rokel River (Downstream Gauging Site)	60	Rokel River				√
Tonkolili	AD04	Addax - Block 7 - Rain Gauge	61	Rain Gauge	√A			
Bombali	AD05	Addax - Block 11 - Rain Gauge	61	Rain Gauge	√A			
Tonkolili	BD01	Bumbuna HEP Dam - Rain Gauge	265[2]	Rain Gauge	√A			
Tonkolili	BD02	Bumbuna HEP Dam - Weir	165[3]	Rokel River			√B	√L
Tonkolili	BD03	Bumbuna HEP Dam - Reservoir	240	Dam Reservoir		√		
Bombali	MD01	Makeni Weather Station (SL Met Dept)	80	Rain Gauge	√A			

[1] SN1 to SN23 are monitoring sites established during this project.
Elevation is estimated from 10m interval contours on "Motion X" GPS Terrain Maps.
[2] Site GPS Elevation readings are used where these correlate with contour plan.
[3] Elevation is based on a digital logger sited at Bumbuna Dam Weir.

√ Equipment installed and data collected
( ) Equipment installed from May to July 2013.
R, A Project rain gauge (R) or another type of rain gauge (A) in use
L, B Logger (L) and/or barologger (B) in use. BB = 2 barologgers
45°, 60° V-notch weir in use (angle of weir indicated)

The spatial density of the pilot network is greater than is necessary for translation into a national monitoring network. However, the primary purpose for selecting sites has been to learn what is practically achievable by engaging with local communities and to identify issues that need to be addressed before building a national network. Operating this pilot network has provided many practical insights into how government organisations, local communities and commercial organisations can work together to deliver good quality hydrological monitoring data for the benefit of the country as a whole. This experience, along with details of equipment, monitoring methodology and lessons learnt is described in Volume 2.

Data provided by other organisations in the project area

A summary of data provided by other organisations in the project area is set out in Table 3. Data collected from these sources in 2013 are provided in Annex C.

Table 3 Current monitoring data shared by other organisations

Data Type	Item	Site Numbers	Data period	Organisation providing data
Rainfall	Daily rainfall, Makeni	MD01	Ongoing	Sierra Leone Met Department station, Makeni
	Daily rainfall, Bumbuna Dam	BD01	Jan 2007 / ongoing	Bumbuna Dam Site
	Rainfall at automatic weather stations	AD01	Feb 2013 / ongoing	Addax Bioenergy
	Daily & monthly rainfall at 3 manual sites sites	SN02, AD02, AD05	Ongoing	Addax Bioenergy
River Flow	Spot river gauging measurements	AD02, AD03	Apr & Jun 2012; Feb & Mar 2013	Addax Bioenergy
	30 minute / 15 minute River flow at Bumbuna Dam downstream weir	BD02	Apr 2010 / ongoing	Bumbuna Dam Site
Lake Level	2-hourly water levels in Bumbuna Dam reservoir	BD03	Jan 2009 / ongoing	Bumbuna Dam Site

Summary data for all the above are in Annex C. Detailed data are provided on line at www.SaloneWaterSecurity.org.

Monitoring personnel

Monitoring was carried out with the co-operation and support of district councils, paramount chiefs, village communities, schools, government organisations and industry representatives. Technical support was provided by personnel from the Ministry of Water Resources (MWR) and the Ministry of Energy (Bumbuna Watershed Management Authority - BWMA) who were trained in the use of equipment and were responsible for the on-going management of the monitoring network and for liaison with communities, district councils and national government bodies.

Monitoring measurements

A summary of monitoring measurements taken at each site is included in Table 1 and Annex A. A brief description of these follows.

- **GPS Co-ordinates** were collected at all monitoring locations by team members using a variety of GPS devices (eg Garmin eTrex10) and an iPhone App (Motion X GPS). Positional accuracy is anticipated to be ±10m. In most cases the co-ordinates in Table 1 and Map 10 are that of the water source (groundwater or surface water). Additional co-ordinates of rain gauge sites are provided in the site description sheets included in Annex B.

Figure 1 Example of a project site information sheet

SN03

Makeni – Bombali District Council

Bombali District

Hand dug well with electric and hand pump

GPS Co-ordinates

Location	Latitude	Longitude
Well	8.87945	-12.08185
Rain gauge	8.87935	-12.08184

Notes on Water Source

Both an electric and hand pump are fitted to the well. The electric pump delivers water to a $2m^3$ storage tank serving the District Office.

Well Measurements

Date	18/1/2013
Time	12:45
Datum description	Rim edge of access cover.
Datum height	0.59 m above ground level

Inside diameter	1.2 m
Depth to water	5.87 m below datum
Well depth	8.57 m below datum

Logging Equipment Installed in Well

Model	Rugged TROLL 100 / 30m
Serial number	328770
Depth in well	On base in container.

Baro logger	Rugged Baro TROLL
Serial number	328857
Depth	1.5 m below datum

Loggers is installed within a 2.5 litre plastic container, weighted with gravel, on base of well.

Rain Gauge

Model	ClimeMet 1016 / 225mm
Fencing	3m x 3m Fencing
First record date	31 May 2013

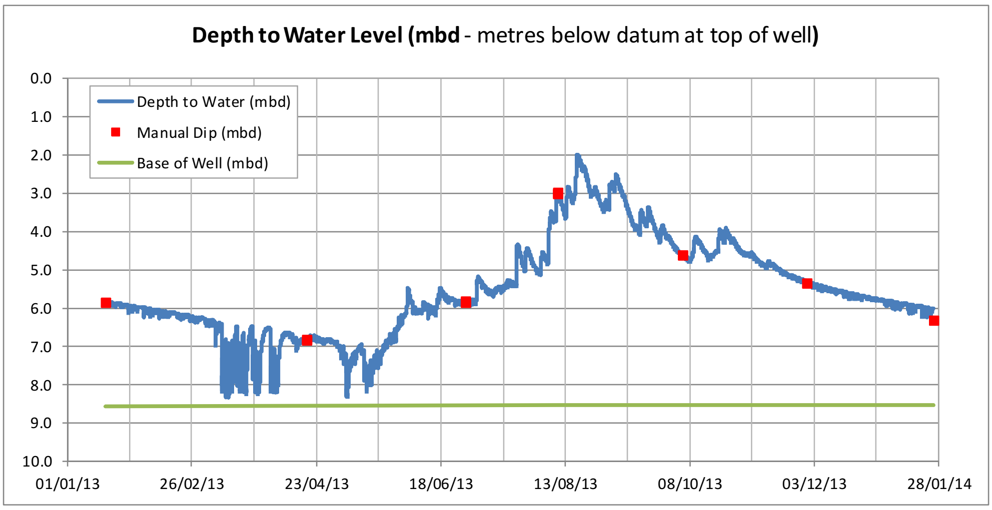
Fenced compound for rain gauge is located within 5m of well.

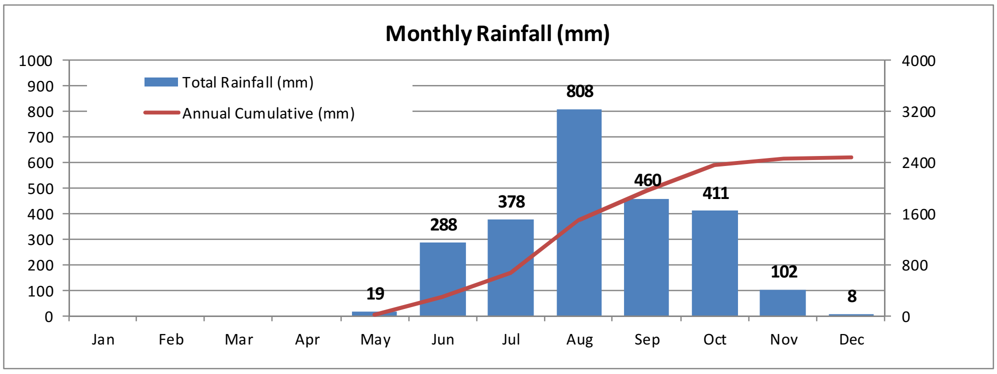
Contacts / Trained Rain Gauge Observers (T)

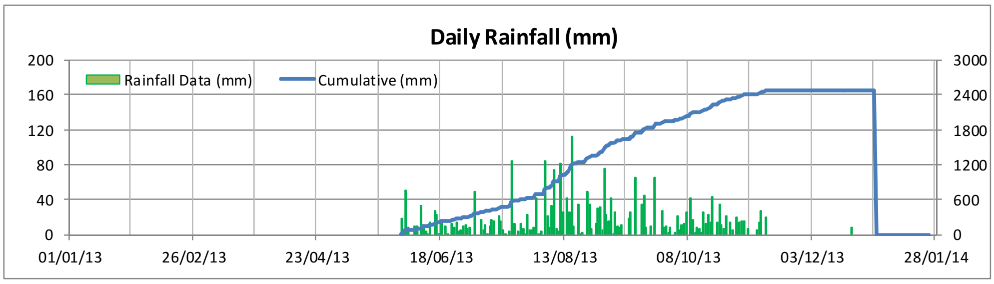
Name	Title	Telephone
Mohamed Sesay (T)	WSD Supervisor	077 157 936
Sanunu A Sesay (T)	Lab Technician	030 437 204

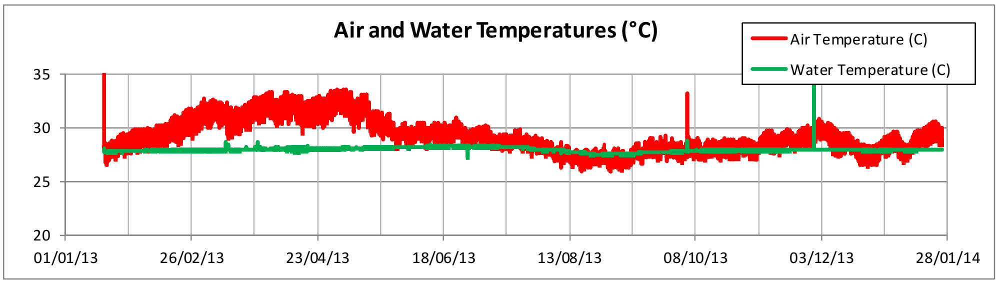
Figure 2 Example of a project site data summary sheet

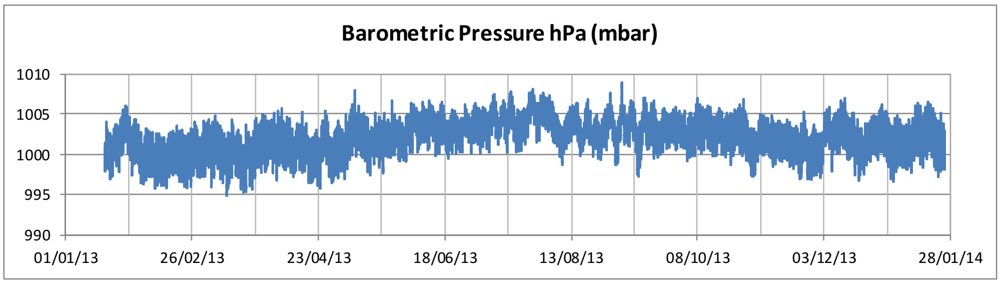
SN03 - Makeni - Bombali DC - BSD Well











- **Ground Elevations** were derived by comparing field GPS readings to on-line terrain contour maps (e.g. "Google Maps" with contour interval of ±20m and "Motion X GPS" terrain map with contour interval of ±10m). Where field GPS elevation readings fell within the mapped contour range, the field GPS elevation value was used. Where there was a significant discrepancy, an estimate was made using map contours. All elevations are rounded to 1m though should not be assumed to be accurate to any better that ±20m.
- **Rainfall monitoring** was established at 20 sites of which 17 involved the construction of post and wire-mesh fenced compounds. A 225mm capacity "ClimeMet 1016" rain gauge was used for daily measurement of rainfall by locally appointed observers trained by the project team. In general, rainfall monitoring was established as close as possible to each surface water or groundwater monitoring site. Daily readings of rainfall were recorded onto monthly record sheets by local observers and these sheets collected after the end of each month by BWMA or MWR staff.
- **Surface water flows** were measured at 4 unprotected upland springs or stream sources by recording the head of water within the water channel immediately upstream of purpose-built 'v-notch' weirs. Water levels were recorded manually at intervals from weekly to monthly by BWMA staff and combined with automatic (and experimental) recording at 15 minute intervals using "In-Situ Rugged TROLL 100" total pressure loggers. Loggers were positioned below water level in plastic "stilling well" tubes secured in the stream. Data were downloaded monthly by BWMA staff.
- **Groundwater level monitoring** was carried out from 9 shallow hand dug wells and 4 boreholes distributed throughout the project area. Water levels were recorded at 15 minute intervals using "In-Situ Rugged TROLL 100" total pressure loggers. These were positioned in 2.5 litre plastic containers, drilled with holes and weighted with gravel, resting on the base of the well. Manual water level measurements using conventional electric water level "dip tapes" were recorded for validation purposes by BWMA or MWR staff each time the loggers were downloaded and re-programmed.
- **Barometric pressure and air temperature** were recorded from 11 instruments located at 9 sites (2 v-notch weirs, 5 wells, 1 borehole and 3 instruments used at a dedicated barometric site at the BWMA office). Measurements were taken automatically at 15 minute intervals using "In-Situ Rugged Baro Troll" instrument. These were downloaded and programmed by BWMA and MWR staff and used to compensate data collected from the submerged total pressure loggers.
- **Water temperature** was automatically recorded from all the submerged pressure loggers (17 in total).

Interpretation of rainfall data

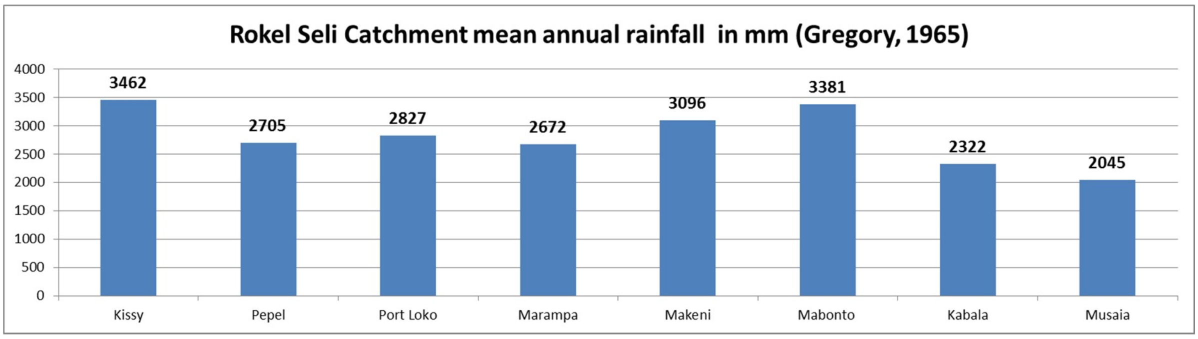
In the following chapter, four specific questions are posed:

1. What is the mean annual rainfall and its distribution in Sierra Leone and across the Rokel-Seli catchment?
2. What are the long-term trends in annual rainfall in Sierra Leone and the Rokel-Seli catchment?
3. What is the seasonal pattern of rainfall and its long-term trend?
4. How good is the rainfall data collected from the pilot monitoring network?

Mean annual rainfall distribution

The mean annual rainfall in Sierra Leone varies from over 4000 mm along the south-west coast and 5000 mm in the western Freetown peninsula decreasing inland to less than 2000 mm on the north-eastern border with Guinea. This north-easterly trend is interrupted by an area of slightly higher rainfall (over 3000 mm) in the centre of the country (Maps 4a and 4b). This spatial pattern is followed clearly north-eastwards within the Rokel-Seli river basin (Figure 3).

Figure 3 Mean annual rainfall (1941 to 1960) from SW to NE in the Rokel-Seli basin



A full year of rainfall data has not yet been collected from the project area, but taking the month of August 2013 (Figure 4) the variation in rainfall across the central part of the catchment area is demonstrated. Highest rainfall is centred on the Makeni - Magburaka – Mabonto area reducing both westwards and north-eastwards.

Trends in annual rainfall

Within the Rokel-Seli catchment only one rainfall station (Makeni) has remained operational since 1921 to the present day, with a few gaps during the 1990s from which total annual rainfall figures are available (Figure 5). Until 1983, the total annual rainfall varied around a mean of 3121 mm with a maximum of 3867 mm and minimum of 2516 mm. Since 1984 there has been a significant reduction in the mean annual rainfall to 2857 mm (-8.4%) and a corresponding increase in variation with the 1921 to 1983 maximum and minimum values being reached or exceeded on several occasions.

Figure 4 Spatial distribution of rainfall in the Mid-Rokel-Seli catchment (August 2013)

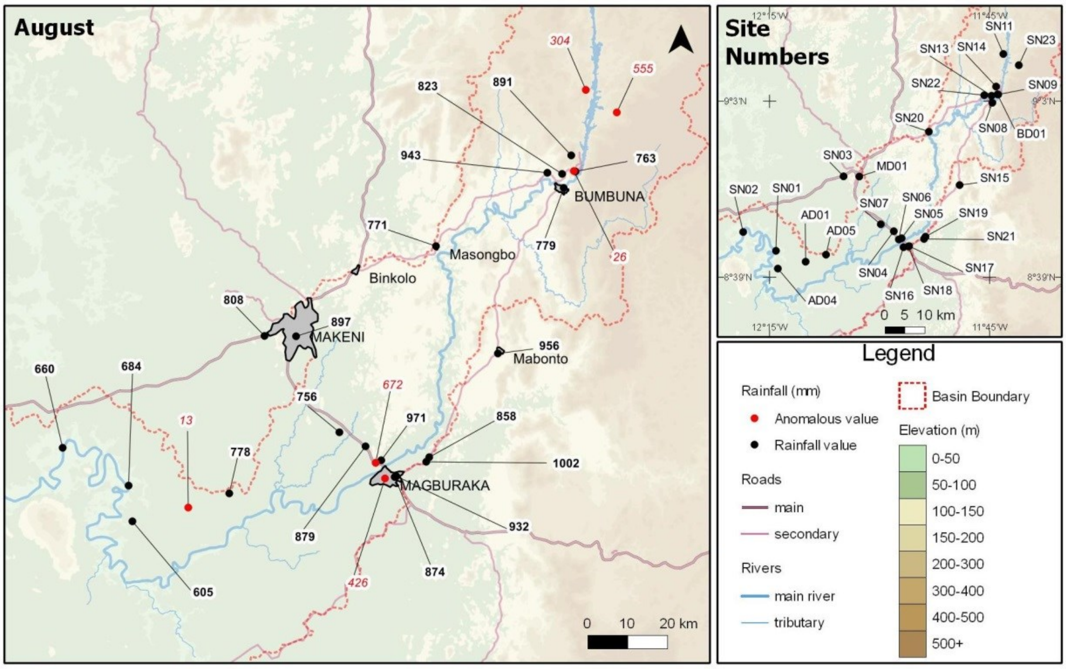
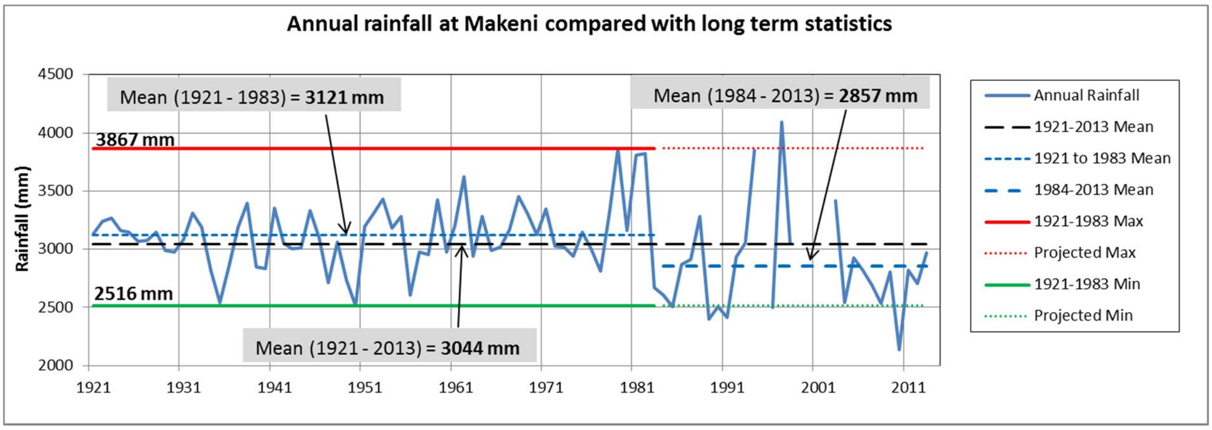


Figure 5 Annual total rainfall at Makeni (1921 to 2013) compared to long-term means



Seasonal rainfall patterns

There are distinct wet (May to November) and dry seasons (December to April) with 80 to 95% of rain typically falling during the wet season. Significant variations occur between the maxima and minima recorded for any one month (Figure 6) and this pattern varies spatially across the Rokel-Seli basin from Port Loko in the west to Kabala in the north-east (Figure 7).

Figure 6 Comparison of 2013 monthly rainfall at Makeni to long-term statistics.

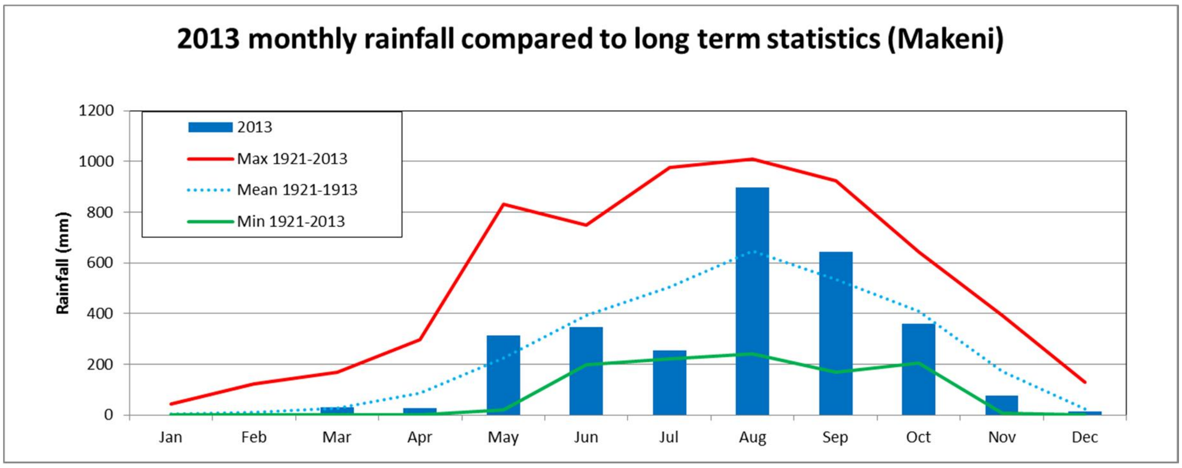


Figure 7 Mean monthly rainfall (1941 to 1961) across the Rokel-Seli basin (Gregory 1965)

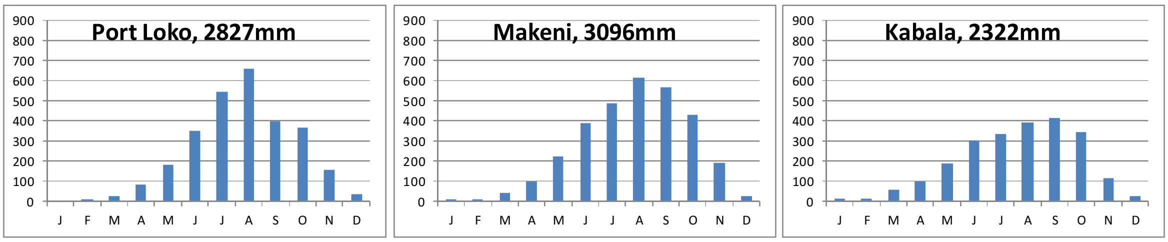
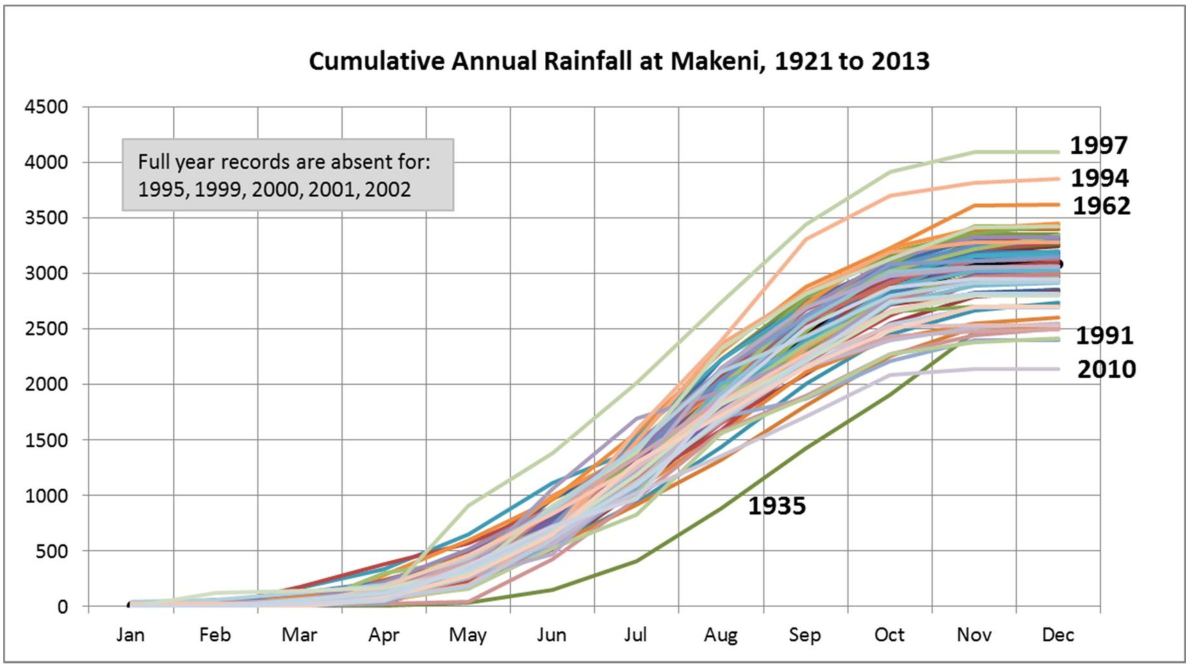


Figure 8 Cumulative annual rainfall at Makeni, 1921 to 2013



Monthly cumulative rainfall plots for 88 individual years at Makeni are provided in Figure 8. Whilst there is significant variation in the exact timing of events and rainfall totals, the general trend is for the rains to commence in April, building in intensity through May to October and into November, with little or no rain from December through to the end of March. Years with unusually high or low annual rainfall are indicated and most of these fall in the last 20 years.

Some notable statistics from Makeni

Other notable long-term statistics (1921 to 2013) from the Makeni data are:

- Highest total annual rainfall: 4094 mm (1997)
- Lowest total annual rainfall: 2137 mm (2010)
- Highest total monthly rainfall: 1008 mm (August 1964)
- Highest daily rainfall since 2002: 152.4mm (23 August 2008)

Project rainfall data, 2013

Rainfall monitoring sites in the pilot monitoring area were established during the first half of 2013 with most being completed in May and June (Table 4). Rain gauge sites operated by other organisations in the basin area are also included in Table 4.

Table 4 Monthly rainfall data for 2013 from project and other observer sites

Site No	Site		First Record	Total Monthly Rainfall (mm) in 2013												Total	Total
				Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*(Jul to Dec)*	*2013*
SN01	Addax Office		21 Feb 13	nd	nd	33	77	204	119	398	684	412	453	118	7	2071	**2504**
SN02	Addax Lungi		2012	0	0	45	54	255	337	514	660	524	555	195	nd	2448	nd
SN03	Makeni BDC		31 May 13	nd	nd	nd	nd	nd	288	378	808	460	411	109	8	2173	nd
SN04	Mayagba CHMS		04 Jun 13	nd	nd	nd	nd	nd	nd	357	879	525	444	59	13	2277	nd
SN05	Mayawlaw PS		04 Jun 13	nd	nd	nd	nd	nd	nd	377	971	669	416	72	10	2514	nd
SN06	Mayawlaw SDAS	8	04 Jun 13	nd	nd	nd	nd	nd	nd	314	672	665	434	80	0	2164	nd
SN07	Rosinth - WCSL	11	03 Jun 13	nd	nd	nd	nd	nd	nd	308	756	505	474	nd	0	nd	nd
SN08	Bumbuna Boyo MBS		06 Jun 13	nd	nd	nd	nd	nd	nd	217	779	341	378	41	3	1757	nd
SN09	BWMA Office		05 Jun 13	nd	nd	nd	nd	nd	nd	242	763	403	325	80	5	1816	nd
SN11	Kakutan	*	20 Jun 13	nd	nd	nd	nd	nd	nd	177	304	175	221	nd	0	nd	nd
SN13	Kamathor 2		11 Jun 13	nd	nd	nd	nd	nd	nd	327	823	406	364	91	4	2012	nd
SN14	Kasokira		06 Jun 13	nd	nd	nd	nd	nd	nd	293	891	446	397	93	4	2123	nd
SN15	Mabonto TDCS		30 Jun 13	nd	nd	nd	nd	nd	nd	426	956	449	501	147	0	2478	nd
SN16	Magburaka BSS	8	04 Jun 13	nd	nd	nd	nd	nd	nd	404	426	637	454	57	0	1978	nd
SN17	Magburaka NCSS		04 Jun 13	nd	nd	nd	nd	nd	nd	406	932	638	454	55	6	2491	nd
SN18	Magburaka TDC		04 Jun 13	nd	nd	nd	nd	nd	nd	398	874	616	377	45	11	2321	nd
SN19	Maraka SLMBS		05 Jun 13	nd	nd	nd	nd	nd	nd	325	858	556	406	71	0	2216	nd
SN20	Masongbo		11 Jun 13	nd	nd	nd	nd	nd	nd	233	771	434	467	87	3	1995	nd
SN21	Mathora RCPS		05 Jun 13	nd	nd	nd	nd	nd	nd	370	1002	573	408	69	9	2429	nd
SN22	Kathombo - RCPS		13 Jun 13	nd	nd	nd	nd	nd	nd	301	943	423	398	87	2	2154	nd
SN23	Waia	8	21 Jun 13	nd	nd	nd	nd	nd	nd	297	555	434	337	76	3	1701	nd
AD01	Addax AWS	*	07 Feb 13	0	0	43	10	115	364	204	13	62	20	8	0	306	**839**
AD04	Addax Block 7	11	2013	0	0	60	nd	135	276	427	605	375	373	nd	nd	nd	nd
AD05	Addax Block 11	11	2013	nd	nd	39	nd	196	276	332	778	275	399	nd	nd	nd	nd
BD01	Bumbuna Dam	*	1997	0	0	44	nd	nd	nd	155	26	nd	nd	nd	nd	181	nd
MD01	Makeni Met Dept		1921	0	0	30	29	312	348	254	897	645	359	78	13	2247	**2965**

nd **Insufficent or missing data.**
***** **Anomalous data record (excluded from statistics)**
8 **Month with anomalous record**
(e.g. 8 = August, 11 = November)

Statistics (excluding anomalous data)							
Month	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	**(Jul to Dec)**
Min	217	605	275	325	41	0	1757
Max	514	1002	669	555	195	13	2514
Average	343	831	496	417	85	5	**2207**

Data cleaning and validation – how good is the community rainfall data?

The reliability and quality of rainfall data collected at community sites relies primarily on the dedication and competence of individual rainfall observers. It would be unrealistic to expect that records are meticulously collected at 9 am every morning for 365 days each year. An objective assessment of data quality is therefore necessary to both validate (check observer results at one site against other sites for consistency) and clean (remove or edit anomalous records) before using the data for analysis.

The daily and monthly data collected from the majority of observer sites visually demonstrate a high degree of correlation with those recorded at Makeni and when compared to each other (Figure 9). To test whether any stations are significantly different, Figure 10 compares the cumulative rainfall total at each site (y-axis) to the cumulative rainfall at Makeni (x-axis) whilst in Figure 11 the cumulative total rainfall at each site is compared to the mean cumulative rainfall of all sites. These charts are typically used to compare records from rainfall stations in close proximity to each other to test if there are similar trends in rainfall (Shaw et al 1994). Total rainfall will always be different due to factors such as elevation and surrounding land features, but for sites in the same weather system the trend in rainfall totals should be similar. Consequently any deviation from a straight line in these charts would indicate some anomaly in the data record for a particular site.

The comparison of cumulative daily data from each site to the single rainfall station at Makeni (Figure 10) shows a stepped correlation. This may be indicative of natural spatial variation in rainfall, but could also be caused by differences in the timing of record keeping. For example some sites have gaps at weekends, during holidays or during periods of high rainfall, others may occasionally mix up which day is being recorded, particularly following several days of dry weather. When stations are compared to an overall daily average (Figure 11) a smoother correlation is apparent.

Three sites stand out as having anomalously low records (Figures 10 and 11). Site numbers AD01 and BD01 have missing records. Site SN11 could have naturally low rainfall due to its location in a forested upland, or record keeping may be poorly controlled. Six other sites have single months (usually August – Figure 4) with anomalously low data (Table 4). All these data are excluded from data analysis and statistical summaries.

Comparison of 2013 community rainfall records to Makeni data

Monthly rainfall trends followed the pattern recorded at Makeni (Figure 9), but with monthly rainfall data only available in full since July 2013, it is not possible to draw too many conclusions on long-term trends.

Spatial variability can be examined on a monthly basis using the total monthly rainfall from the community observer sites. An example for August 2013 is provided at Figure 4. Total rainfall of between 800 and 1000 mm fell in the Makeni-Magburaka-Mabonto areas with lesser amounts westwards and north-eastwards. In detail the pattern of rainfall distribution is more complex, however, this monthly example follows the national pattern of rainfall distribution indicated in Maps 4a and 4b.

Some statistics from community rainfall sites for 2013

Other notable statistics from the network of observer sites for 2013 include:

- Highest cumulative rainfall (July to December): 2514 mm (SN05)
- Highest monthly rainfall (August): 1005 mm (SN21)
- Lowest monthly rainfall in August: 605 mm (AD03)
- Highest daily rainfall: 188.5 mm (SN14, 16 August 2013)

Figure 9 Typical daily and monthly rainfall records from observer sites (June to December 2013)

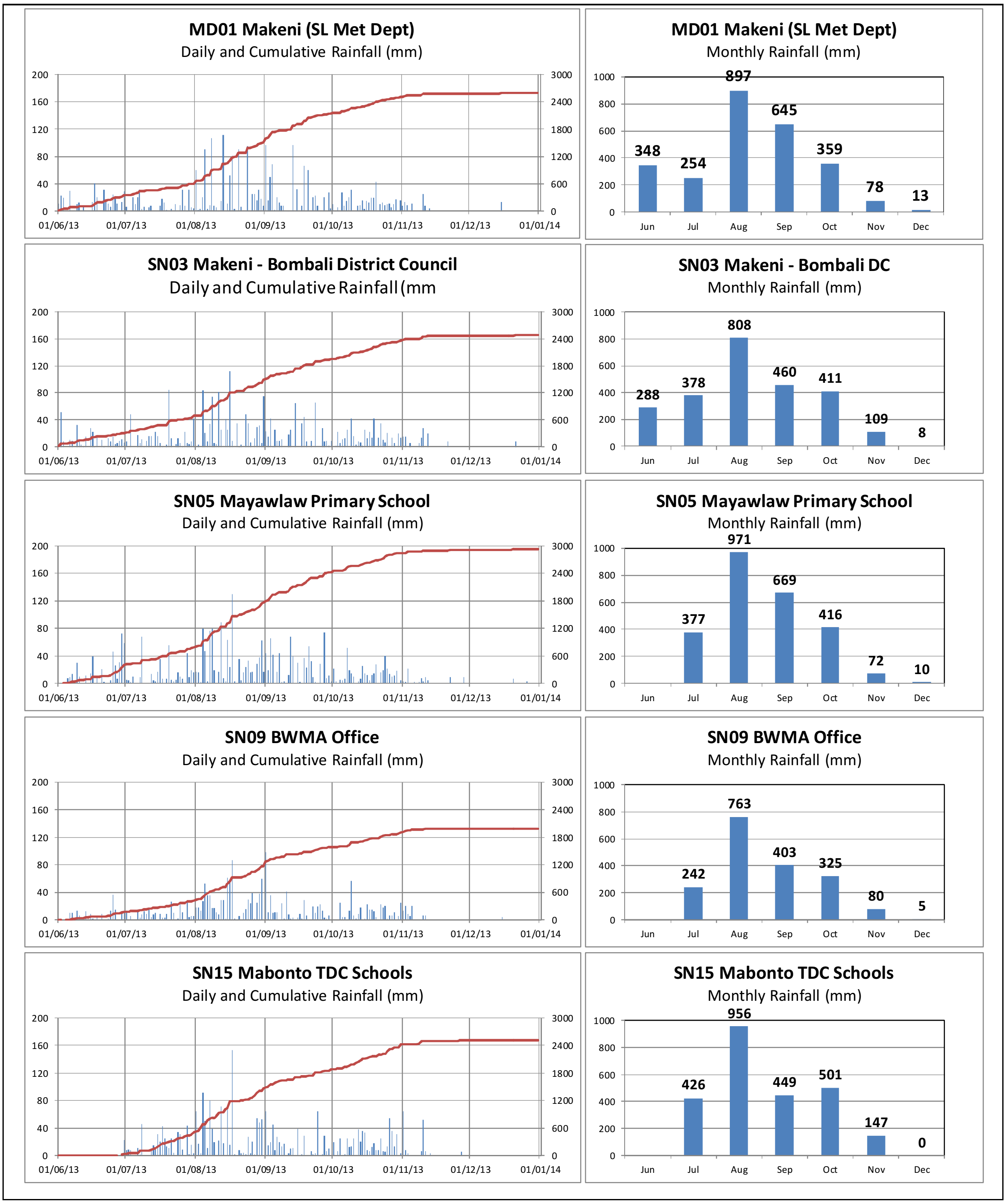


Figure 10 Comparison of cumulative daily rainfall at observer sites to cumulative daily rainfall at Makeni weather station (29 June to 31 December 2013)

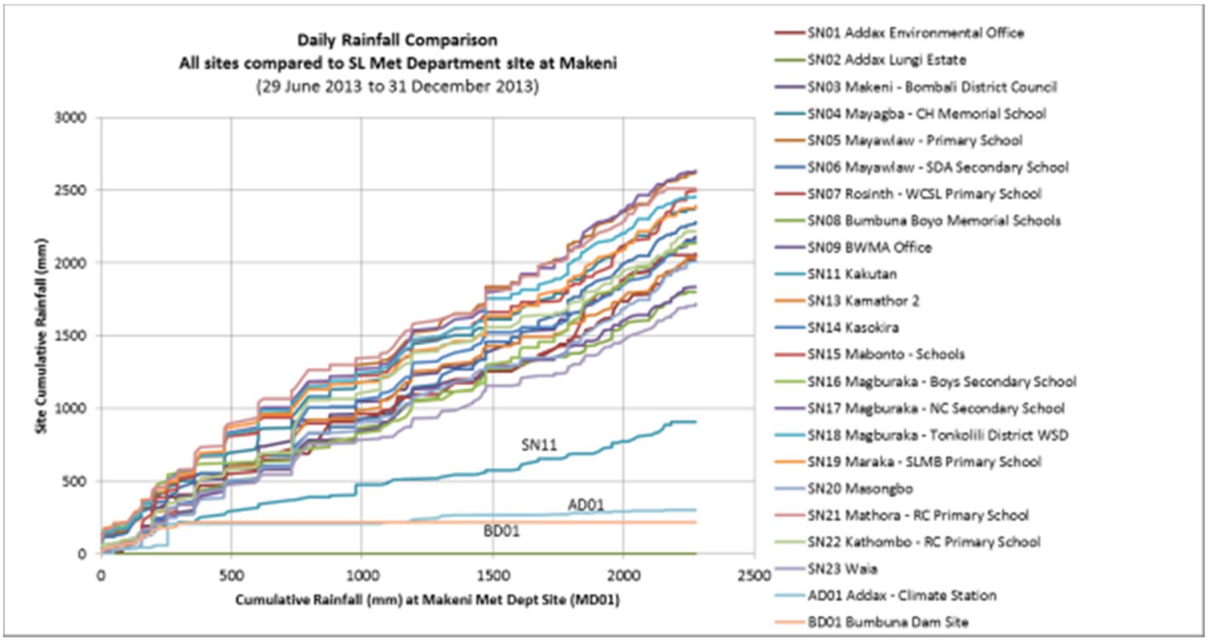
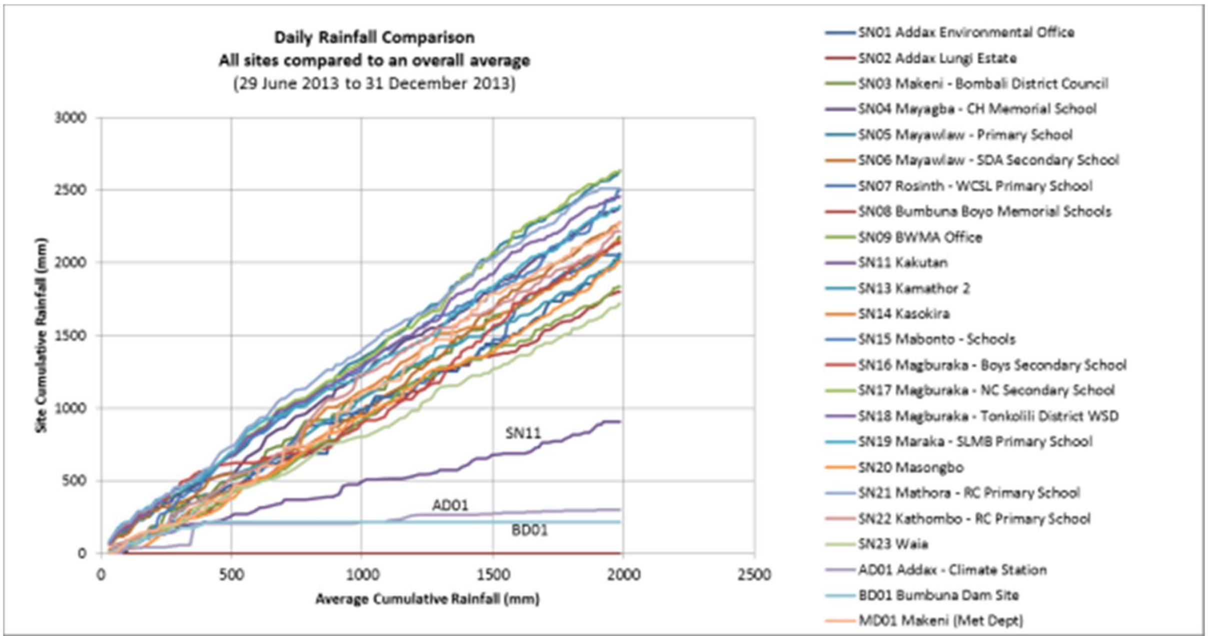


Figure 11 Comparison of cumulative daily rainfall at observer sites to the cumulative average daily rainfall for all sites (29 June to 31 December 2013)



Interpretation of groundwater levels

This chapter presents an overview of the geology and hydrogeology of Sierra Leone, ending with a preliminary conceptual model of groundwater flow. The main part of the chapter provides answers to four specific questions:

1. What are the depths of wells and boreholes in the project area?
2. What is the seasonal variation (range) in groundwater levels?
3. How quickly do groundwater levels respond to rainfalls?
4. At what rate and for how long do groundwater levels recess (fall) to the end of the dry season?

Hydrogeological setting

A summary of the classification of four hydrogeological units identified within Sierra Leone (Adekile 2013) is provided and a simplified geological map included as Map 5. Each unit can be further sub-divided each with differing hydrogeological properties (Table 6). The most important of these is the basement complex occupying over 75% of the country area and which can vertically be subdivided into an upper weathered zone overlying poorly fractured bedrock.

Table 5 Primary hydrogeological units and geological descriptions.

Hydrogeological Unit (after Adekile 2013)	**Geological Age**	**Geological Descriptions** (see Map 10)
Bullom Group: unconsolidated sedimentary rocks	Cenozoic (Tertiary and Quarternary to Recent)	Marine and estuarine poorly consolidated sediments - sands, gravels and kaolinitic clays with some lignite
Ultrabasic Igneous Intrusives:	Mesozoic (Jurassic to Triassic)	Freetown Peninsula Complex and other intrusives.
Saionya Scarp[1] and **Rokel River Group**[1]: consolidated sedimentary rocks	Lower Palaeozoic and Proterozoic	Variegated shales, siltstone, mudstone interbedded with volcanics and quartzite bands
Precambrian Basement Complex: ancient crystalline granitic gneiss with supracrustal volcanic and sedimentary belts.	Neoarchean and Archean	**Marampa Group** metasediments and volcanics / **Kasila Group** granulites Basement granites, gneisses, and migmatites. Volcanic greenstone, amphibolite and gneiss

[1] *The Saionya Scarp group is Lower Palaeozoic (Cambrian), occupying a relatively small area of outcrop.*

Aquifer and well properties

It is not an objective of this project to record or measure aquifer and well properties, though these form an important part of any hydrogeological monitoring record. There are very few published records of aquifer properties for Sierra Leone or indeed throughout the whole continent of Africa (Bonsor & MacDonald, 2010a, b). Well yield in litres/second (L/s) is the most commonly recorded statistic from borehole testing programmes and is often used as a proxy for transmissivity. Other properties such as storativity or specific yield values are usually derived from estimates of effective porosity based on an assessment of rock composition (MacDonald et al, 2010, 2012).

Well yields and transmissivity

A typical hand pump in a hand dug well or borehole can be operated at between 0.1 to 0.3 L/s. A motorised pump providing water for irrigation or urban water supplies typically requires a yield of 5 L/s or greater (MacDonald et al, 2010). Well yield values therefore provide more information about the capacity of the pumping system being used than the ability of the aquifer to transmit water. Transmissivity and well yield may vary with water level and should be measured in both wet and dry season conditions to establish the efficiency of the well, particularly when groundwater levels fluctuate naturally by several metres per year as in Sierra Leone.

MacDonald et al (2010), Chilton and Foster (1995) and Wright (1992) record measurements of well yield, hydraulic conductivity (permeability) and transmissivity values (the product of aquifer thickness and hydraulic conductivity) in the weathered Basement Complex in other parts of Africa as follows:

Weathered basement

- Well yield: 0.1 to 0.3 L/s
- Hydraulic conductivity 0.01 to 5 m/d
- Transmissivity 0.2 to 10 m^2/day

Values can fall below and above these ranges. Well yield values reported in the weathered basement of Sierra Leone are between 0.3 and 1.5 L/s (Table 6). It is likely the higher yield values are derived from boreholes with motorised pumps. For sedimentary formations, such as the unconsolidated coastal sediment of the Bullom Group, well yields are significantly higher and values of up to 6 L/s have been reported (Table 6). No well yield data has been identified to date for the consolidated sediments of the Rokel River Group.

Other sources of well and aquifer data viewed include:

- A spreadsheet of over 350 boreholes provided by Dr Mustapha Thomas (Department of Geology, Fourah Bay College, University of Sierra Leone) provides yields from 231 boreholes of between 0.4 to 12 L/s (mean of 3.6 L/s). These results are not correlated against hydrogeological units.
- Akiwumi (1987) records a transmissivity value of 188 m^2/d from weathered basement in southern Sierra Leone. This value is unusually high. Elsewhere in central Sierra Leone an average hydraulic conductivity (permeability) value of 10^{-4} cm/s (0.09 m/d) is recorded by the same author. Were this permeability value distributed evenly through, for example, 15 m of weathered material, the resulting transmissivity would be 1.4 m^2/d.
- Akiwumi (1987) also reports a transmissivity value of 196.3 m^2/day for “valley fill” material within the basement complex in the southwest of Sierra Leone. In the same report Akiwumi makes reference to the engineering investigation of bedrock properties associated with the construction of the Bumbuna Dam site. Hydraulic tests carried out within 657m linear metres of boreholes drilled into the upper 50m of bedrock resulted in 55% of tests having

permeability values of less than 1 lugeon (approximately 0.01 m/d) and 17% being greater than 10 lugeons (approximately 0.1 m/d).

Table 6 Hydrogeological units and characteristics from published sources

Hydrogeological Unit[1]	Aquifer type[1]	Approx % of Land Area[1]	Sub-Units	Well or Borehole depths (m)[2,3]	Well yields (L/s)[2]
Precambrian Basement Complex	D	78%	Valley fill deposits	up to 15m	Nd
			Weathered zone (lateritised, clay-rich)	up to 20m (max 37m)	0.3 – 1.5
			Fractured crystalline bedrock	35m (average) 60m (max)	0.3 – 1.5
Saionya Scarp / Rokel River Group	M	9%	Weathered layer?	nd	nd
			Fractured sediments	nd	nd
Bullom Group	C	12%	Unconsolidated sands and clays (inland alluvial & coastal)	10 to 20m	up to 3
			Interbedded sands and clays	30 – 80m	up to 6
Ultrabasic Igneous Intrusives	D	1%	Fractured gabbros	nd	nd
			Weathered and fractured dolerites	nd	nd

C: Continuous aquifer / D: Discontinuous aquifer / M: Mixed aquifer.
nd: no data identified
Sources: 1 BGR et al (undated) / 2 Adekile 2013 / 3 Akiwumi 1987

Aquifer storage coefficient

In the absence of field measurements, unconfined storativity (specific yield) values in Africa are usually based on estimates of effective porosity for different aquifer compositions. Ranges of values typically used follow (after MacDonald et al, 2012):

- Weathered basement: 1 to 10% (mean 5%)
- Fractured sedimentary rocks 3 to 15% (mean 8%)
- Mixed intergranular and fractured rocks 10 to 30% (mean 15%)
- Intergranular aquifers 20 to 35% (mean 25%)

Depths of hand dug wells and boreholes

A summary of typical well and borehole depths in Sierra Leone is provided in Table 6 based on Adekile (2013) and Akiwumi (1987) who record that hand dug wells in Sierra Leone range in depth from less than 10 m to over 20 m. Boreholes in fractured rock and sediments are drilled to depths of up to 80m. Borehole depths recorded from 359 locations listed in Dr Thomas's spreadsheet varied from 9 to 63 m (with a mean of 33.6 m).

Of the sixteen groundwater monitoring sites in the Rokel-Seli pilot monitoring area (Table 7), nine are hand dug wells in the weathered basement varying from 6.9 to 14.9 m in depth. Two boreholes on the Addax Bioenergy estate are drilled within the Rokel River Group consolidated sediments to depths of 30.9 and 36.4 m. A further two site investigation boreholes in fractured basement rocks near to Bumbuna dam were drilled to depths of 20 m (SN13b) and the second was deeper than could be measured with a 50 m water level tape (SN12).

Seasonal range in groundwater levels

Literature sources

A map illustrating the depth to "static water level" in a limited part of the basement complex of central Sierra Leone is included the MWR / UNICEF manual drilling document (Adekile 2013). Most wells recorded groundwater level within 10 m of ground surface, but in places exceeded 20 m. Seasonal variations are not recorded. Akiwumi (1994) recorded seasonal groundwater level fluctuations from 18 boreholes in weathered basement in the Bumbuna area of between 1.3 m and 8.1 m (mean of 3.6 m). In Dr Thomas's spreadsheet, groundwater levels were recorded on a single occasion in 359 boreholes at between 1 and 21.7 m depth with a mean of 8.1 m. The dates of measurement are unrecorded, though are divided into wet and dry season levels. Only 2 records (both in Kambia District) have groundwater levels in both the wet and dry season indicating ranges of 3.75 and 16.76 m respectively.

Table 7 Summary of groundwater level and recharge data from monitoring wells and boreholes in the mid Rokel-Seli River Basin

Site ID	Site Name	Well or Borehole Details			Lowest & Highest Groundwater Levels			Range in Water Level		Recharge Period		
		Well or borehole (BH)	Type of Pump	Depth to base (mbd)	Lowest unpumped water level prior to recharge (mbd)	Lowest recorded water level including pumping (mbd)	Highest recorded water level (mbd)	Unpumped water level range (m)	Maximum water level range including pumping (m)	Date of onset of seasonal recharge (2013)	Date when maximum water level recorded (2013)	Time from onset of recharge to maximum water level (days)
Hand dug wells in weathered basement												
SN03	Bombali DC	Well	Hand & Electric	8.57	7.69	8.35	2.00	5.69	6.35	15-May	18-Aug	95
SN05	Mayawlaw School	Well	None	9.95	9.39	9.82	2.48	6.91	7.34	29-May	18-Aug	81
SN16	Magburaka Boys School	Well	Hand	9.90	8.00	8.77	3.72	4.28	5.05	21-May	18-Aug	89
SN18	Tonkolili DC	Well	Hand	14.92	14.29	14.73	6.27	8.02	8.46	25-May	19-Aug	86
SN20	Masongbo	Well	Hand	10.40	9.29	9.37	4.18	5.11	5.19	10-Jun	18-Aug	69 P
SN21	Mathora School	Well	Hand	10.46	9.59	10.33	3.24	6.35	7.08	27-May	18-Aug	83
SN22	Kathombo School	Well	Hand	8.70	7.75	7.78	1.26	6.49	6.53	18-Jun	17-Aug	60 P
SN08	Bumbuna Boyo Schools	Well	Hand	7.29	5.87	7.22	3.19	2.68	4.03	15-May	18-Aug	95
SN15	Mabonto Schools	Well	Hand	6.85	5.10	5.10	2.21	2.89	2.89	15-May	17-Aug	94
			Statistics (recharge onset times exclude partial records)									P Partial record
			Min	6.85	5.10	5.10	1.26	2.68	2.89	15-May	17-Aug	81
			Max	14.92	14.29	14.73	6.27	8.02	8.46	29-May	19-Aug	95
			Average	9.67	8.55	9.05	3.17	5.38	5.88	21-May	17-Aug	89
Boreholes in Rokel River Group consolidated sediments (on Addax Bioenergy Estate)												
SN01	Addax Environmental Office	BH	None	36.36	13.44	13.49	6.51	6.93	6.98	16-May	20-Aug	96
SN02	Addax Lungi Nursery	BH	Electric	30.88	10.58	12.20	7.34	3.24	4.86	11-May	28-Jun	48 P
Site Investigation Boreholes in fractured basement (near Bumbuna Dam Site)												
SN12	Kamathor 1 - Joule Africa BH4	BH	None	>50	25.11	25.16	21.65	3.46	3.51	15-Aug	30-Oct	76 P
SN13b	Kamathor 2 - Joule Africa BH8	BH	None	19.95	1.83	1.84	0.64	1.19	1.20	16-May	17-Aug	93

P Partial record

Project area

Statistics summarising groundwater level variations in each of the boreholes and wells monitored in the pilot area are presented in Table 7 and hydrographs for each of the monitoring wells plotted and grouped by hydrogeological unit in Figures 12 and 13.

The measured seasonal range in groundwater levels (excluding drawdown due to pumping) are:

- **Weathered basement** (9 hand dug wells) 2.7 to 8.0 m (average of 5.4 m)
- **Fractured basement** (2 boreholes) 1.2 and 3.5m
- **Rokel River Group** (1 borehole) 7.0 m

Groundwater level response to rainfall

The first significant daily rainfalls of 2013 fell at Makeni rainfall station on 7 and 8 May (17.8 mm and 21.2 mm respectively) with an increase in intensity and frequency of rainfall from 14 May onwards. Rainfall at Bombali District Council offices on the outskirts of Makeni (Site SN03) was recorded fully from the beginning of June 2013, approximately 6 weeks into the wet season (Figure 14). Peak rainfall intensity is reached around the third week of August and declines through to the end of the first week in November, after which there are only occasional and relatively light rainfalls.

The groundwater level hydrograph for the hand dug well at Bombali District Council (Figure 14) shows a remarkably rapid response to the start of wet season rainfalls with levels rising within 1 day of the first rainfall on 14 May. This responsiveness to rainfall recharge continues over a period of 95 days through to the 17 August when rainfall intensity reached its peak and groundwater level achieved its highest point 5.7 m above the dry season water level and 2 m below the top of the well.

Groundwater recession

Groundwater levels rise in response to rainfall recharge as long as the recharge rate is greater than the rate at which groundwater moves laterally through the weathered basement and ultimately discharges into surface water streams and rivers. From 18th August onwards in the Bombali District Council well (Figure 14) groundwater levels began to fall indicating the rate of rainfall recharge became less than the groundwater discharge rate. This marks the start of the recession period.

The initial rate of recession from mid-August was approximately 1.5m per month reducing to 1m per month from the end of October through to the year end. Using data from the end of dry season at the start of 2013 suggest the decline will continue at around 1m per month and by mid-March will be close to being fully discharged.

Other wells in the weathered basement and Rokel River Group demonstrate recharge-discharge relationships (Table 7, Figures 12 and 13) with differing ranges in water levels reflecting the heterogeneity between different parts of the weathered basement complex and other hydrogeological units.

Figure 12 Groundwater levels in hand dug wells in weathered basement

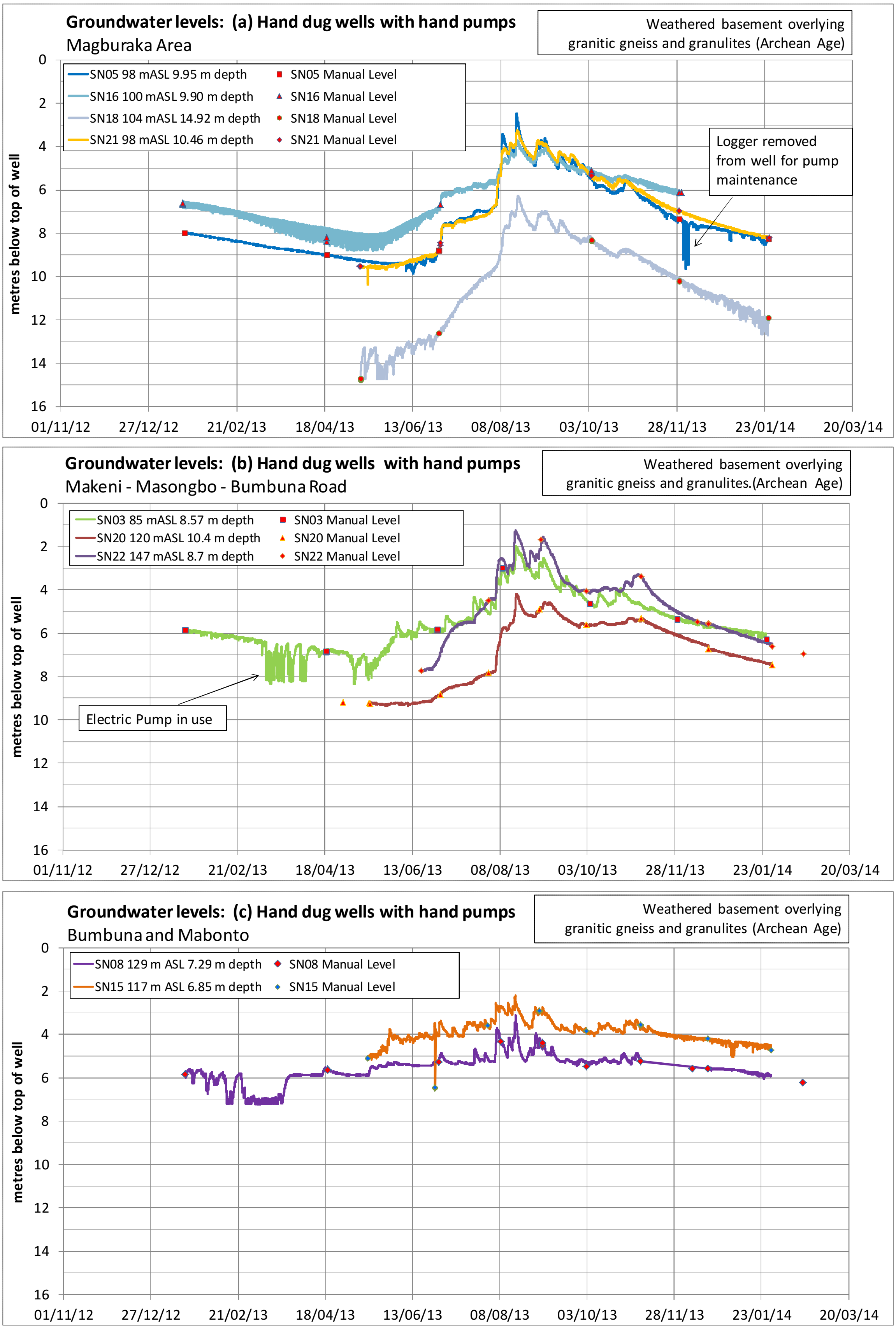
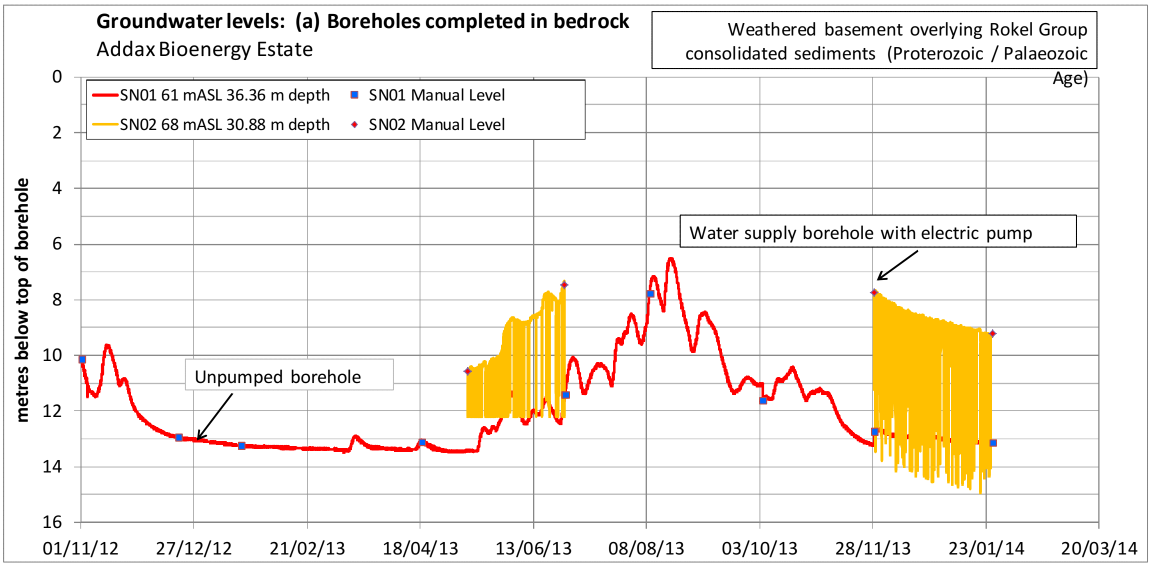
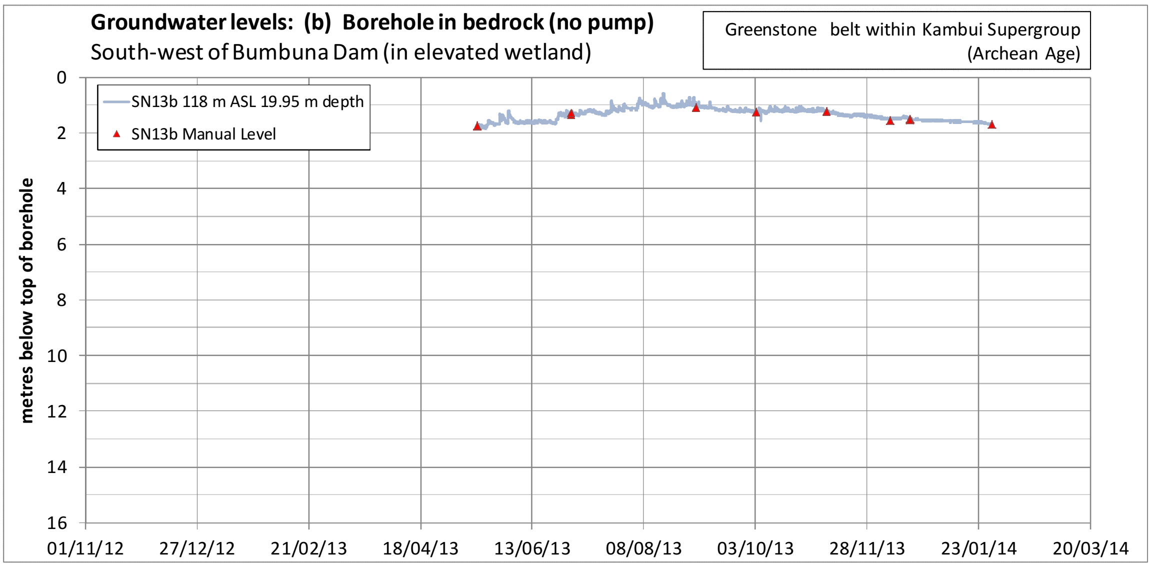


Figure 13 Groundwater levels in boreholes





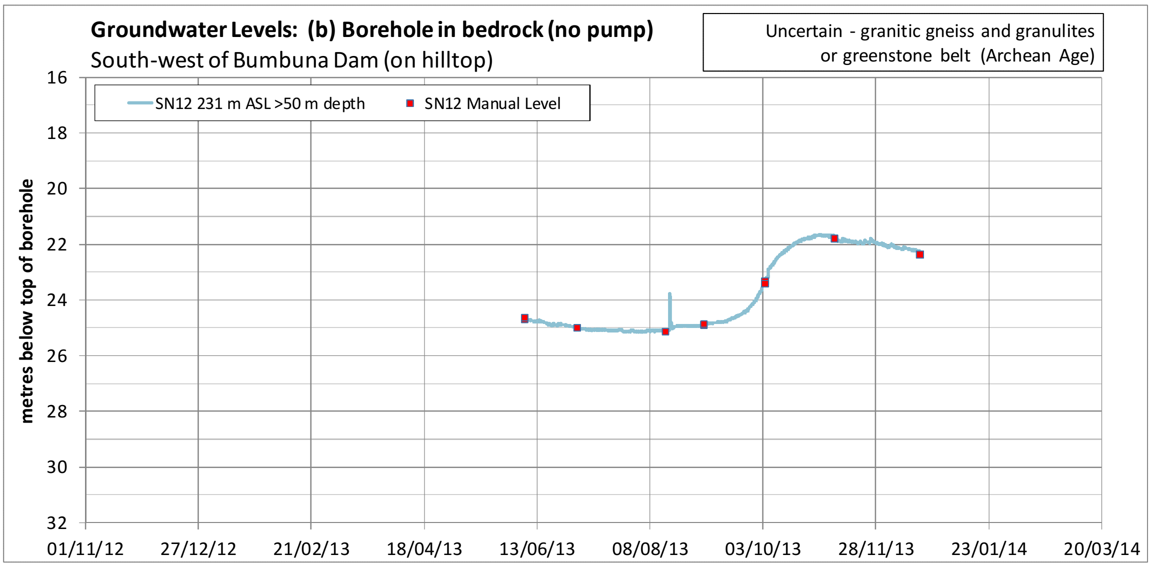
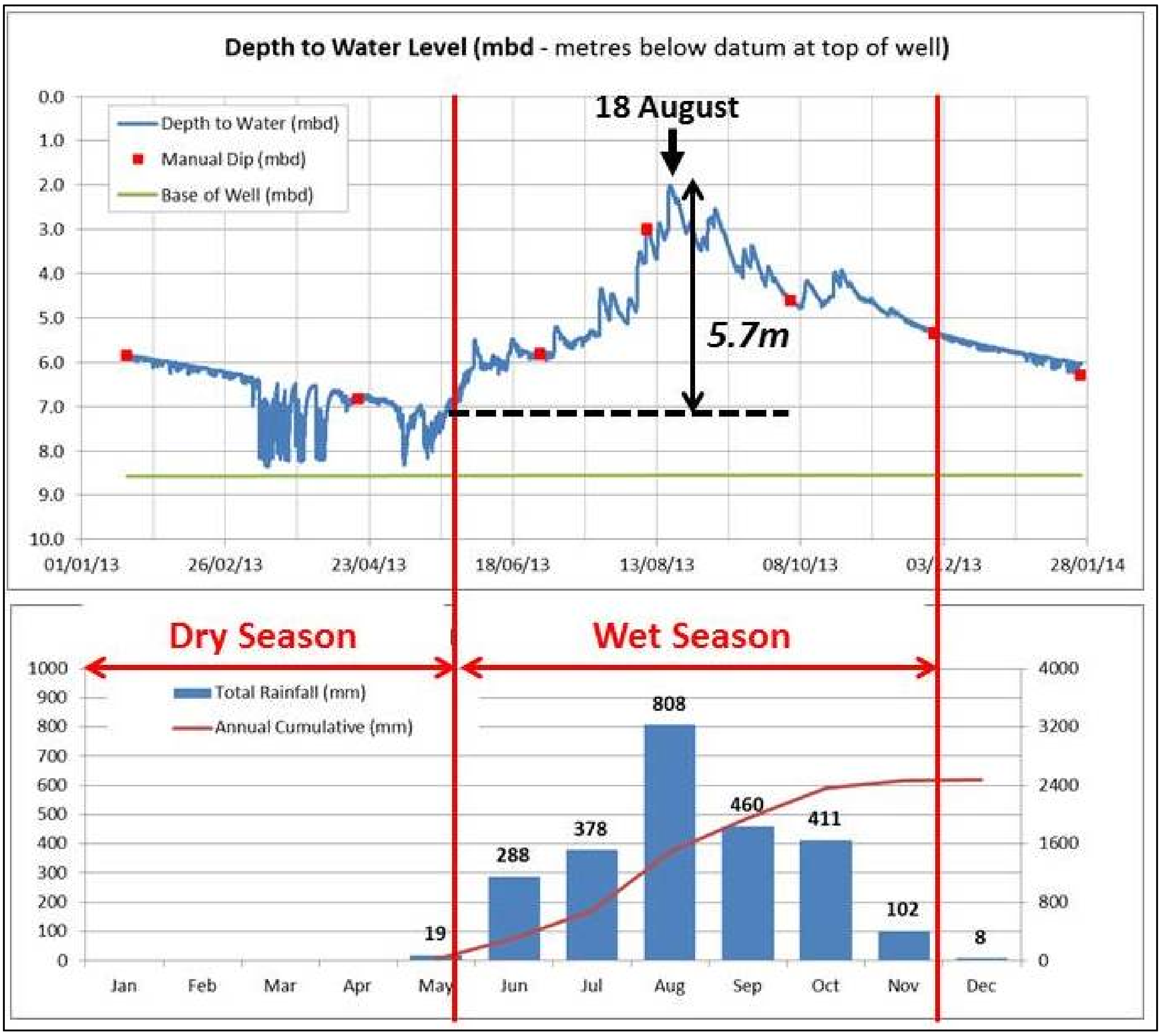


Figure 14 Example groundwater hydrograph with rainfall record (SN03 Bombali DC Well)



This type of analysis confirms a rapid recharge-discharge relationship between rainfall and groundwater level. Storage in the weathered basement and consolidated sediments is limited to the extent that full discharge of waters occurs before the end of the dry season.

Conceptual model of groundwater flow

Observation of the trends in groundwater levels in the basement complex allows the development of a preliminary conceptual model for groundwater flow (Figure 15). This model is very specific to the weathered basement in the mid-Rokel Seli River basin. It may not be representative of flow in the upland areas upstream of Bumbuna nor does it necessarily reflect conditions in other geological environments such as the Rokel River Group. The model will vary, particularly where the base of the weathered basement is very irregular or where local streams or wetland areas are developed.

The model presumes there is continuous groundwater flow through the weathered basement discharging as base flow to the main rivers. There is relatively little or no groundwater flow in the deeper bedrock of the basement. The entire groundwater system fills and empties in the period of a hydrological year.

The flow model will be locally modified by the presence of bedrock where this outcrops as isolated hills or ridges of higher ground rising through the weathered parts of the basement. This is certainly the case in the Magburaka area (Figure 16) where the topographic highs shown in the cross-section and contour plan are generally associated with bedrock outcrops.

Figure 15 Preliminary conceptual model of groundwater flow in the weathered basement of the Rokel-Seli river basin between Bumbuna and Magburaka

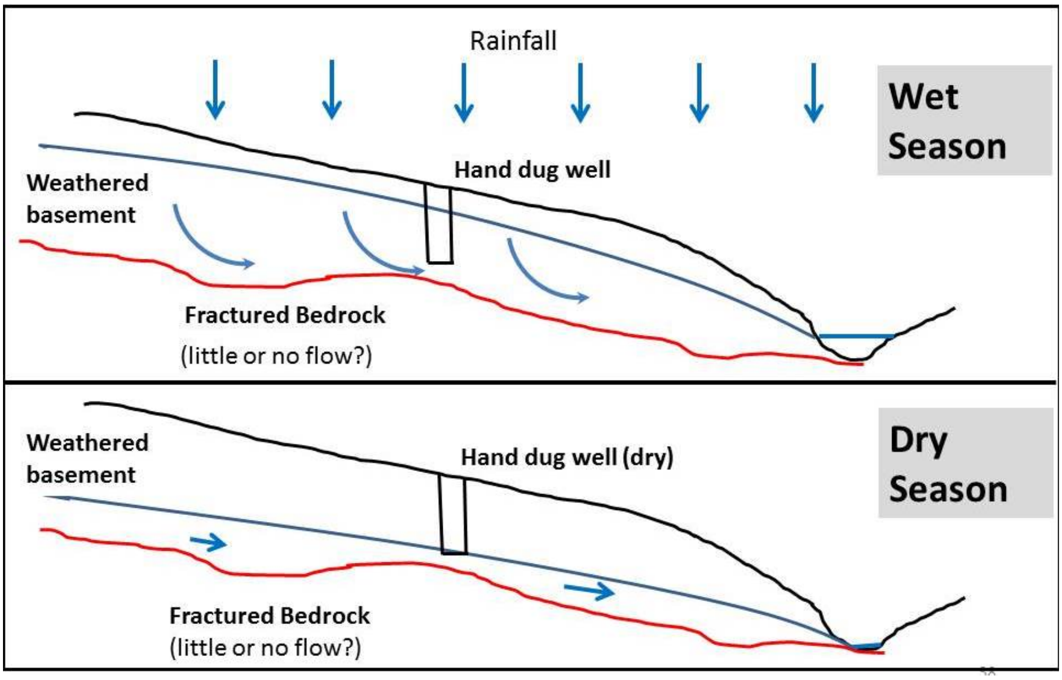
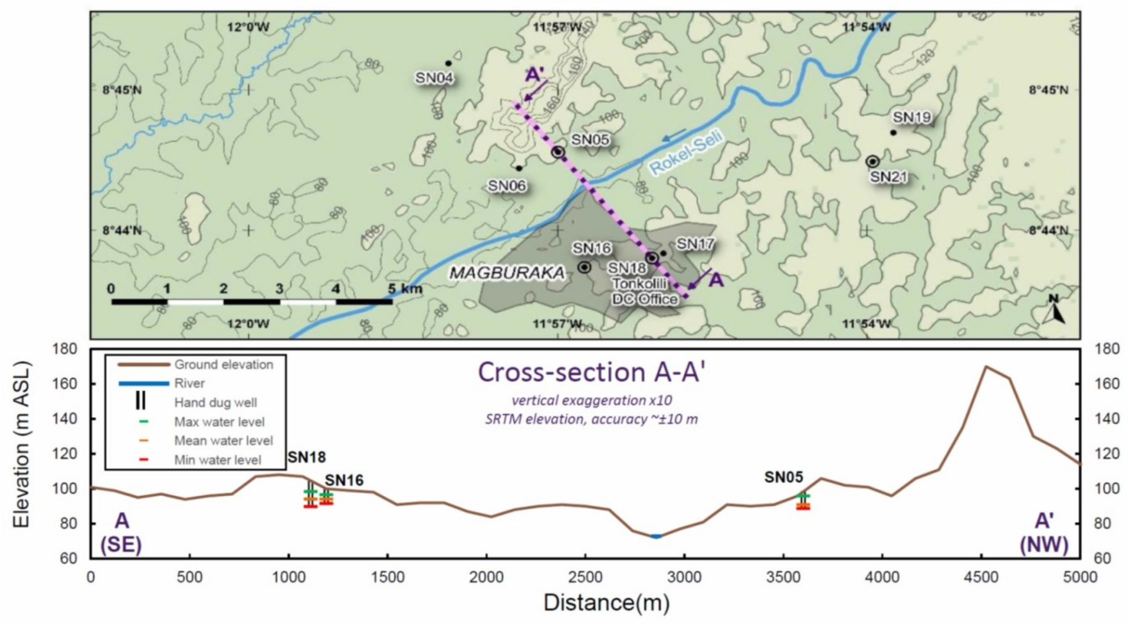


Figure 16 Simplified cross-section through the Rokel-Seli river at Magburaka



Interpretation of small surface water flows

Four v-notch weirs were installed into small streams and springs within the area managed by the Bumbuna Watershed Management Authority (BWMA) in the vicinity of Bumbuna Dam. All these locations (SN10, SN11, SN13, SN14 – Table 2, Map 10) were in use by communities for water supply and were chosen with the intention of providing data for the design of storage and protection schemes to improve the water sources for the benefit of these communities.

One of these locations at Kadala (SN10) was replaced with a spring box after one month of monitoring by the BWMA. A storage system was installed at Kasokira (SN14) by the BWMA team in February and March 2014. Others will be assessed for improvement during 2014-15.

Flow data from the three v-notch weirs are shown in Figure 17 and summarised in Table 8. Monthly mean flows are shown in Figure 18. Flow data from loggers does not always match that from manual measurements and this illustrates a few practical problems when using loggers in these locations. Measurement changes are sometimes lower than the accuracy achievable by the loggers (± 1 to 2 cm); they are probably moved by the curious; the v-notch weirs tend to be overwhelmed in high rainfall periods, so high flows are unreliable; and there appears to be a back-up of water in the stilling tubes during excessively high rainfalls (possibly due to debris being trapped behind the weirs) leading to artificially high heads and apparently high peak flows. It is important therefore when using loggers to record both the crest height of the weir and its maximum possible flow measurement to ensure anomalies are treated as such.

In this chapter the three sites with monitoring data are addressed individually to answer the following two questions:

1. What variation is there in flow rates throughout the year?
2. How do these sources respond to rainfall?

Kakutan spring (SN11)

This is an upland spring gathering water from a relatively small (undefined) high level catchment area. Water seeps into a spring pool which forms the primary water source for the village. When seepage inflow is insufficient, another spring at a greater distance from the village is used. The Bumbuna Dam reservoir (within 1 km of the village) is not considered by the community to be an acceptable alternative water source. The spring lies at a higher elevation than the village and could conceivably be gravity-fed to a more convenient collecting point. During 2013 more than one attempt was made to dig a new well within the village, but without success.

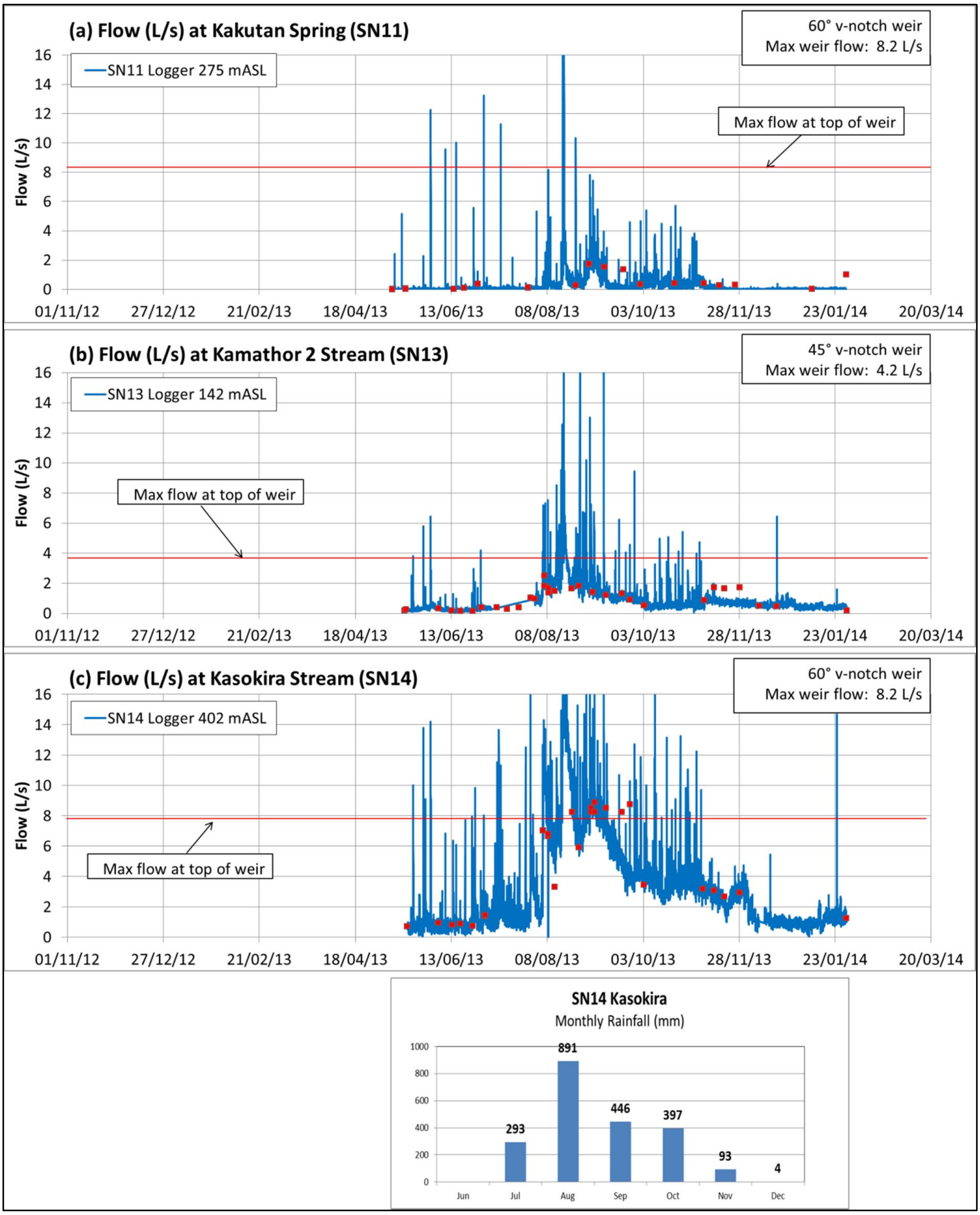
The weir is located immediately downstream of the spring pool. Flows rates vary from zero to very low flows averaging less than 0.04 L/s in May and below 0.02 L/s in December (Table 8). Peak short-term flows in excess of the maximum measurement of the weir (8.2 L/s) occur during heavy rainfall events (Figure 17) and last for a few hours at best. It is only during August, September and October that the base flow from the spring remains above 0.2 L/s between rainfall events (Figures 17 and

18). During the early part of the wet season (May through to early August) spring flows remained low. This will be a challenging site to improve.

Table 8 Summary of flow rates at v-notch weirs

Monitoring Location	SN10 Kadala Weir	SN11 Kakutan Weir	SN13 Kamathor 2 Weir	SN14 Kasokira Weir
Approx Elevation (mASL)	281	275	142	402
Weir Details				
Type of Weir	V-notch	V-notch	V-notch	V-notch
Angle of V notch plate	45°	60°	45°	60°
Max height (cm)	14	16	14	16
Max Flow (L/s)	4.23	8.24	4.23	8.24
Data Record				
Date of First Record	6 Jun 2013	9 May 2013	16 May 2013	18 May 2013
Date of Last Record	22 Jul 2013	29 Jan 2014	29 Jan 2014	29 Jan 2014
No of Records	4423	25419	22309	24300
Flow range (L/s)				
Minimum	0.00	0.00	0.04	0.00
Maximum	0.76	25.64	33.41	85.93
Average	0.11	0.28	0.88	3.21
Average Flows (L/s)				
May 2013	0.01	0.04	0.33	0.96
June 2013	0.23	0.11	0.30	0.91
July 2013	nd	0.12	0.34	1.73
August 2013	nd	0.74	2.44	8.18
September 2013	nd	0.75	1.34	6.40
October 2013	nd	0.44	0.56	3.77
November 2013	nd	0.15	0.74	2.95
December 2013	nd	0.02	0.62	1.26
Total Monthly Flow (m^3)				
May 2013	37	97	886	2570
June 2013	590	286	767	2368
July 2013	nd	333	921	4636
August 2013	nd	1986	6543	21921
September 2013	nd	1944	3465	16581
October 2013	nd	1180	1505	10091
November 2013	nd	383	1928	7657
December 2013	nd	57	1668	3363

Figure 17 Stream flows at v-notch weirs



Kamathor 2 stream (SN13)

This is an upland stream gathering a series of springs emerging from a cultivated hillside and in which the stream channel is poorly defined and often bypassed. It is located approximately 0.5km from the village centre. The overall catchment area is undefined. The stream is understood to flow all year round and is the preferred water source for the village despite there being a well in the village itself. The weir is constructed in a narrow channel and at times of higher flows provides a barrier behind which silt gathers. It therefore requires frequent cleaning.

Mean monthly flow varies from around 0.3 L/s in May, June and July to 2.4 L/s during August, falling to 0.6 L/s in December (Table 8, Figures 17 and 18). During heavy rainfall events there are peak flows in excess of the maximum measurement of the weir (4.2 L/s) (Figure 17) which last over a period of days – indicative of some short term storage capacity in the catchment above the weir.

A spring box is a possibility for this site.

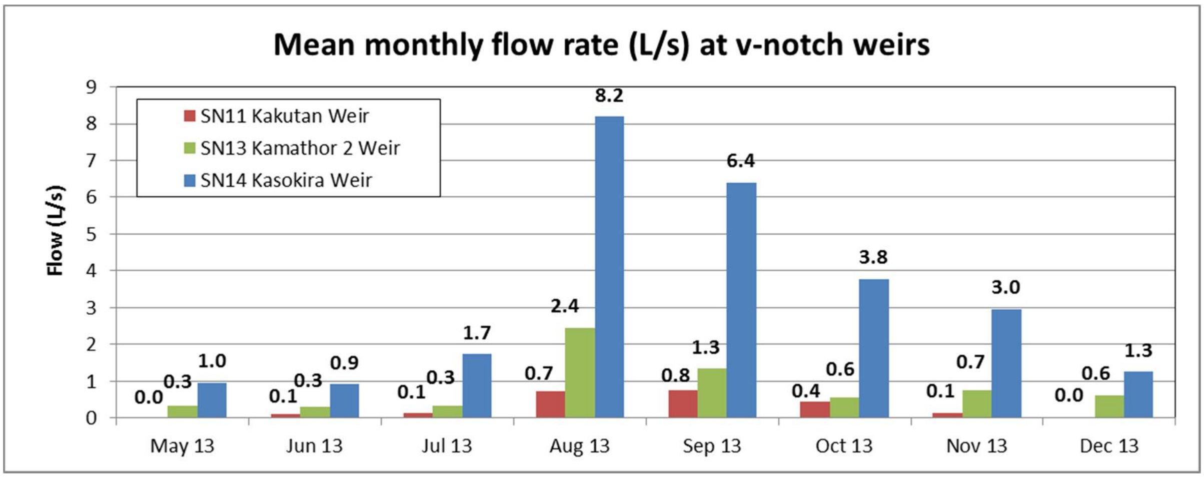
Kasokira stream (SN14)

The stream at Kasokira lies approximately 0.5 km from the village in the centre of a broad upland valley gathering water from a relatively large (as yet undefined) catchment area. The stream is understood to flow all year round and is a reliable source for the village, which has no well. The weir is sited immediately downstream of a disused concrete storage tank previously used to collect water. This was replaced in February and March 2014 with a new storage tank.

Mean monthly flow varies from around 1 L/s in May and June to in excess of 8.2 L/s (the maximum for the weir) in August, falling to 1.3 L/s in December (Table 8, Figures 17 and 18). There are frequent peak short-term flows in excess of the maximum measurement of the weir during heavy rainfall events (Figure 17) which last over a sustained period of several days and during which base flows increase.

This looks like an excellent site to improve as a long term water resource for the village.

Figure 18 Mean monthly flow at v-notch weirs



Other hydrological data for the Rokel-Seli River

Other data in the catchment from historical and on-going monitoring programmes includes

- Flow measurements for the Rokel-Seli River at Bumbuna (pre and post dam construction) and some manual flow measurements of flow in the Rokel-Seli river up and downstream of the Addax estate.
- Water level data for the Bumbuna Dam reservoir which is regulated in order to optimise and maximise energy production.

At the time of writing this report other river flow and rainfall data was coming to light including flow records from a 1976 Hydrological Yearbook on the Rokel-Seli river at Badala and Bumbuna. These are not reported here, but will be included on-line as data is collated and digitised.

Data presented in this chapter are not interpreted. Interpretation of river flows and the water balance of the entire river basin will be undertaken in a separate report.

Flow measurements for the Rokel-Seli River

Historical (pre-dam construction) flows 1971 to 1978

Mean monthly and annual flows in the Rokel-Seli river at Bumbuna for the period 1971 to 1978 are presented graphically in Figure 19.

The total annual river flow in this 8 year period varied from a low of around 3000 Mm^3/year (1971) to a high of 4400 Mm^3/year in 1972 and 4100 Mm^3/year in 1976.

Total and average monthly flows vary from peak values in September and October exceeding 450 m^3/s (1200 Mm^3/month) to dry season flows in March and April of below 2 m^3/s (5 Mm^3/month). The mean flow recorded during the driest period in March and April is between 6 and 6.8 m^3/s (16 and 18 Mm^3/month) and in September and October around 325 m^3/s (850 Mm^3/month).

Recent (post-dam construction) flows downstream of Bumbuna Dam 2010 to 2013

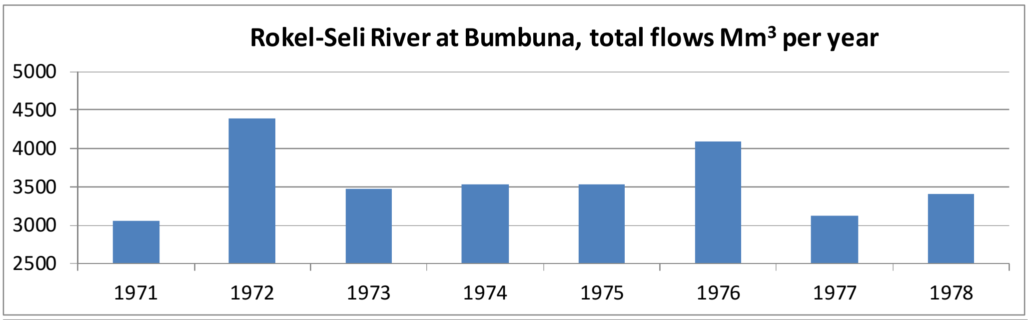
The flow in the Rokel-Seli river is recorded at a concrete weir located immediately downstream of the spillway from the dam (monitoring location BD02, Map 9). Records start during 2010, and have been recorded at 30 minute intervals (with occasional downtimes). Flow data are presented almost continuously for the period from October 2010 to the beginning of December 2013 (Figure 20).

Discharges from the dam during the dry season are regulated to optimise hydro-electric generation. During the wet season the reservoir naturally refills and once full (usually by mid-August, Figure 21) will overspill.

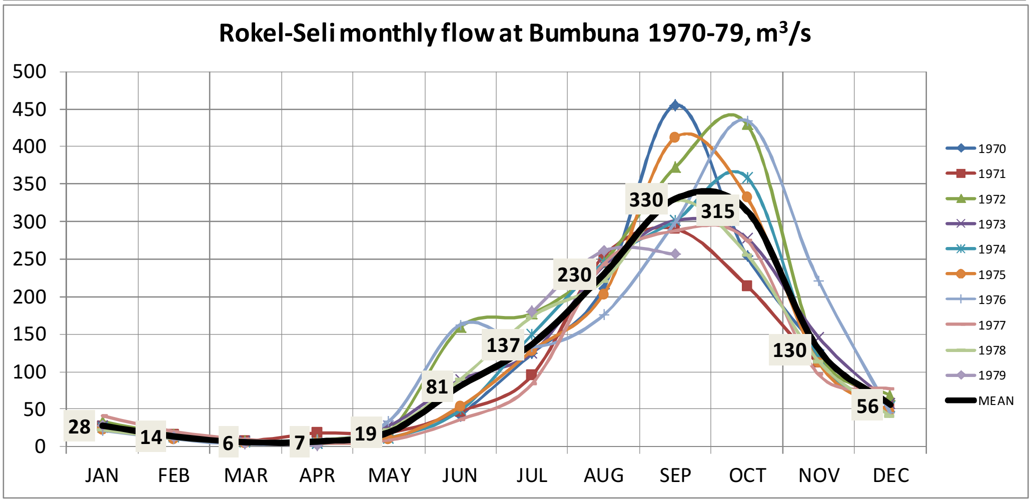
Peak short term flows in August and September are between 350 to 400 m^3/s with mean monthly flows for these months (Figure 20) reaching between 500 and 650 Mm^3/month (190 to 250 m^3/s).

This is approximately 75% of the mean river flow recorded in 1978 (Figure 21) but comparable to ranges seen in the historic data from the 1970's.

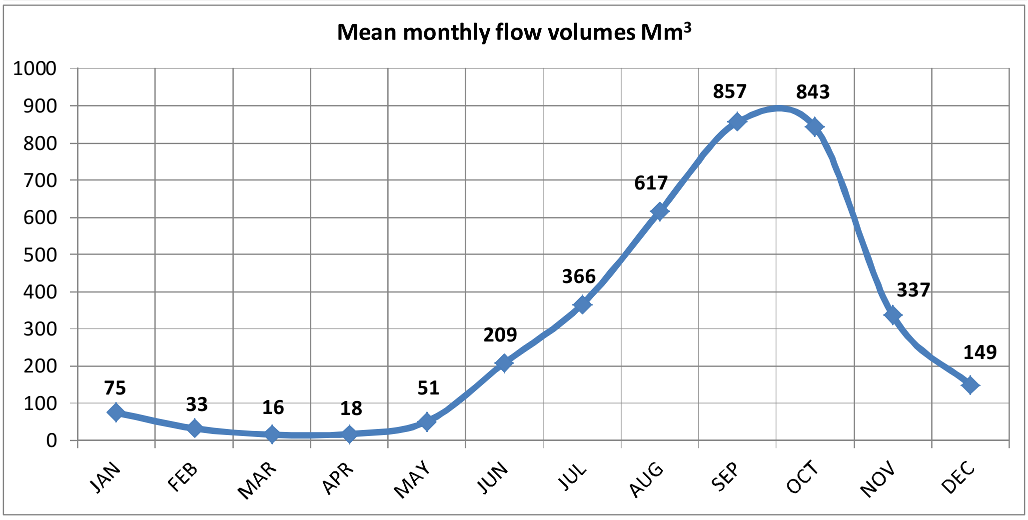
Figure 19 Flow in the Rokel-Seli river at Bumbuna (1971 to 1978)



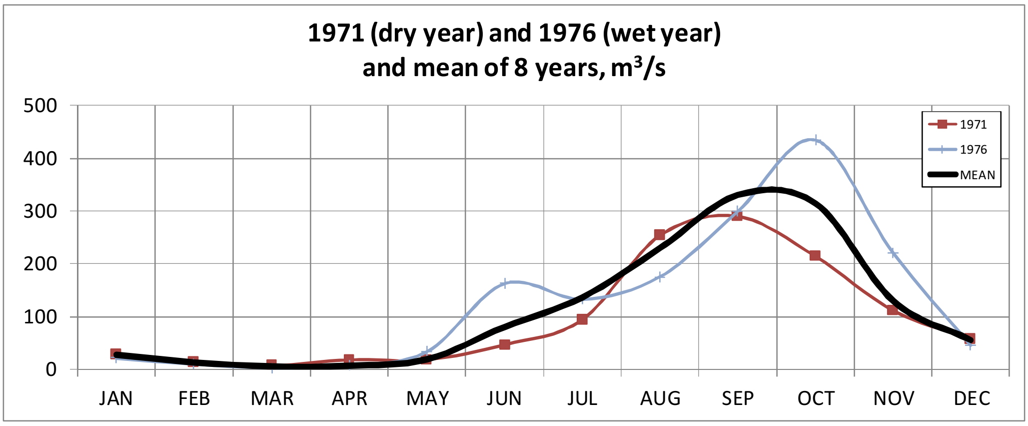
Rokel-Seli River at Bumbuna, total flows Mm³ per year
5000
4500
4000
3500
3000
2500
1971
1972
1973
1974
1975
1976
1977
1978



Rokel-Seli monthly flow at Bumbuna 1970-79, m³/s
500
450
400
350
300
250
200
150
100
50
0
28
14
6
7
19
81
137
230
330
315
130
56
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
MEAN

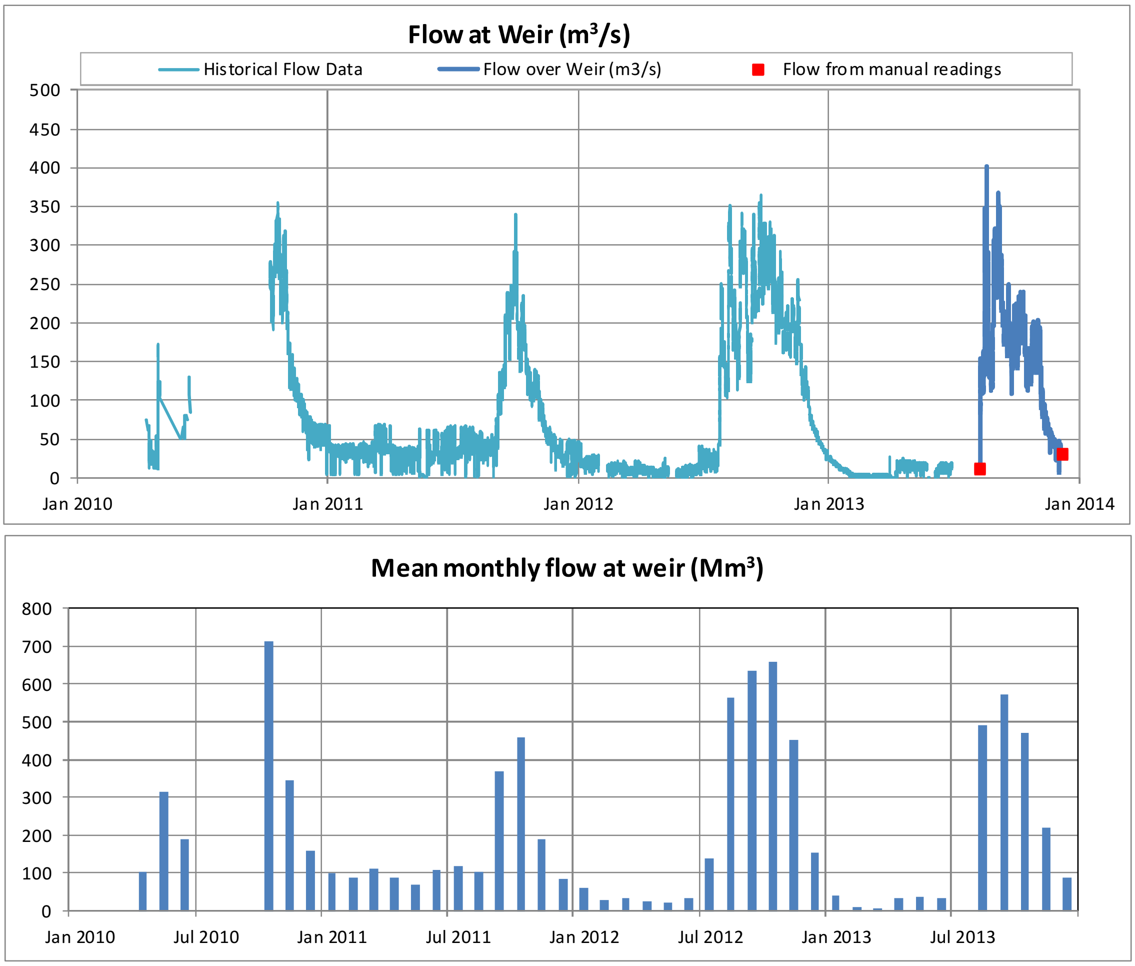


Mean monthly flow volumes Mm³
1000
900
800
700
600
500
400
300
200
100
0
75
33
16
18
51
209
366
617
857
843
337
149
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC



1971 (dry year) and 1976 (wet year)
and mean of 8 years, m³/s
500
400
300
200
100
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1971
1976
MEAN

Figure 20 Flow in the Rokel-Seli river at Bumbuna Dam weir (2010 to 2013)



During the period from December to August, flows from the dam are strictly controlled to optimise energy production. Discharges to the river are typically 25 to 35 Mm^3/month (9 to 14 m^3/s) but have been as low as 8 Mm^3/month (3 m^3/s) in February and March 2013 (Figure 22). These are higher than historic dry season flows.

Flow measurements in Rokel-Seli river at Addax Bioenergy estate

Dry season abstraction rates from the Rokel Seli River to irrigate sugar cane growth at the Addax Bioenergy site are planned to be 7m^3/s. This equates to a maximum abstraction rate of 21Mm^3/month during the dry season (assuming continuous abstraction for 24 hours each day).

Flow in the Rokel-Seli river has been measured by Addax environmental staff at two locations upstream (AD02) and downstream (AD03) of the estate (Map 9). Measurements have been recorded on four occasions since April 2012, mainly in the dry season, by measuring the depth profile of the river and with surface velocity measurements across the profile (Annex C). Results are summarised in Table 9 and compared to the mean monthly discharge rate at the Bumbuna Dam weir during the month of measurement.

The river flow passing the Addax site includes water collected from the catchment area downstream of Bumbuna Dam and should be naturally higher than that discharged from the dam. If the anomalously high downstream flow of June 2012 is excluded, measured flows passing the Addax site were between 2 and 7 times greater than the flow discharged from the dam site. The planned abstraction rate for irrigation amounts to approximately 50% of the dry season flow of the Rokel-Seli River.

Table 9 Summary of flow measurements in Rokel-Seli river at Addax Bioenergy Estate compared to mean monthly discharge rate from Bumbuna Dam.

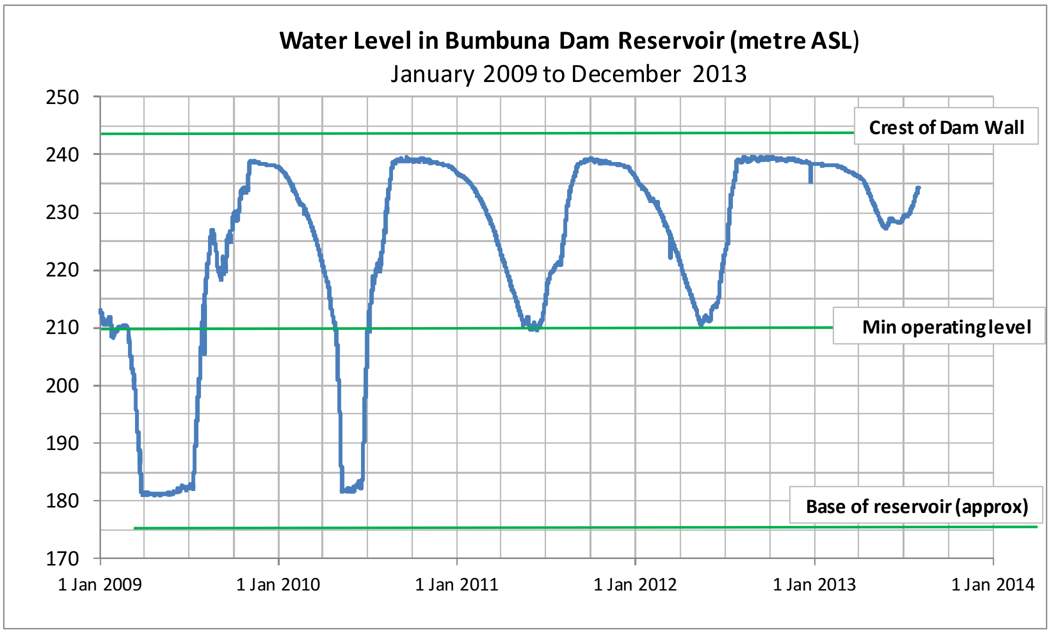
Month of measurement	Flow (m^3/s)		
	Upstream (AD03)	Downstream (AD02)	Mean monthly discharge from Bumbuna Dam
April 2012	19.5	18.7	9.6
June 2012	85.9	152.4	12.3
February 2013	14.7	17.3	3.3
March 2013	15.7	14.2	3.0

The actual date of flow measurement is not recorded. All flow rates at the Addax site should be considered as approximate.

Water level in Bumbuna Dam reservoir

The level of water in the Bumbuna Dam reservoir has been monitored every 2 hours with data available since January 2009 (Figure 21). During the dry season in 2009 and for a shorter period in 2010, the reservoir was fully drained to allow repairs to the dam wall lining. In 2011 and 2012 the reservoir was gradually drawn down, reaching its lowest operating level in August, before naturally refilling through the remainder of the wet season. During 2013 only one turbine was operational and electricity production halved. Less water was consequently discharged resulting in reservoir levels remaining at relatively high levels throughout the dry season.

Figure 21 Water level in Bumbuna Dam Reservoir (2009 to 2013)



Other significant activities and plans for the river basin

There are a number of major and minor activities occurring in the river basin which have so far not been fully documented, but during 2014 further quantitative and water quality data will be sought to put into perspective impacts on river flows and water quality from:

- Mining activities
  - Water management, abstractions, discharges from the Tonkolili iron ore mine (African Minerals) into the Tonkolili river.
  - Water management, abstractions and discharges from the Marampa iron ore mine (London Mining) into the Tonkolili river.
  - Other commercial gold mining activities along the Tonkolili and Rokel-Seli rivers.
  - Artisanal gold mining activities along the Tonkolili and Rokel-Seli rivers.
- Agri-Business
  - Magbass Sugar abstraction requirements for irrigation
  - Addax Bioenergy abstraction and discharge records
- Urban water supply abstractions
  - Freetown Water Supply Plans
  - Magburaka intake
  - Lunsar intake
- Large and small HEP plans
  - Bumbuna II dam development
  - Other mini HEP schemes

Conclusions

Historical hydrological data

Historical hydrological data including rainfall and river gauging records are being gradually rediscovered, collated and digitised. This includes rainfall records (e.g. Map 4), and river flow data.

Pilot monitoring network

A pilot hydrological monitoring network has been established in the mid-Rokel-Seli river basin consisting of a network of 33 monitoring sites (24 set up by this project, 9 from other organisations).

Within this pilot network there are 26 rain gauge sites, 16 sites recording groundwater levels and 4 sites from which flows at small surface water sources lows are recorded using v-notch weirs. 3 sites record flow in the Rokel-Seli river. One site provides the level of water in Bumbuna Dam reservoir at Bumbuna. A raingauge has been provided as close as possible to each water source being monitored.

In developing the network, personnel from the Ministry of Water Resources and the Ministry of Energy (Bumbuna Water shed Management Authority) have been trained to use equipment, collect data and to liaise with government, industry and communities from whom data is either being voluntarily collected or shared.

The spatial density of the pilot network is greater than is necessary for translation into a national monitoring network. However, the primary purpose for selecting sites has been to learn what is practically achievable by engaging with local communities and to identify issues that need to be addressed before building a national network. Operating this pilot network has provided many practical insights into how government organisations, local communities and other organisations can work together to deliver good quality hydrological monitoring data for the benefit of the country as a whole.

Data validation, cleaning and publishing

As data has been collected it has been checked for consistency against other data records and where appropriate cleaned to remove erroneous data. Community collected rainfall data has in most cases proved as reliable, and sometimes more reliable, than data collected from professional organisations.

This report represents the first publication of any significant body of hydrometeorological monitoring data in Sierra Leone since before the Civil War and forms an important water resource reference source. Summaries and graphical representations of data are included as printed appendices to this report with all data (historical and new) being posted as digital files to a website for open access to others (www.SaloneWaterSecurity.org).

Data interpretation

Preliminary interpretations of rainfall , groundwater level and surface water flows are provided in which data from the pilot monitoring network collected in 2013 is compared or used alongside historical data records.

Rainfall in the mid-Rokel-Seli river basin varies spatially and seasonally in accordance with historical rainfall patterns, though annual rainfall records collected since 1921 at Makeni demonstrate increasing variance in rainfall totals and a reduction by 8.4% in mean annual rainfall since the mid 1980s.

Groundwater in the weathered basement complex of the Rokel-Seli basin appears to act as a continuous hydrogeological unit. Groundwater levels vary by between 2.7 to 8.0m seasonally, respond rapidly to rainfall events and fully discharge to surface water by the end of the dry season.

Monitoring of small traditional surface water sources demonstrate the high variability in flows dependent on rainfall and their catchment setting.

The interpretation of the water balance for the whole of the Rokel-Seli catchment area is beginning to become possible using data from the Bumbuna dam site and will be addressed in more detail during 2014 using newly rediscovered historical data river flow data.

Understanding impacts on water resources

There are multiple stakeholders dependent on both the quality and quantity of water resources in the Rokel-Seli river basin ranging from the large scale (commercial mining, hydropower and irrigation, plans for Freetown water supply, plans for enhanced HEP at Bumbuna 2) to smaller scale (urban and community water supply and sanitation, community agriculture, artisanal mining). All of these activities use water and to differing extents are potential or actual sources of pollution. Some activities are better controlled than others and achieving a fair regulatory balance to sustain water flows and water quality in the river basin will be a key challenge for the Government of Sierra Leone over the next few years.

Monitoring, measuring and sharing of data is the building block on which informed judgements can be made on the combined impact of existing and planned water use activities in the river basin as a whole. This first year of monitoring has demonstrated that with co-operation and good will between organisations, communities and government, much can be achieved to collect good data. The challenge in the second year will be to demonstrate how this data can be used to help decision makers understand the impacts of any activity, existing or new, on the overall sustainability of water usage for future generations.

Recommendations

Rokel-Seli river basin pilot monitoring network

The pilot monitoring network established in the Rokel-Seli river basin is being extended to the upper and lower parts of the river basin during 2014-15 with more active engagement with both Port Loko and Koinadugu District Councils. It is recommended that following another year of monitoring that this pilot network is then refined (reduced) and integrated into the planned development of national monitoring networks for surface water and groundwater (Maps 2, 3 and 5).

Data collation, cleaning and management

Historic hydrometeorological data and other technical information is beginning to be rediscovered from a number of sources. It is recommended that as data comes to light it is either digitised or scanned and made accessible on-line.. Discussions should continue with individuals with knowledge of past history of monitoring (eg Fenda Akiwumi, GoSL personnel and academics) and "grey literature" should be explored further.

There are currently no resources in place to adequately manage the data collected from monitoring programmes. There is a need to start to evolve institutional processes for managing data and to identify software and paper filing systems to store information systematically and demonstrate these systems can work using resources available (staff, budgets and hardware) in Sierra Leone.

Skills training and knowledge transfer

Data will continue to be collected in-country during 2014-15 alongside training of technical staff. The technical skills of staff need to improve and in turn be extended to wider groups of technical personnel in district and government organisations. This should continue during 2014-15.

River basin water balance

There needs to be better understanding and more transparent regulation of abstractions and discharges both in terms of quantity and quality.

The management of water quantity needs to focus on impacts during the dry season when irrigation and other water abstraction requirements will be at their greatest whilst flows in the river systems and groundwater levels will be at their lowest.

There are plans to expand commercial mining, agri-business and small scale HEP schemes across Sierra Leone as well as the ever present need to improve local water supply and sanitation for all. Any proposed commercial activity relies on external consultants providing impact assessments based on poor or little hydrological data. Frequently in these reports the average rather than dry season river flow is used to benchmark water abstractions thereby ignoring the period of greatest impact.

The development of a preliminary water balance model is a necessary step in improving understanding of the overall water resource in a river basin, particularly during the dry season. From these models, impacts and regulatory controls can be tested, rationalised and applied in a transparent way. However, good models require a good conceptual understanding of the whole catchment supported by good monitoring data and so must be developed hand in hand with field evidence.

Starting with the Rokel-Seli catchment we recommend that work is commissioned to evolve a GIS-based river basin water balance management tool as a preliminary step to providing planners and other decision-makers access to information on the availability of water resources when assessing proposals for new large scale water abstractions in a catchment. This tool may also be an aid to water licensing.

References

Adekile, Dotun (2013) Water point construction and maintenance guidelines for Sierra Leone (Draft). Water and Sanitation Programme, World Bank.

Akiwumi Fenda A. (1987) Groundwater exploration and development in crystalline basement aquifers. In Groundwater Exploration and Development in Crystalline Basement Aquifers V2 (Proceedings Harare, Zimbabwe workshop, June 1987,431-438. Commonwealth Science Council. (89) WMR-13, Technical Paper 273.

Akiwumi F. (1994) reducing costs of monitoring networks in developing countries by collation and analysis of pre-existing hydrogeological data. Future Groundwater Resources at Risk (Proceedings of the Helsinki Conference. June 1994). IAHS Publication 222. 481-490.

BGR, CapNet, WANet and WaterNet (Editors) (undated -post 2007), Groundwater resources and management: Capacity Building for Groundwater Management in West and Southern Africa. 65pp. http://capnet.org/sites/capnet.org/files/GWCB_final_report.pdf

Bonsor H.C. and MacDonald A.M. (2010a) Groundwater and climate change in Africa: review of recharge studies. British Geological Survey Internal Report, IR/10/075. 30pp.

Bonsor H.C. and MacDonald A.M. (2010b) Technical note: a systematic review of aquifer properties studies in Africa. British Geological Survey, Internal Report, IR/10/076. 30pp.

British Geological Survey African Groundwater Maps (website): http://www.bgs.ac.uk/research/groundwater/international/africanGroundwater/maps.html). accessed march 2014.

Chilton John P. and Foster Stephen S.D. (1995) Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa. Hydrogeology Journal V3 (1) 36-49.

Climate Research Unit, University of East Anglia web site: www.cru.uea.ac.uk accessed March 2014

Geological Survey of Sierra Leone (2004) Geological Map of Sierra Leone. Map reproduced from Koidu Holdings web site. http://www.koiduholdings.com/images/kkp_geology_fig1_large.jpg (photographed image)...accessed on 1 March 2014.

Gregory, S (1965) Rainfall over Sierra Leone. Research Paper, Dept of Geography, University of Liverpool. The Acorn Press, Liverpool. 58pp

HydroSHED GIS web site: http://hydrosheds.cr.usgs.gov/index.php. accessed in March 2014

MacDonald A.M., Bonsor H.C., O'Dochartaigh B E and Taylor R.G. (2012) Quantitative maps of groundwater resources in Africa. Environment Research Letters V7 024009. 7pp

MacDonald, Alan, Davies Jeff, Calow, Roger and Chilton, John (2010) Developing Groundwater. A guide for rural water supply. Practical Action Publishing Ltd. UK. 358pp

Nippon Koei UK, BMT Cordah and Environmental foundation for Africa (2005) Bumbuna Hydroelectric Project Environmental Impact Assessment (Vols 1, 2 and 3). Report prepared for ministry of Energy and Power, Government of Sierra Leone. http://www.ecowrex.org/eg/bumbuna

Thomas M.O (undated Powerpoint presentation) Hydrogeological overview (of Sierra Leone)

Wright E.P (1992) The hydrogeology of crystalline basement aquifers in Africa. In Wright E.P. and Burgess W.G (eds), 1992. Hydrogeology of crystalline basement aquifers in Africa. Geological Society Special Publication No 66, 1-27

Moijue, Francis (undated powerpoint presentation) "Project Inception Workshop: strengthening climate information and early warning systems in western and central Africa for climate resilient development and adaptation to climate change – Sierra Leone".

Ndomahina E.T. and Kabia I.S. (2004) A review of the Water Supply and Sanitation Sector. Poverty Alleviation Strategy Coordinating Office, Government of Sierra Leone. 93pp

Shaw, Elizabeth M, Beven Keith J., Chappell Nick A. and Lamb Rob (1994). Hydrology in Practice. Spon Press, UK. 543pp

Thomas, Mustapha (undated). Spreadsheet with data from 359 boreholes in Sierra Leone. Personal communication

UNDP / Ministry of Energy and Power, Water Supply Division, Sierra Leone (1976) Hydrological Year Book of Sierra Leone. Data compilation 1 may 1970 – 31 March 1976. UNDP pilot project for the determination of surface water resources of Sierra Leone. SIL/72/007. October 1976.

UNICEF / Ministry of Energy and Water Resources (MEWR), Sierra Leone (undated) Feasibility study for manual drilling. Mapping of favourable zones. UNICEF, Practica Foundation, Enterprise Works / VITA (Relief International)

World Climate website: www.worldclim.org accessed March 2014

WSP / UNICEF / Ministry of Energy and Water Resources (MEWR), Sierra Leone (2012) Sierra Leone Water point Report. Hirn Maximillian. WSP, UNICEF, UKAid. 14pp

Annexes