Republic of Sierra Leone

Ministry of Water Resources

Water resources monitoring in Sierra Leone

The 'why' and how' of water resources monitoring

Volume 2 of a three-volume set

March 2015

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A v-notch weir at Kasokira for monitoring small stream flows – installed by participants in a Water Security training course, December 2013.

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) Water resources monitoring in Sierra Leone. Volume 2 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 3 Data and hydrological understanding generated in the Water Security Project*.
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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. This document sets out some of our recent experience of monitoring water resources 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 2 of 3, in which practical guidance is given on aspects of the monitoring of water resources. Volume 1 provides strategic and policy-level guidance to Government, while Volume 3 sets out analyses of the data collected so far in the Water Security Project.

This Volume begins by setting out the reasons why monitoring of water resources is so important, even in a country as well-endowed with water resources as Sierra Leone. It then goes on to explain in detail how monitoring of rainfall, groundwater levels and spring- and stream-flows can be undertaken. The final sections draw out conclusions and recommendations from the experience of the Water Security Project, as local and national attempts to scale-up these experiences continue.

The single publicly available UN estimate of Sierra Leone's water resources is almost certainly a gross over-estimate. Before the war Sierra Leone had extensive meteorological and hydrological monitoring networks, although now almost all the physical infrastructure and most of the data from that period has been lost. Despite the heavy dependence of its predominantly rural population on groundwater, Sierra Leone has never had a groundwater monitoring network.

The first step in managing water resources is to 'know what you've got' – in other words to re-establish (and establish new in the case of groundwater) appropriate hydrometeorological monitoring networks in order to quantify the nation's water resources and understand the quality of those waters.

This Volume draws on the experience of the Water Security Project to set out practical guidance on monitoring of rainfall, groundwater levels and spring- and stream-flows. These were the variables focused on in the Water Security Project, within a limited geographical area. Other observations and recommendations are made concerning variables which have not yet been monitored, and concerning the extension of our local experience to national scale.

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. This Volume is a contribution to the practicalities of monitoring. Volume 3 provides the analysis arising from the Water Security Project, and Volume 1 draws out the implications for national policy on Water Security.

Box 1 Sierra Leone's river basins

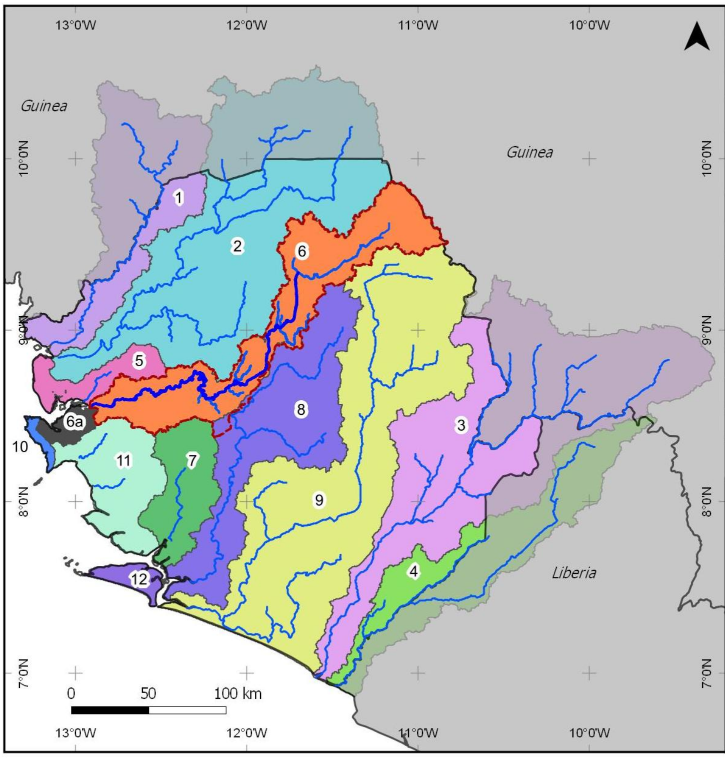
Between ten and thirteen main river basins and water resource areas (WRAs) have been identified in Sierra Leone following those shown in a 1988 map in Ndohamina and Kabia 2004. Map 1 is updated from the 1988 map using the same numbering system but with boundaries generated by USGS HydroShed (http://hydrosheds.cr.usgs.gov/index.php). 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 HydroSHED 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 Hydroshed 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 Hydroshed 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 HydroSHED 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

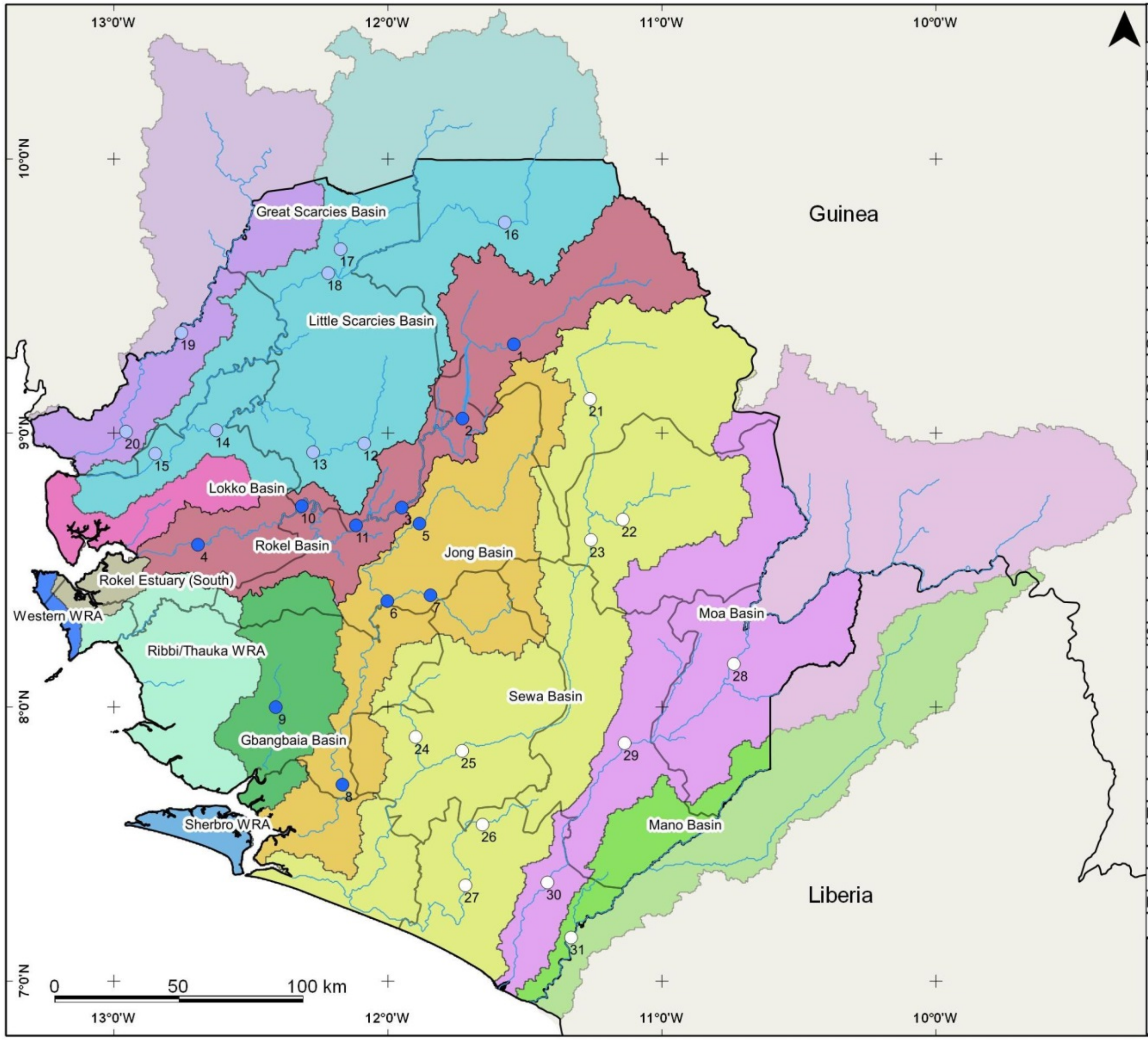
Map 1 Sierra Leone river basins



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



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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		

Sites used in Previous Hydrological Networks:
N Pilot Network (1970 to 1976)
OCP Onchocerciasis Project (1988 to 1991)

Legend

Proposed river gauge sites
- Phase 1
- Phase 2
- Phase 3

Admin Boundaries
- Country Border
- Distict Boundaries

Main Rivers

UKaid from the British people

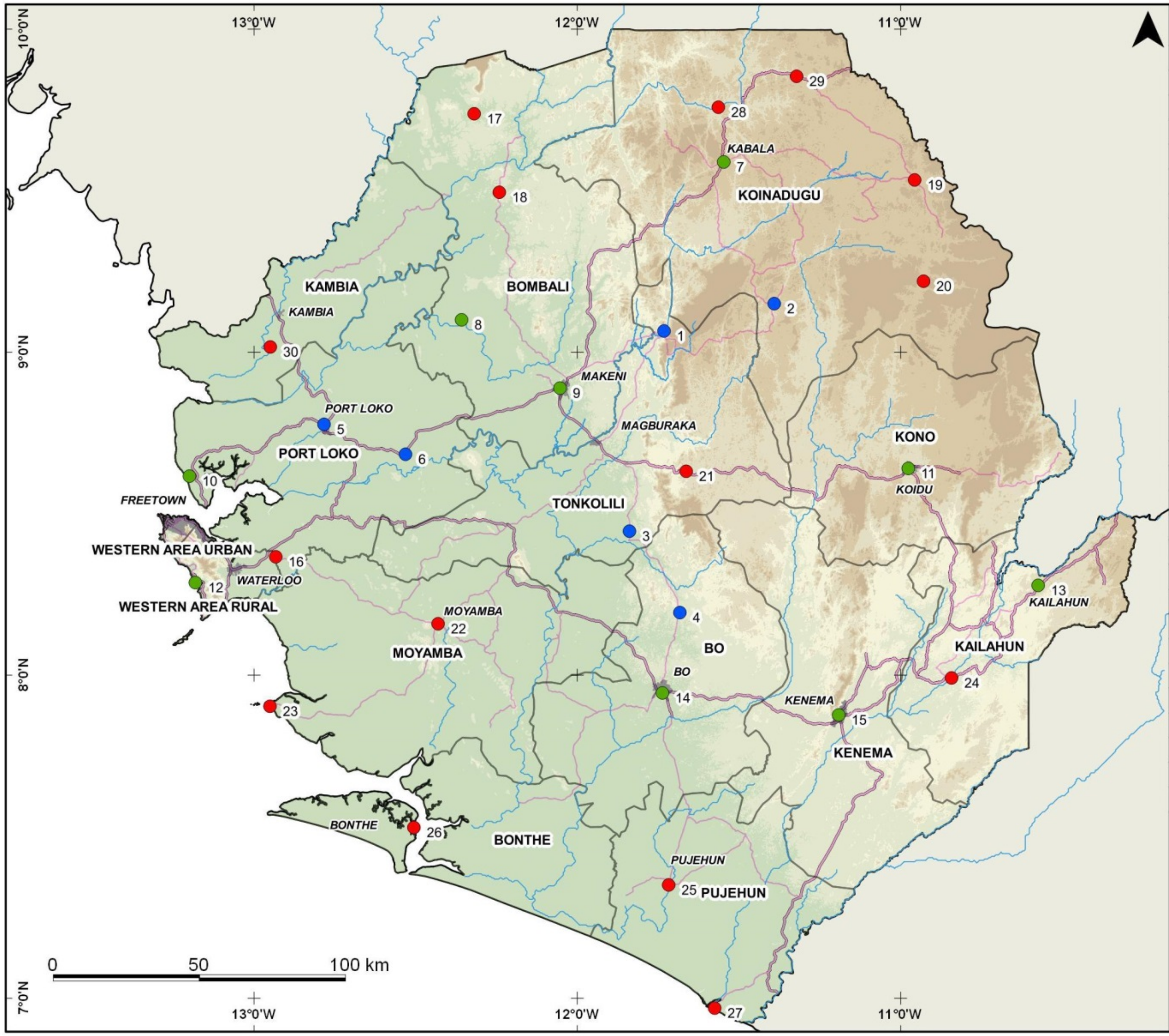
Sierra Leone Proposed River Monitoring Network

V 1.0, September 2014

Projection: WGS84
OpenStreetMap

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)



INDEX

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

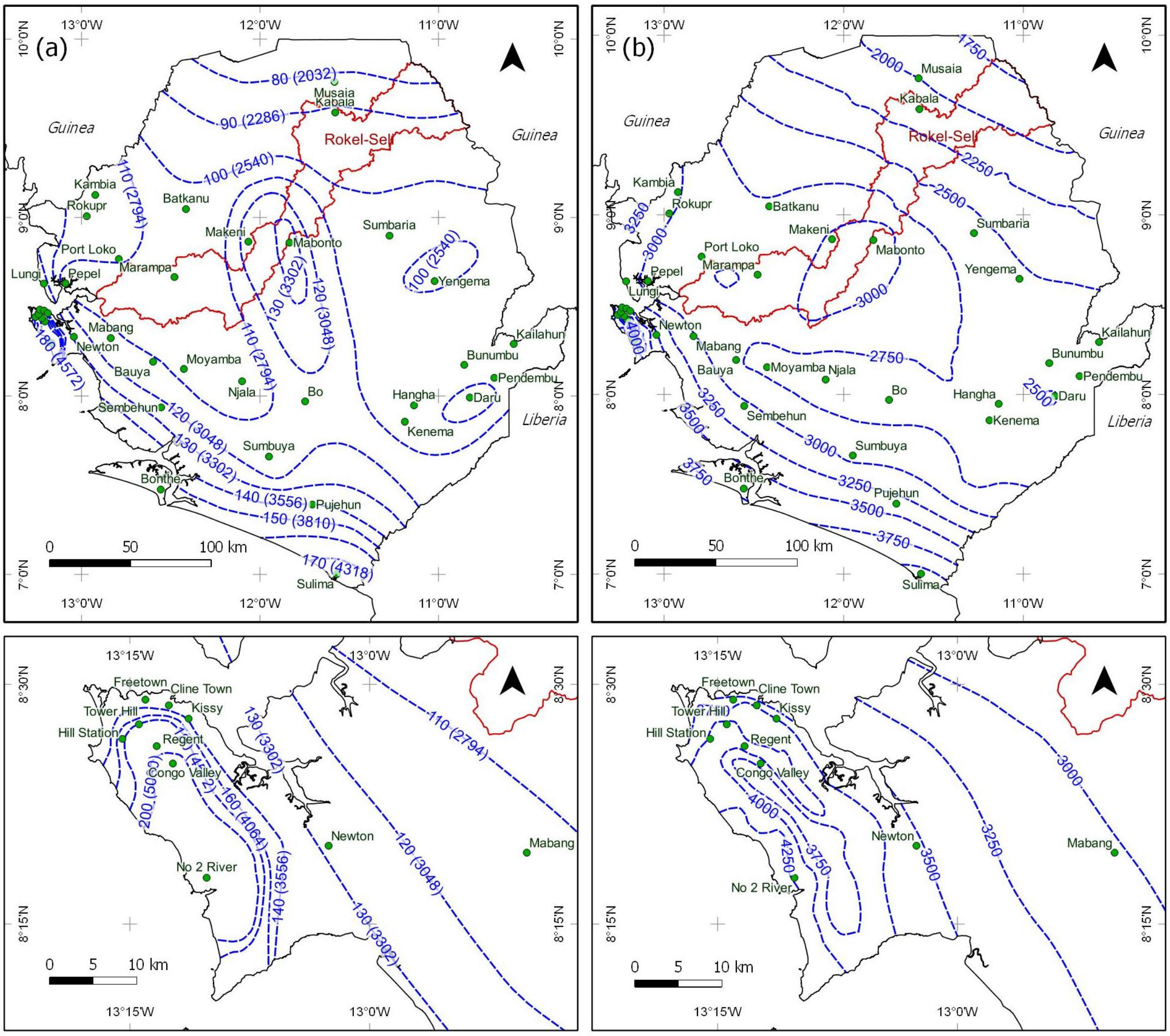
Sierra Leone Proposed Meteorological Monitoring Network

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.

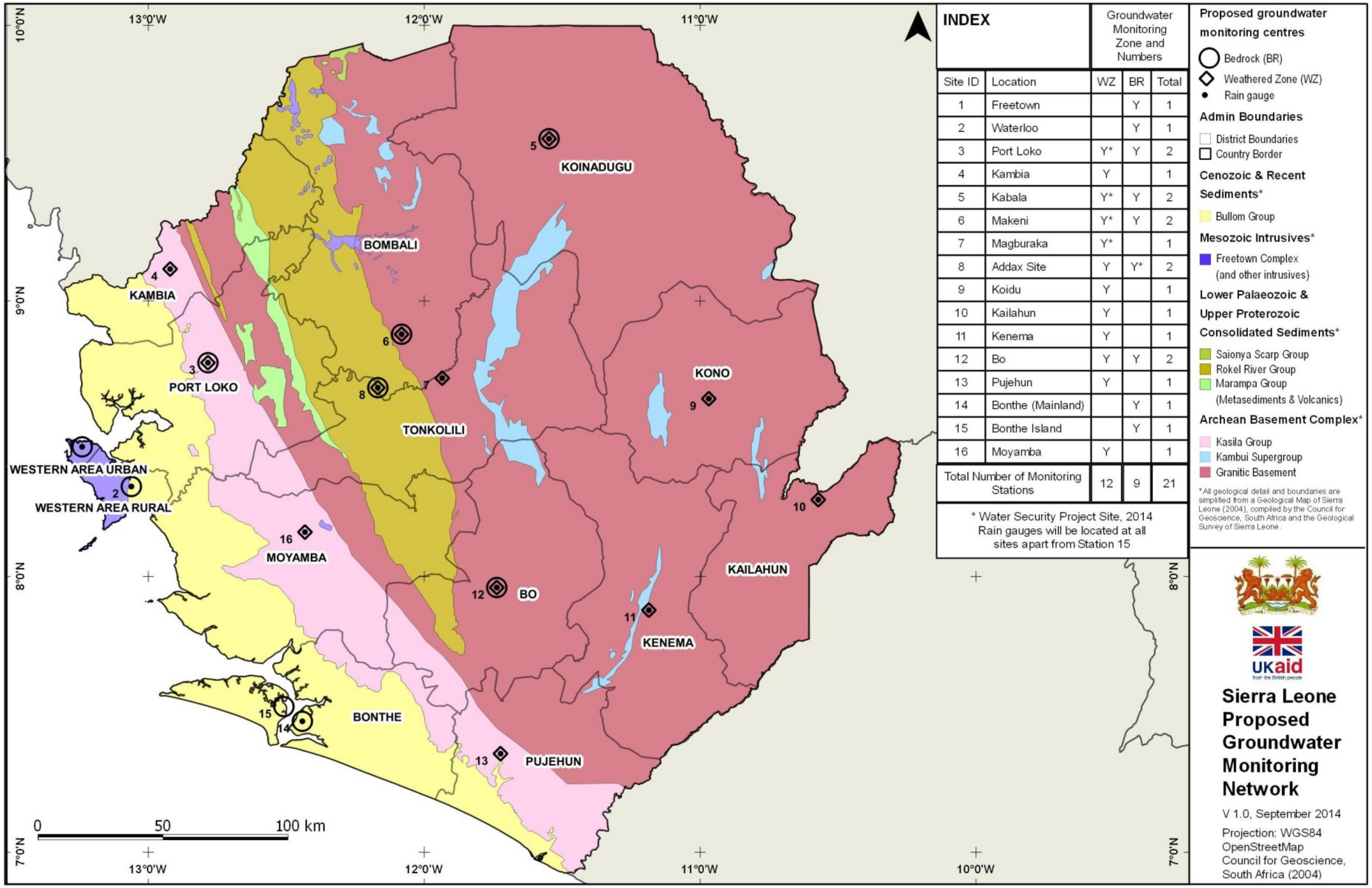
Map 4 Sierra Leone mean annual rainfall



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

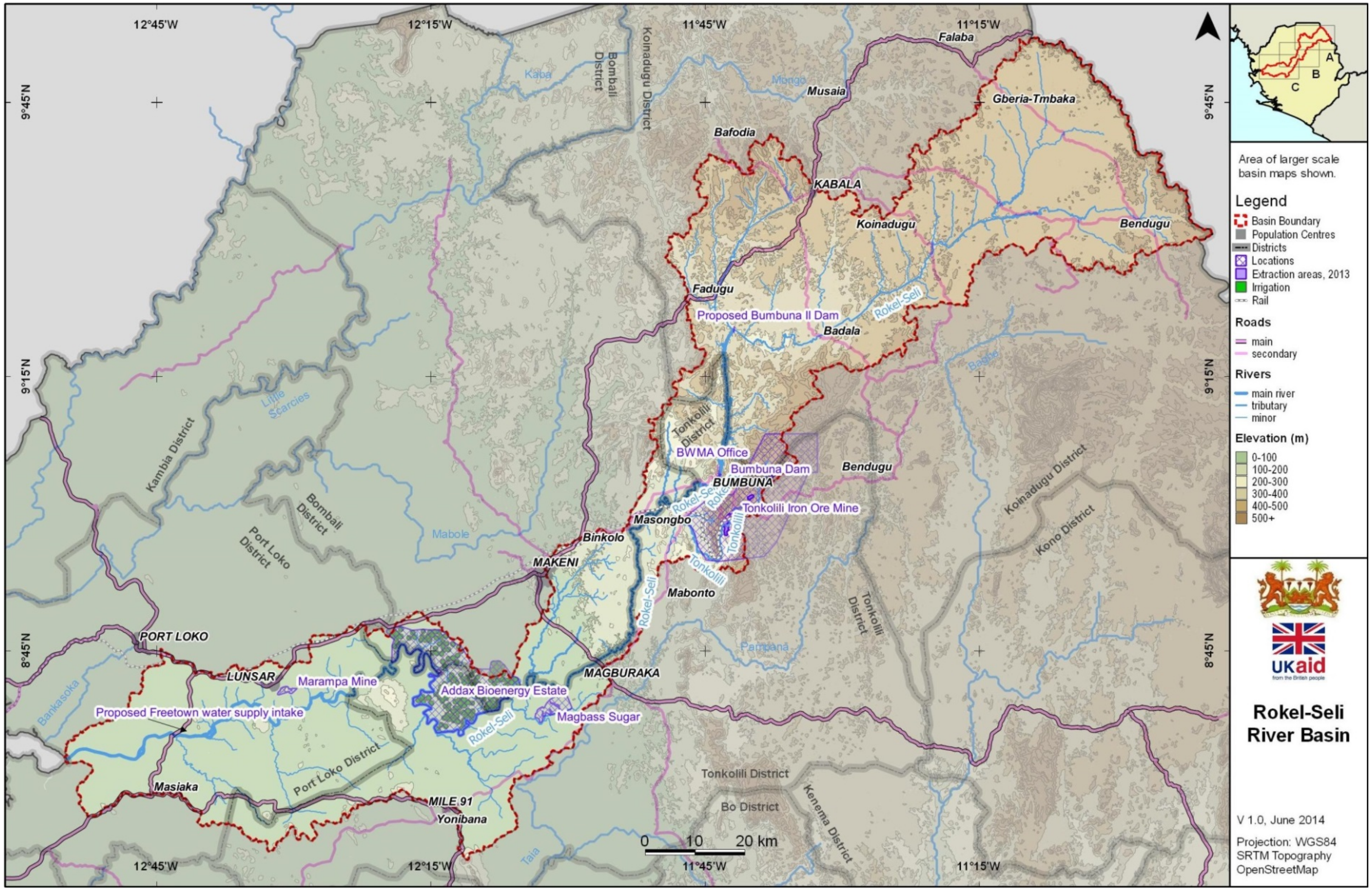
Map 5 Sierra Leone geology and proposed groundwater monitoring network (2014)



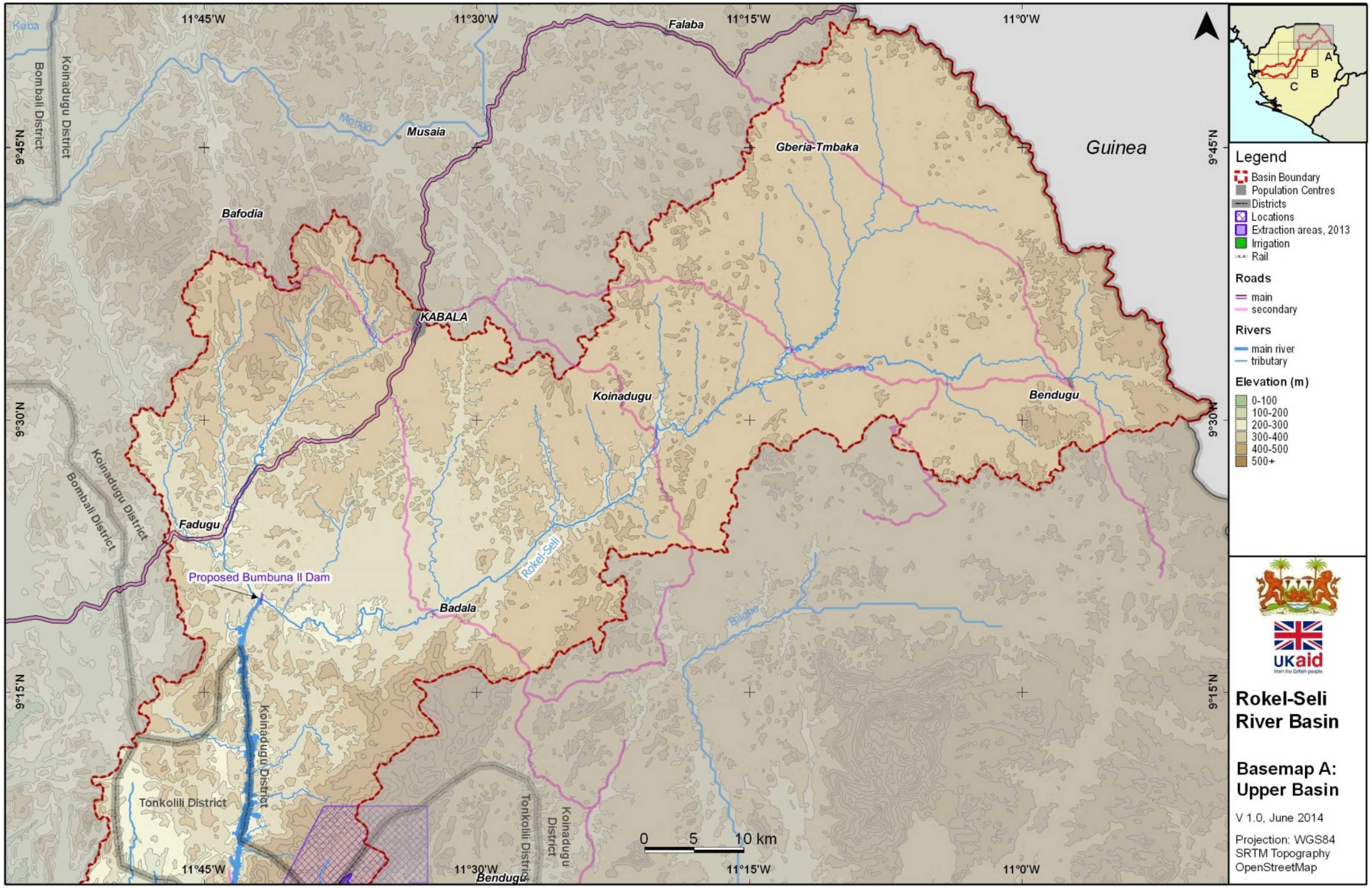
Site ID	Location	WZ	BR	Total
1	Freetown		Y	1
2	Waterloo		Y	1
3	Port Loko	Y*	Y	2
4	Kambia	Y		1
5	Kabala	Y*	Y	2
6	Makeni	Y*	Y	2
7	Magburaka	Y*		1
8	Addax Site	Y	Y*	2
9	Koidu	Y		1
10	Kailahun	Y		1
11	Kenema	Y		1
12	Bo	Y	Y	2
13	Pujehun	Y		1
14	Bonthe (Mainland)		Y	1
15	Bonthe Island		Y	1
16	Moyamba	Y		1
Total Number of Monitoring Stations		12	9	21

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*)

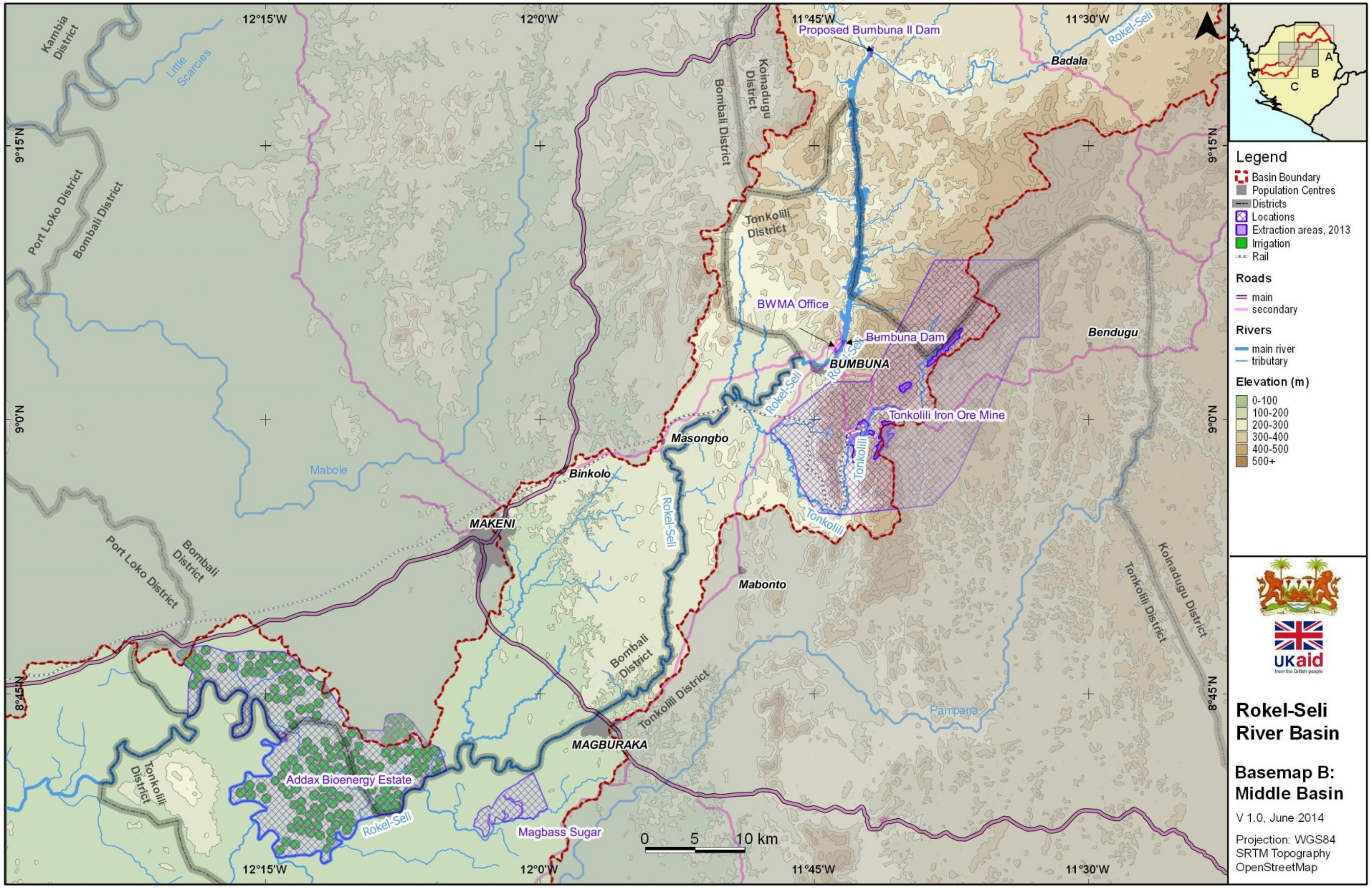
Map 6 Rokel-Seli River Basin



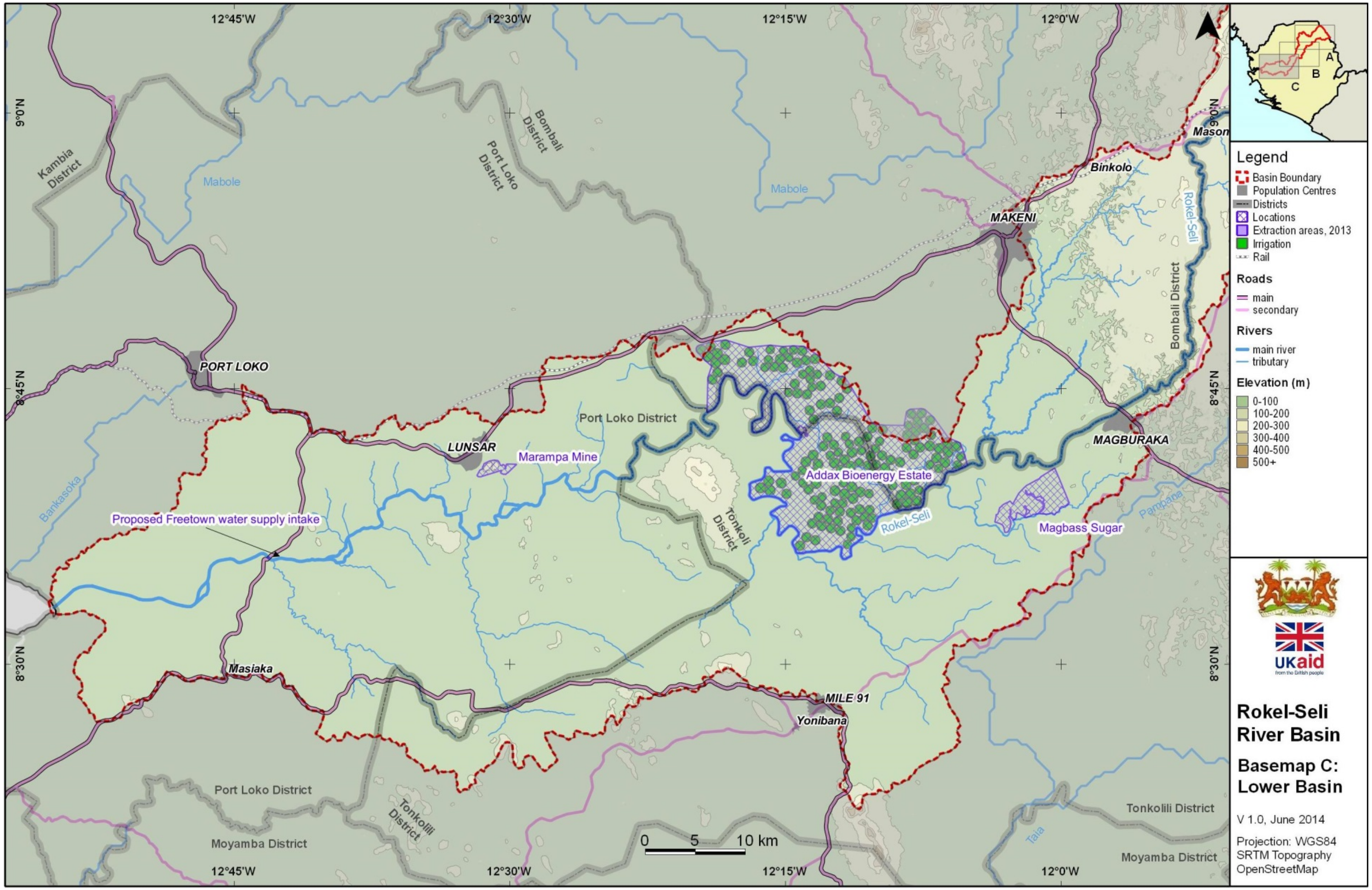
Map 7 Rokel-Seli River Basin – Upper Basin



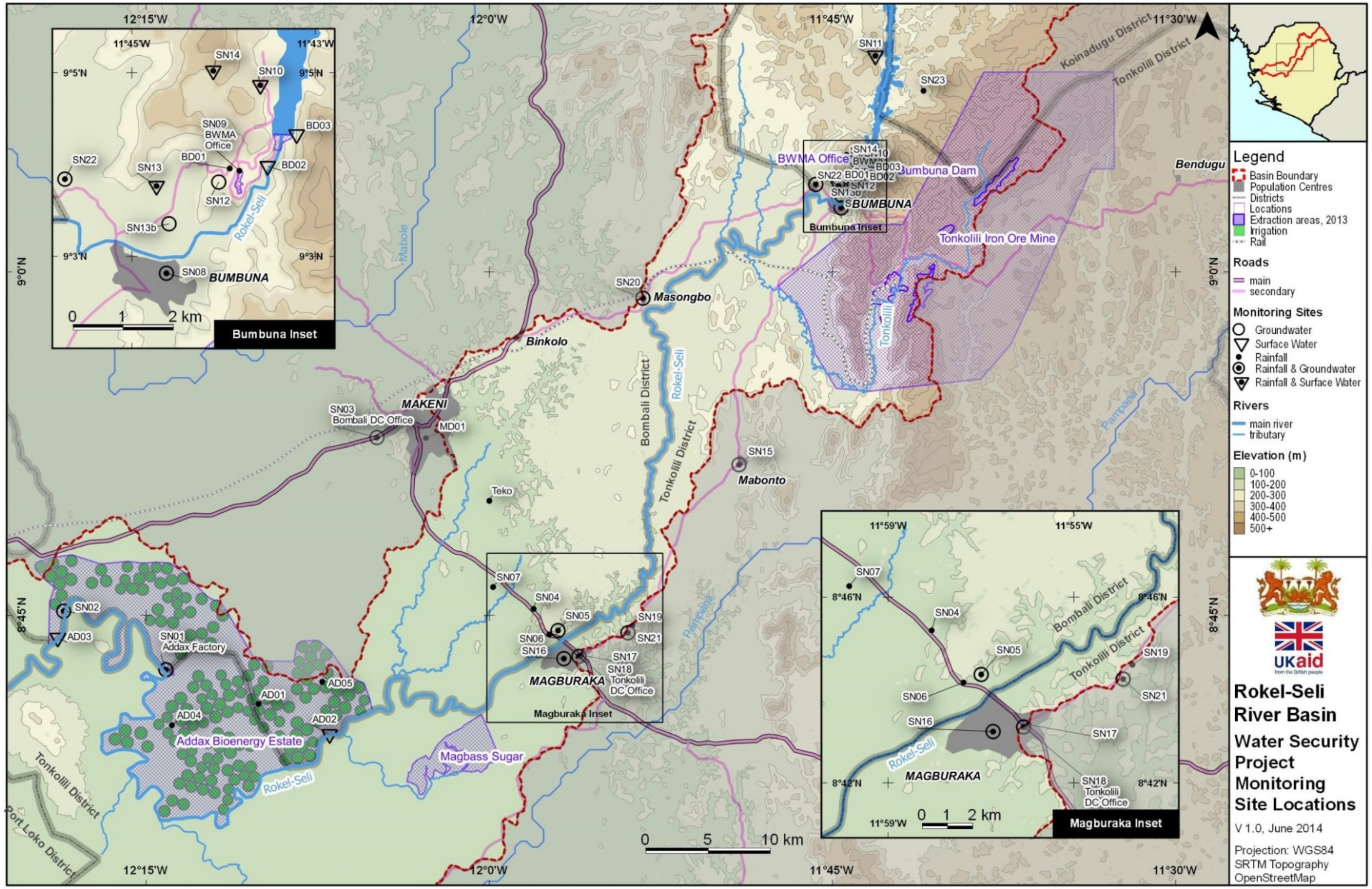
Map 8 Rokel-Seli River Basin –Middle Basin



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 any elevation of about 900masl. It runs a total distance of about 390km, discharging into the Atlantic Ocean north of Freetown. The catchment area is estimated as 8236km^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 catchment 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 catchment 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 Volume is to explain **why** monitoring of water resources is necessary, and to set out in detail the **practicalities** of such monitoring. The document draws on experience of monitoring rainfall, groundwater levels and *small* surface water flows. It does not address the important topic of monitoring of major river flows.

Although the document is based on experiences in one of Sierra Leone's river basins, it also draws out the implications for the design, operation and maintenance of **national monitoring networks**. This Volume 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.

Why water resources monitoring matters

Although Sierra Leone is exceptionally well-watered , this should give no grounds for complacency. The United Nations Food and Agriculture Organisation (FAO) has estimated Sierra Leone's internal renewable freshwater resources as 160km^3/a. This is almost certainly a gross over-estimate (given that the mean annual rainfall of 2,526mm amounts to 181km^3/a, and the difference, 21km^3/a, would be a serious under-estimate of evapotranspiration. The true figure for renewable freshwater resources is probably in the range 80-100km^3/a. In the absence of significant surface water storage or major aquifers, much of the runoff discharges to the sea unused. Furthermore, trends in population, land use, minor and major abstractions and effluent discharges all conspire to put Sierra Leone's water resources under threat.

Sierra Leone's water resources monitoring infrastructure (raingauge and meteorological networks, and the river gauging network) were almost completely destroyed during the civil war. In past times extensive networks existed (Volume 1, Annexes A to C), and these were able to provide substantive analysis of Sierra Leone's rainfall patterns (this volume Map 4). It appears that almost all the river flow data has been lost.

The approach taken in the Water Security Project has been to re-build experience of water resources monitoring incrementally, with the eventual aim of scaling up to sustainable national networks once again in the near future.

The Encyclopaedia of the Earth (Kundell, 2008) includes this telling comment on the present state of affairs: "*As water resources have never been a serious constraint to development in Sierra Leone, no base exists for their management (except for the water supply and sanitation sector).*"

Against this background, different stakeholders have different concerns about quantity and quality of water resources as the basis for water supply, or as the recipient of discharges.

- Communities which so far lack improved water supply express concerns about seasonality of quantity and quality of (self-supply) water sources (mainly springs and streams);
- Communities with improved water supply cannot take the reliability of their engineered sources for granted. The recently populated waterpoint database (www.SL-wash.org) shows

that 37% of the 28,850 waterpoints were non-functional at the time of the survey (early 2012), and that 51% of waterpoints are seasonal, ie they fail to deliver water year-round.

- For both the preceding categories of water consumer, seasonal groundwater level fluctuations are a matter of concern.
- GoSL and the operators of hydroelectric dams are concerned to maximise energy production while assuring dam safety. Together these legitimate preoccupations can affect both upstream and downstream communities and entities which are affected by reservoir water levels or dam releases.
- GoSL, represented by its watershed management authorities , is concerned about the environmental and social impacts of large scale reservoir storage, both on lakeside communities, and for water users downstream of major impoundments.
- Major abstractors drawing water from rivers are rightly concerned about quantity and predictability of flows, as well as water quality (depending on the purpose to which water is to be put).
- Minor abstractors of river water for domestic consumption are especially concerned with water quality, and the extent to which that may be impacted by upstream effluent discharges by rural and urban communities and mining companies.
- Industrial and other entities which discharge effluent into surface or groundwater should be concerned about (a) meeting acceptable standards of effluent quality whether imposed by a regulator or not, and (b) avoiding potential bad publicity which may arise from failure to observe the highest professional environmental and social standards.

Although the above list of water security concerns is probably not fully comprehensive, it does reflect some of the most pressing water concerns in Sierra Leone. Furthermore, all these issues can be found within the Rokel-Seli catchment, either upstream or downstream of the Bumbuna dam. Consequently the decision to focus the Water Security Project initially in this catchment was highly appropriate. The Rokel-Seli catchment immediately upstream and downstream of the Bumbuna Dam represents a microcosm of Sierra Leone's water resources management issues.

A starting point for the project was the imperative to monitor water resources (quantity and quality). The justification for this is that there is currently a dearth of routinely collected data; most of the former monitoring infrastructure and many of the data records were destroyed in the war (1992-2002); and in the absence of hard data, improved management, decision-making, design and infrastructure improvements can only be based on hearsay and anecdote.

It is clear however, that better monitoring must lead to action, in the form of better water management or better water infrastructure (or both), ultimately enhancing the quantity, quality and reliability of supply while minimising adverse impacts. If not, the incentive to continue monitoring will evaporate.

The project had limited resources and limited duration. It focused therefore on the development of models of good practice in data collection, sharing, publication, decision-making, water management and infrastructure improvement. It led the way via grounded practice and experience-sharing, but it could not establish national hydro-meteorological monitoring systems and water management institutions alone .

Approach to monitoring in the Water Security Project

In the Water Security Project, our monitoring work had two main aims, *first* to gain experience of 'what works' and 'what doesn't work' in regard to practical hydrometeorological monitoring; and *second*, to gather a significant quantity of data with which to start to develop a better understanding of the surface and groundwater hydrology of Sierra Leone. The first of these is reported in this Volume, while the second is reflected in Volume 3 in this series.

Our general approach was to **start small, start local, and start something**. The philosophy was to gain experience through action and learning-by-doing, rather than to invest a great deal of time in developing a strategy which would then be implemented in a top-down fashion. On the contrary, the approach was to build up guidance and strategy from the bottom up; the conclusions in regard to national strategy for water security are presented in Volume 1 of this set.

At the outset of the Water Security Project we became aware of a number of major initiatives to develop hydrometeorological monitoring in Sierra Leone. More than two years later, there has been only limited progress in most of these national programmes, while in contrast we have been able to implement a significant programme of monitoring and data collection, albeit in only a limited geographical area.

General issues arising

A number of general issues arise when undertaking hydrometeorological monitoring. These are discussed here in the form of questions and answers. The answers summarise our experience in the Water Security Project.

Where should monitoring take place?

Sierra Leone is a relatively small country, and international guidelines regarding the density of monitoring instrumentation are not especially demanding. The number of sites needed for rainfall and other aspects of meteorology, surface water and groundwater monitoring are each in the order of a few tens (not hundreds of locations). The capital costs of re-establishing (or in the case of groundwater, setting up for the first time) monitoring networks are relatively modest. The most important considerations with regard to monitoring networks are the costs and human / organisational capacities needed to operate them, and the human resources required for data analysis and dissemination.

In the Water Security Project we have implemented a rather high density of raingauge and groundwater monitoring stations, but this has been with the aim of gaining experience of 'what works', in terms of instrumentation and monitoring practice.

At each of the sites used in the Water Security Project,

- **GPS Co-ordinates** were collected at all monitoring locations by team members using a variety of devices including various GPS devices (e.g. Garmin eTrex10) and an iPhone App (Motion X GPS). Positional accuracy is anticipated to be ±10m.
- **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.

How should monitoring equipment be chosen?

Ideally, equipment should be selected to meet national standards, or if these are not specified, then to meet international standards as described for example by the World Meteorological Organisation (WMO). However, the standards appropriate for the relatively small numbers of instruments which are part of national and international networks may be more stringent than necessary for local-level monitoring. A raingauge at a school, for example, need not be of such a high specification as one in a Meteorological Department weather station. There is a trade-off between cost and accuracy, in which slightly lower specification instruments (eg plastic raingauges) generally give more-than-adequate results at far lower costs than higher-specification instruments.

Automatic / recording instruments appear to offer the prospect of greater reliability compared to manual instruments as they may be thought to minimise observer errors. This is not always true however, for two reasons: first, even automated instruments require significant human interaction (for programming, calibration and downloading of data); and second, the electronic systems inside automated instruments can often malfunction or fail. Manual instruments are indeed prone to observer error, or worse still, fabrication of data. However such errors are often easier to detect in the data cleaning stage of data processing (see below).

The third issue regarding instrument selection relates to operation and maintenance costs. Too often it is only the capital costs of establishing hydrometeorological monitoring which are quantified, while the running and repair costs are ignored. If the full operation and maintenance costs are taken into account, they probably amount to at least 10-20% of the capital costs of the monitoring network **per annum**.

Who should operate the monitoring instruments?

In the Water Security Project, 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 Bumbuna Watershed Management Authority (BWMA) who were trained in the use of equipment and were responsible for the ongoing management of the monitoring network and liaison with communities, district councils and national government bodies.

Costs of monitoring can be kept down by involving community members and educated individuals such as school teachers in the day-to-day work of observing rainfall and water levels. The question inevitably arises as to the competence and willingness of such individuals to undertake this important work.

It is our experience that not only is there willingness (which can be encouraged by regular recognition and small incentives), but that the quality of data and record-keeping can be as good as the records obtained from paid observers and automatic instruments.

In some cases – for example down-loading of data from automatic instruments – specialist technical staff with appropriate training are needed.

How should data be recorded?

Clear, simple paper-based and electronic forms should be used for recording of data. Where standard national forms exist, these can be used, but if not, then forms need to be designed. The Annex to this Volume holds the form designed for community-level rainfall recording in the Water Security Project.

How should data be collated?

It is best if record forms are collected in person by a technically trained individual who can identify any obvious problems with the data and raise appropriate questions with the observers. These forms then need to be copied, entered into the chosen software, and retained in a safe and organised manner.

What is data cleaning?

Once the data is entered into a spreadsheet or other software package it is important to check it and correct it for any internal inconsistencies or obvious errors. This is known as data cleaning. There is no formula for doing this – rather it requires common sense and a knowledge of the likely ranges of different data values. Anomalies and outliers may not be incorrect, but they should always be questioned.

How should data storage be undertaken?

Data should be stored in an appropriate software package – a spreadsheet such as MS-Excel, a generic database such as MS-Access, or a proprietary hydrometeorological data software package. The choice should be based on the familiarity of the user with the software options, the need for anything more sophisticated than a spreadsheet, and the cost of the various alternatives.

How should data be disseminated?

Ideally all data which is collected using public funds should be made available publicly. This can be done either through an on-request service or via the internet. However, both of these services cost money to operate, and so it may be appropriate to charge for the supply of data (as opposed to charging for the data itself).

The question arises as to what data to disseminate – raw data, cleaned data, or analysed data? Whichever choice is made, it needs to be made clear to other users exactly what they are getting.

Monitoring rainfall

The following guidance applies to the use of mountable plastic raingauges (Figure 1) suitable for use in communities and schools. These gauges (ClimeMET CM1016) can hold 225mm of rain, but the internal measuring cylinder can only contain 25mm.

Figure 1 Installation of a raingauge in a local community

Site location

The rain gauge should be placed on level ground, preferably surrounded by low cut vegetation. The gauge should be located in open ground and at a distance greater than twice the height of the nearest tree or building or any other tall structure. Position the gauge on a post at 1.0 - 1.5m above ground level with the rim of the funnel above the height of the post. A fence should be constructed around the raingauge, enclosing an area of about 3.5m x 3.5m and about 1.6m high.

Hours of observation

The rainfall is to be measured at 0900 each morning and the amount of rainfall entered on the record sheet against the date the reading was taken. During the analysis of the data, the values will be 'thrown back' to the previous day, on the assumption that most of the rainfall measured at 0900 today actually fell yesterday.

Reading the raingauge

If all the rainfall is contained in the central graduated measuring cylinder, read the level of water in the cylinder by bringing your eye directly opposite the level of water and reading the position of the bottom of the curved surface of the water to the nearest 0.5 millimetre mark on the scale.

If rainfall has overflowed into the outer container, then carefully remove the entire rain gauge from its mounting bracket. Remove the central graduated cylinder and pour water from this into a separate large storage vessel. Take care not to spill any water. Next pour the contents of the outer container into the vessel.

To measure the rainfall amount, fill the graduated cylinder to about the 20 mm mark and note the reading. Pour this water back into the main rain gauge container. Repeat this process until all the water is measured. The last reading will usually be a value less than 20mm.

The totals should be added together - for example 20.0mm + 16.5mm +18.0mm + 6.0mm = 60.5mm.

Recheck the measurement if necessary by repeating the process. When satisfied with the result, write the total rainfall value onto the rainfall form and empty the rain gauge by pouring water onto the ground. Carefully return the rain gauge back to its mounting bracket taking care not to damage the bracket.

Small amounts

If it has rained a small amount but the water does not rise above 0.5 mm in the graduated cylinder, record the word “trace” or “T” on the rainfall form.

Large amounts

If it has rained very heavily and the outer cylinder has overflowed, record the word “overflowed” on the rainfall form. *(Note: when full the rain gauge has a capacity of 225 mm).*

Missed reading

If a reading is missed for any reason, then when the raingauge is next read, record the total rainfall amount on the day of measurement. Record the words “no data” or “nd” in the missing days prior to this. If you know there was no rain on any of these days, record these as 0.0.

Mode of entry

The rainfall result is always to be entered in 0.5 mm units. When writing millimetre readings the decimal point is always inserted even for zero values of whole numbers. Do not write “mm” on the form. Examples of the correct style for numbers include: 0.0 or 5.5 or 43.0 or 16.5.

The form designed for use in the Water Security Project is included as Annex A.

Monitoring groundwater levels

In the Water Security Project, we installed automatic recording water level loggers in wells and boreholes. Barometric loggers were installed in the air space above the water level in a number of wells and boreholes to allow correction for atmospheric pressure variations.

Instrumentation

Data loggers (Figure 2) are used to automatically record changes in water levels at regular intervals. Manual water levels are taken at the beginning and end of the monitoring period to validate readings.

In-Situ "Rugged TROLL" absolute pressure data loggers have been used for this project. These respond to changes in water and air pressure and require compensation to remove the effects of air pressure using a separate barometric logger.

Loggers have fixed pressure ranges. In this case equipment with 9m or 30m ranges have been used.

Well measurements

Whilst many hand dug wells have access covers, boreholes fitted with hand pumps often do not and one may need to be cut before loggers can be used. After arranging permission to do so, the following measurements should be recorded at every well site when first visited: date and time; GPS coordinates; depth to the base of the well; depth to the water level; height of measuring point above ground level. Record how water is abstracted (pumped or by use of buckets), and the type and status of pumps. Is the well used all year round or only in certain seasons? Take a photograph of the well and its environs.

Figure 2 A "Rugged TROLL" data logger (actual length approx 100mm)

Programming loggers

Most hand dug wells have a water level variation of less than 9m. If greater than this a 30m or greater range logger should be used. Loggers are programmed with a laptop / PC connected via a docking station. Before programming, check that the time settings on the laptop are set to the correct international time zone and the correct time to avoid errors when synchronising logger times. Always synchronise the logger time to the laptop during programming.

In most cases, programme the logger as follows: site name - use village or town name followed by the location, e.g. Magburaka NC School. Set up a Log name, eg Magburaka NC School. Make sure SI units are used (metres, mbar, °C). Set the logging interval to 15 minutes. Allow up to 30 minutes from when you programme the logger until its scheduled starting time and always start the logger either on the hour or a 15 minute interval between hours.

Use the "depth to water level" option for recording level measurements in wells. This requires the depth to water level in the well to be re-measured. Use this value in the field titled: "set first logged reading". Set specific gravity to "custom" value of 1.0000. Send values to logger. Turn off connection to PC, remove logger and securely screw on the logger cap.

If a "Baro" Logger is to be used at this location, select the same site name as for the main logger and use the same Log name preceded by "Baro-", eg Baro-Magburaka NC School. Programme to start at the same scheduled time. Figure 3 shows logger programming in action.

Preparing loggers for installation in wells

Before installing a monitoring device into a well, sanitise all equipment being placed in the well with a chlorine solution. This includes, loggers, dip tapes, sampling equipment or containers. The most readily accessible form of chlorine is in household bleach which usually comes as a liquid, with concentration of between 5.25 to 6.15 percent sodium hypochlorite. This can be purchased in most supermarkets BUT read the label on household cleaning products carefully to ensure purchase of only sodium hypochlorite. A 1-in-5 dilution of household bleach with water (1 part bleach to 4 parts water) is effective against many bacteria and viruses. The solution is corrosive and equipment needs to be thoroughly rinsed with clean water afterwards. Water from the well can be used for rinsing equipment in the field. When not in use, all sanitised monitoring equipment should be kept in a dry, sanitised storage area, and not allowed to come into direct contact with the ground surface or any other unsanitised object before placing equipment in a well.

In hand dug wells, the loggers are installed inside the top of a 2.5 litre plastic container which has previously been drilled with 5mm diameter holes and approximately one-third filled with gravel to provide weight and stability (Figure 4) whilst leaving sufficient open depth for the logger.

Thread the logger cord (Kevlar or equivalent) through a hole drilled in the cap of the container. Tie one end to the logger and place logger inside the container below the cap (leave some slack in the cord below the cap). Cut and tie the other end of the cord to the handle of the container. Tie a rope to the handle of the container and lower to the bottom of the well.

If a BaroTROLL is used, lower this as far as possible into the well so that it will always remain above the water level (typically this will between 1 and 2m below the top of the well. Tie to the same rope if convenient.

Figure 3 Programming a water level logger

Figure 4 Logger installation in hand-dug wells

Cut and tie the rope to any convenient point below the well cover, making sure it is secure and safe. If the water level in the well is changing (particularly if the well is in use at the time of the installation) wait until the time the logger starts and re-measure the water level. Record this along with the date and time in your notebook. Shut the well cap using a padlock or provide one to the community if necessary (Figure 5).

Figure 5 Installation of logger and closure of well

Retrieving and reprogramming the logger

Before disturbing the instruments in the well, measure the depth to water level at a time corresponding with a 15 minute logger reading. Remove the logger (and "Baro" Logger) from the well and download data.

When retrieving and re-installing the logger you have two choices:

1. **Stop the logger**. Re-programme and reinstall the loggers following the same procedure and using the same site and Log names as above. Re-measure and use the current water level to set up the logger. Take a further manual water level reading after the logger is installed and at the time the logger is started. Record these in your notebook along with the date and time of each manual reading.
2. **Leave the logger running**. Reinstall the logger taking a further manual water level reading at the time the logger is reading. In this case it is important that the logger and barologger are returned to exactly the same depth positions on each occasion they are moved and downloaded.

Procedure 1 provides greater control on accuracy by adjustment to a manual water level at the start or end of each logging period and creates a separate logger for each logging period. Procedure 2 allows a continuous logging record to be appended to the same file record which can be more convenient when managing large numbers of loggers.

Monitoring small surface flows

In the Water Security Project it has not been possible to monitor large surface water discharges (with one exception – see below), for reasons of cost. We did however consider that the monitoring of spring flows and small surface water was important to enhance our understanding of catchment responses to rainfall. We consequently installed v-notch weirs at four sites, and the following text describes the practical detail of the installation and monitoring.

What is a v-notch weir?

A V-notch weir (Figure 6) is an accurate and relatively simple device for measuring low flows. Since it is the low flows in the dry season which are most critical for community water supply, v-notch weirs are useful for monitoring the flows of (unimproved) water supplies from unprotected springs and streams.

V-notch weirs are made in various sizes. The angle of the "V" can vary from 90° down to as little as 22.5°. The vertical height of the "V" determines the range of flows which can be measured. The height (or head) of water above the vertex (or point) of the "V" is used to determine the flow through the weir. The head needs to be measured a little way (a minimum of 3-4 times the maximum head) upstream of the weir itself.

Figure 6 A v-notch weir made out of stainless steel

The example in Figure 6 is a v-notch plate made of stainless steel, bolted to a timber structure across the watercourse. The steel plate is sharp-edged and chamfered (angled) on the downstream side. The water must drop freely over the weir, so that the nappe (or waterfall) has air behind it (it is then referred to as being ventilated). If the nappe clings to the weir (typically at very low flows), then the measurement will be inaccurate.

The water level is measured (Figure 7) on a graduated rule attached to a stable post. In this case a tube, with holes near the base, has also been mounted to allow a water level logger to be inserted. This can then provide a low-accuracy but near-continuous record of water level to complement the periodic observations on the rule.

Figure 7 Water level measurement upstream of a v-notch weir

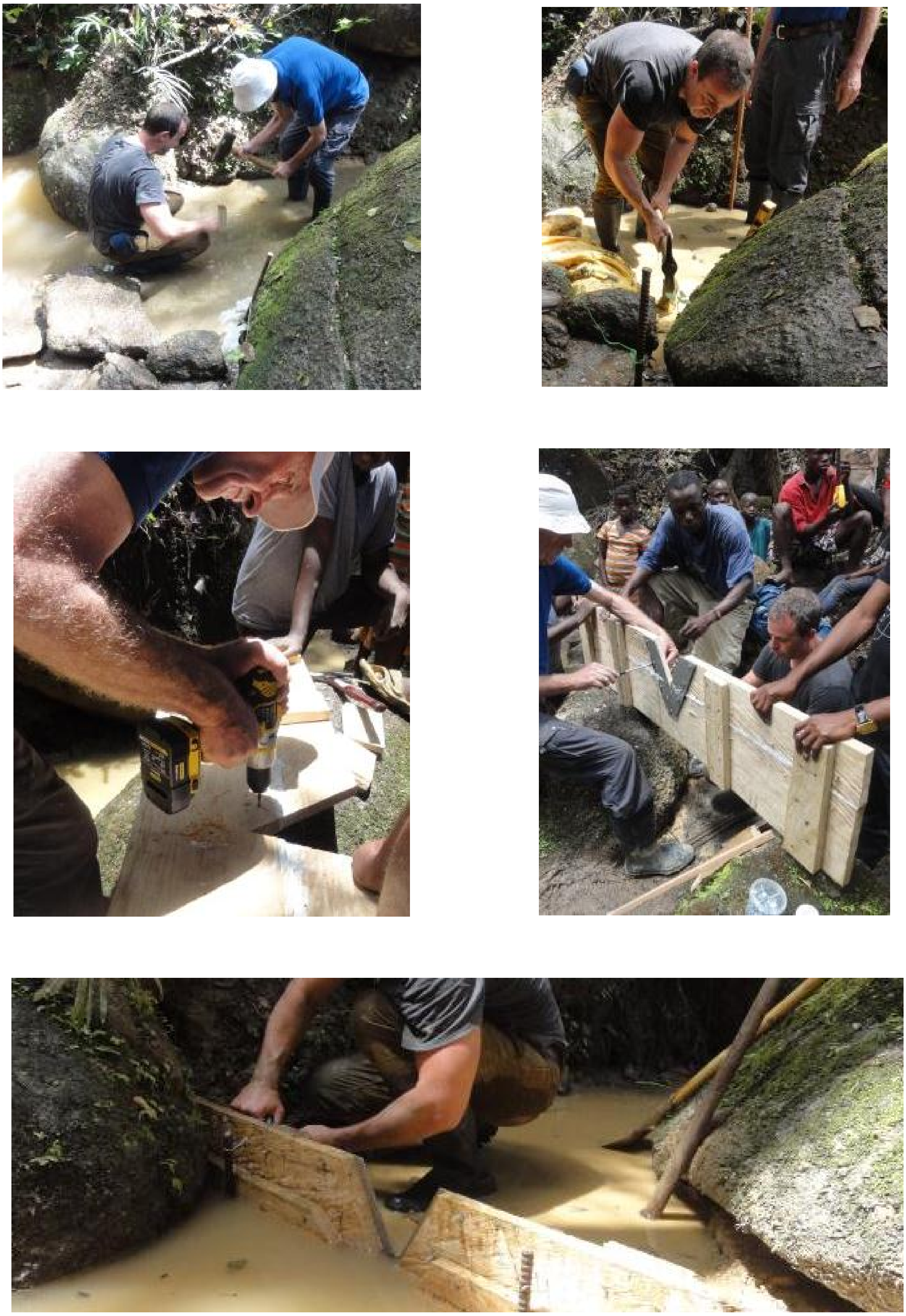
V-notch weir installation

Installation of the weir may be easy or more difficult depending on

(a) how easy it is to keep the site dry,
(b) how much rock is encountered in the excavation to install the weir,
(c) how much fall there is to take water away from the weir, downstream.

The photographs in Figure 8 show in succession the site before installation (placing setting-out stakes to indicate water level), excavation of the trench across the watercourse (here carried out in difficult wet conditions), the assembly of the weir itself, and its final installation, securing it with reinforcing steel driven into the bed of the stream.

Figure 8 V-notch weir installation



V-notch weir calibrations

The general equation describing the relationship between head and discharge for a v-notch weir is

$$Q = 0.533\sqrt{2g}.C.\tan\left(\frac{\theta}{2}\right).h^{2.5}$$

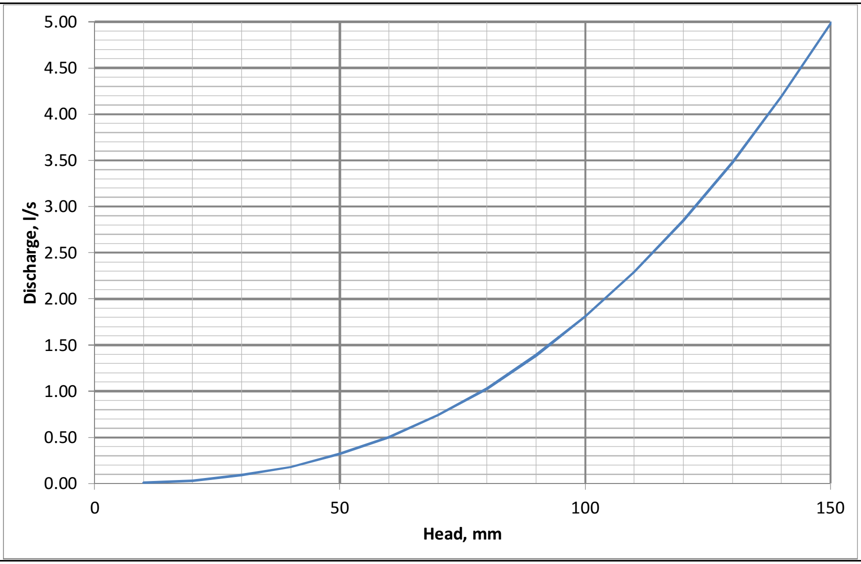
where

g is the acceleration due to gravity (9.81m.s^{-2}); the coefficient C is assumed to take a value of 0.59; θ is the angle of the v-notch (we have used 45° and 60° v-notches); and h is the head over the weir (m). Figure 9 gives the rating tables and curves for the 45° and 60° v-notches.

Figure 9 Rating tables and curves for 45° and 60° v-notch weirs

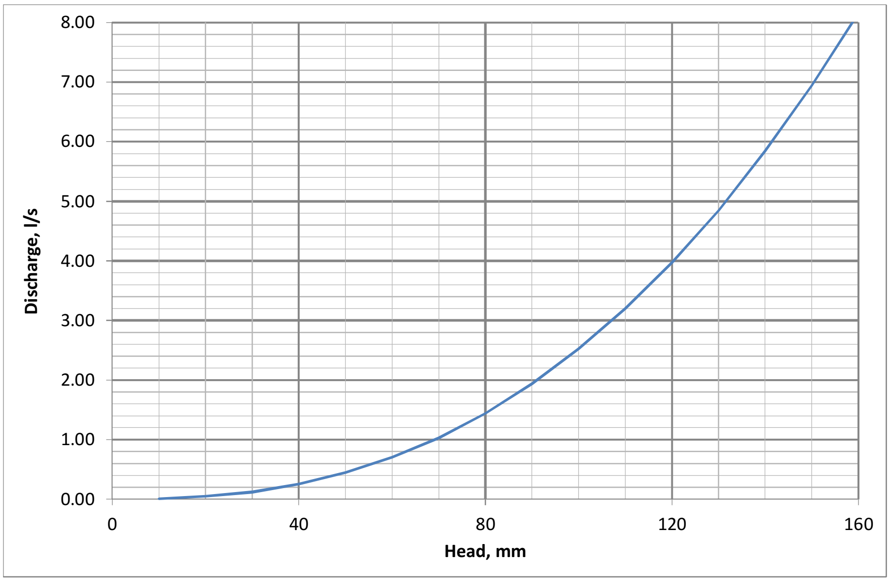
45° v-notch

Head (mm)	Discharge (l/s)
10	0.01
20	0.03
30	0.09
40	0.18
50	0.32
60	0.51
70	0.75
80	1.04
90	1.40
100	1.82
110	2.32
120	2.88
130	3.52
140	4.23



60° v-notch

Head (mm)	Discharge (l/s)
10	0.01
20	0.05
30	0.13
40	0.26
50	0.45
60	0.71
70	1.04
80	1.46
90	1.95
100	2.54
110	3.23
120	4.01
130	4.90
140	5.90
150	7.01
160	8.24



Other aspects of hydrometeorological monitoring

Monitoring of major river flows

The gauging of discharges in major rivers generally involves the combination of river water levels and spot-measurements of discharge into so-called rating curves. A rating curve relates water level (also known as stage) to discharge, and it is built up from pairs of measurement made over a period of time (often months or years) during which a range of stages and discharges are measured. This is the normal routine at natural sites, where there is no man-made structure such as a weir, for which the stage-discharge relationship is known.

At both natural and man-made gauging sites, river stage is measured in a stilling well, a vertical shaft adjacent to the river channel which is designed to link to the river, but to even out the short-term fluctuations in water level which would make it difficult to accurately measure river stage.

In the case of the Water Security Project we have one man-made structure (a concrete uncontrolled ogee crest weir) just downstream of the Bumbuna dam (Figure 10). Adjacent to the weir is a stilling well into which we have installed a water level logger programmed to record water levels at 15-minute intervals. These data can be readily transformed into discharge data for the Rokel-Seli River (see Volume 3 in this set).

Figure 10 The uncontrolled ogee crest weir on the Rokel-Seli River d/s of the Bumbuna Dam

Automated logging of small surface water flows

In the Water Security Project we installed automatic water level loggers in perforated vertical plastic tubes at all the v-notch weir sites. Generally these performed well, but they gave some anomalous 'spikes' in measured water levels which we have so far been unable to explain (see Volume 3).

From local to basin-wide and national networks

The density of monitoring used in the Water Security Project is much higher than that which would be appropriate for national networks. However, it would be very cost-effective for example if every secondary school (and some primary schools) in Sierra Leone were to operate a manual raingauge, and if every organisation constructing wells and boreholes were to be required to monitor a small proportion of them. Either of these two possibilities would immediately deliver a high intensity network of monitoring points through devolved management arrangements, reducing the cost to the State significantly.

National networks for monitoring of rainfall and other aspects of meteorology, stream and river flows and groundwater (including both quantity and quality), demand financial and human resources for a number of important functions:

- local observers / equipment operators – salaries or incentives and basic consumables;
- sub-national and national staff, transport and telecommunications for supervision and data collation;
- human resources at national level for data cleaning, analysis and publication;
- human resources and other costs of disseminating information to user organisations.

Too often when new equipment networks are being proposed, the costs and human resource implications of running and maintaining those networks effectively are ignored. It is essential that detailed analysis of these recurrent costs is made, otherwise proposals which are currently on the table will give rise to unsustainable outcomes.

Maps 2, 3 and 5 in this volume show recent proposals for rainfall, river flow and groundwater monitoring networks respectively.

Conclusions

Even a country as apparently well-watered as Sierra Leone needs effective and reliable hydrometeorological monitoring networks. Without effective monitoring, water resources cannot be managed well to the benefit of people, food and energy production, and industrial development.

Demands on water resources, and polluting pressures on those resources are growing. Hence there is an ever-present need for better monitoring of quantity and quality of rainfall, surface water and groundwater.

The Water Security Project has demonstrated some of the aspects of monitoring which work well in Sierra Leone:

- local level (school and community) monitoring of rainfall with simple raingauges and volunteer observers;
- monitoring of groundwater levels using automatic equipment and trained Government staff;
- support to local observers and Government scientific staff through international cooperation;
- integration of information sources provided by extensive on-line and hard-copy document searches, working with a wide range of stakeholders, and undertaking focused field-based monitoring.

It has also been clear that:

- a good deal of training, support and institutional strengthening has been needed in order to make significant achievements in a relatively small geographical area;
- much more will be needed to take the experience of the Water Security Project to national scale.

Recommendations

The following recommendations are made in relation specifically to monitoring of water resources (the subject of this volume):

1. **Monitoring of rainfall** using simple low-cost raingauges should be promoted throughout Sierra Leone, offering the opportunity to schools, communities and local institutions which declare an interest in being involved. The provision of small incentives and recognition by national Government will need to be a part of such an initiative.
2. **Monitoring of groundwater levels** at a small number of wells and boreholes (together with rainfall monitoring at the same locations) should be an expected part of the work of District Councils and of NGOs operating within local Government jurisdictions. Training and follow-up support from national Government scientists will be needed in order to make this effective.
3. **Monitoring of flow at a small number of springs and streams** in each District should also become an expected part of the work of local Government and NGOs.
4. **Monitoring of major river flows** will need to be arranged and managed at national level because of its scale and complexity.
5. **The Ministry of Water Resources** will need to undertake all the national level monitoring, supervision, support, analysis and dissemination activities required to make effective use of water resources monitoring data.

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Annex Rainfall recording form

Sierra Leone Water Security and Water Resources Management Projects — **Rainfall Records**

Location:	**District:**	**Month & Year**
Observer's Names:	**Title**	**Telephone:**

All records to be taken at 9 am each morning (see instruction sheet). Readings should be recorded on the actual date they are taken. (These will be adjusted to the preceding date when processed). Use the space below to include each measurement when the measurement cylinder has overflowed into the outer container (for example: 20.0 + 16.5 + 18.0 + 19.0 = 73.5 mm).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1

Daily Total Rainfall

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1

Please maintain two copies of this sheet for each month.

1 copy is to be kept by the School or Organisation.

1 copy is be collected by the Ministry of Water Resources or BWMA after the end of each month.

Total Rainfall for Month (1st to 31st) ______ mm