RADAR TECHNOLOGIES INTERNATIONAL

Advanced Survey of Groundwater Resources of Northern and Central Turkana County, Kenya

FINAL TECHNICAL REPORT

August 2013

United Nations Educational, Scientific and Cultural Organization

GRIDMAP
Groundwater Resources Investigation for Drought Mitigation in Africa Programme

Republic of Kenya
Ministry of Environment, Water and Natural Resources

KENYA VISION 2030
TOWARDS A GLOBALLY COMPETITIVE AND PROSPEROUS NATION

JAPAN
Official Development Assistance

FRONT COVER
Turkana woman and her children at a natural spring near Lokichogio.

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This report has been prepared by Radar Technologies International (RTI) and commissioned by UNESCO under the GRIDMAP Framework for the Government of Kenya, Ministry of Environment, Water and Natural Resources. The report is a contribution towards the Kenya Vision 2030 and a pilot of the Kenya Groundwater Mapping Initiative. The project was funded by the Government of Japan, Ministry of Foreign Affairs.

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RTI conducts specialized exploration, mapping and assessment of natural resources. We develop tools to unlock the potential of local water and mineral resources and provide tailored advice on how to navigate those resources effectively. Our WATEX™ Groundwater Exploration System™ is a state-of-the-art exploration technology designed to achieve precise, reliable and rapid groundwater prospection in virtually any context.

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Acknowledgements

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Abstract

Radar Technologies International (RTI), on behalf of UNESCO, conducted an investigation of hydrogeological resources of a 36,000 km² zone of northern and central Turkana County in northwestern Kenya for the Government of Kenya from July 2012 to June 2013. The primary aim of the survey was to explore, map and assess the available groundwater resources within the area in order to provide a new basis for understanding water potential and underpin socio-economic development in the region of the country, which has been struck by recurring drought and scarcity. The survey also aimed to provide a set of advanced tools tailored for Turkana County that will help improve the effectiveness of groundwater management projects, which currently are challenged by unreliable information and data. The survey was conducted by implementing RTI's proprietary remote-sensing and geophysics based water exploration technology, the WATEX™ System. Models for shallow alluvial groundwater occurrence and deep aquifers were developed, which enabled precise groundwater maps to be published.

During the course of the study, the WATEX™© has detected and confirmed the existence of shallow groundwater aquifers (between subsurface and 80 m) and deep aquifer structures (below 80 m) affected by dense fracture patterns linked to the evolution of the East African Rift.

Inputs to the survey included existing reports and maps, ancillary field data and raw satellite imagery. The survey results were generated through the implementation of the WATEX™ System, which entails data treatment, processing, interpretation, incorporation and mapping and analysis.

Accurate models for shallow and deep aquifers were generated. High-resolution maps identifying groundwater, soil and recharge were published. The models and maps were validated by exploratory borehole drilling, confirming the existence and accuracy of the WATEX™ groundwater models for Turkana. These models were validated by UNESCO as having high accuracy.

Shallow groundwater potential of northern and central Turkana

A network of shallow alluvial aquifers were found to be spread across the area, much of which is considered to be within easy reach for abstraction, yet hidden only a few meters below the surface. The survey assessed shallow aquifers in the survey area to have an overall recharge potential of 2.08 BCM per year, though storage capacity is undefined given the high variability of soil and geological conditions at the local scale. Aquifers in strategic sites such as Lodwar, the Kakuma Refugee Camp and Lokichoggio were investigated directly in the field. These shallow aquifers were observed to be hosted by multi-layered weathered and fresh volcanic structures interspersed with river sediments and Turkana grits in close proximity to the basement. It is concluded that shallow targets for borehole drilling must undertake careful local geologic analysis before implementing a drilling strategy.

With regards to the area around Kakuma Refugee Camp, the survey assessed the local annual recharge capacity to be 360 MCM/year. Applying conservative assumptions, this translates into a good prospect for constant yields for boreholes drilled within the fracture corridor delineated by the survey along the Tarash River.

As regards the proposed site at Kalobeiyei for a new refugee camp, this survey assessed less than optimum conditions for the area. Recharge capacities at Kalobeiyei are a dispersed across the area, with only 48 MCM/year estimated recharge, and compromising shallow formations.

The groundwater potential in the area around Lodwar on the Turkwel River remains very promising, with a recharge capacity over 1.2 BCM/year and a storage capacity of 20 MCM/year.

Deep aquifer structures of northern and central Turkana

The survey investigated aquifer structures deeper than 80 m in the region and found that the Turkana area was host to five large deep reserves with significant scope. Additional possible reserves were found, but less substantiated by the evidence. Together, the discovered aquifer structures have the capacity to store a minimum of 250 BCM – representing a potentially new strategic resource for Kenya. The deep aquifers were found to have an annual recharge capacity of 1.35 BCM/year.

Two of the aquifers were confirmed with drilling by UNESCO: Lodwar and Lotikipi. Lodwar Aquifer was confirmed to host an estimated 10 BCM, and its recharge is still undetermined due to factors related to Turkwel River replenishment dynamics. The large paleo lake Lotikipi Basin Aquifer covers a surface of 4,146 km² and hosts over 248 BCM in its 3-km-deep graben structure. Its large scale is equal to the Lake Turkana, and thus offers the prospect of serving as a "new Lake Turkana".

Three other minor structures – Gatome, Nakalale, and Kachoda – cover 345 km², 138 km² and 130 km², respectively. The structures were assessed to host a cumulative potential of 30 BCM of freshwater within the same sedimentary environment.

These deep aquifer-bearing structures comprise highly permeable Plio-Pleistocene fluvio-deltaic and lacustrine deposits interlayed with volcanic ash layers reworked by nearby rivers. Groundwater in these aquifers are static in the graben-like structures and partly dynamic in the Lotikipi Basin, which has flows north-northwest towards the greater Nile River Basin in South Sudan. The drainage zones of each deep aquifer structure are complex to assess and may extend far beyond the geographic limitation of this survey.

Taking into consideration the total potential recharge rates of both high-potential shallow aquifers and the five deep aquifer structures, the study estimates the total renewable groundwater resources of northern-central Turkana to be 3.447 BCM per year, which represents only 1.38% of the total storage volume (250 BCM).

The groundwater resources of northern-central Turkana County have great significance at the national scale. These systems raise Kenya's total renewable water resources from 20.2 km3/yr to 23.6 km3/yr, an increase of 17% to the nation's. In real terms, that translates into an additional 83 m3 per year per person in Kenya.

The groundwater in Turkana is sufficient to serve the basic and economic needs of over 39 million people every year. During a humanitarian crisis, the groundwater resources of the region could be enough to satisfy the basic needs (15 L/day) to over 625 million people.

It must be underscored here that despite the prospect of significant quantity that these aquifers represent, the overall rate of recharge of these aquifers is considerably weak. Therefore, extraction of water from these structures should be done with great caution in order to prevent over-exploitation.

The way forward

This survey has generated a wealth of new and updated information and data, establishing a new foundation of knowledge upon which future investigations and localized assessments in Turkana can be based. The data and analysis have been depicted on maps, organize on a GIS database and presented in reports. Other tools for practical groundwater exploration and investigation were derived, such as the Groundwater Exploration Navigation System (GENS) and the Handbook for Borehole Drillers in Turkana. This body of knowledge and associated tools should be shared to the widest audience possible.

Looking ahead, further studies, such as determining the full extent of the deep aquifer structures and content beyond the boundaries of this survey area, particularly into southern Turkana and the full Lake Turkana basin, will be critical to achieving a more complete assessment. An assessment of the Rift System would help assess groundwater dynamics associated with larger urban centers such as Nakuru, Naivasha and Nairobi.

In terms of long term management, the road to ensuring the sustainable use of these resources is long, but a few steps are recommended. Firstly, Kenyan authorities should establish a limit on abstraction rates for both the Lotikipi and Lodwar Aquifers. WRMA can establish the rates for abstraction for normal and emergency situations. Secondly, Kenyan authorities are recommended to gazette the land above the aquifers in order to protect the them from harmful activities. For example, the recharge zone of Lotikipi Basin Aquifer (4,146 km2) can be gazette to ensure that its water quality is conserved. Thirdly, establish a modern aquifer monitoring system to monitor the Lotikipi and Lodwar aquifers. Modern logging equipment can be installed in the UNESCO boreholes at Lotikipi and Lodwar in order to monitor the state of the aquifers and collect additional data.

1. Survey Overview

1.1. Introduction

This report is the final technical document of the "Advanced Survey of Groundwater Resources of Northern and Central Turkana County" undertaken in northwest Kenya from June 2012 to February 2013. The survey was conducted by Radar Technologies International as an official contractor of UNESCO and on the official requested mandate of the Government of Kenya through the Ministry of Environment, Water and Natural Resources (formerly the Ministry of Water and Irrigation). The survey, including all of the resulting maps and information, is an officially recognized contribution to the Kenya Vision 2030, the country's national development programme, which has prioritized the development of water resources in Turkana, one of Kenya's poorest and driest regions.

The survey has been implemented under the auspices of the UNESCO-led regional mapping initiative, *GRIDMAP* (Groundwater Resources Investigation for Drought Mitigation in Africa Programme), which aims to combat drought and famine in Africa and other regions by identifying emergency and sustainable water supplies and delivering measures to mitigate against long-term water scarcity.

In August 2011, Kenya and its neighbours experienced the worst drought and famine in 60 years, causing great calamity for the people living in the arid and semi-arid regions. At the request of the Member States of the Intergovernmental Authority on Development (IGAD), UNESCO was requested to assist the countries most affected by drought and apply its specialized capacities in science and technology to find a more sustainable solution to the issues. As a response to this request, UNESCO developed the GRIDMAP framework, which is centered around delivering practical tools to countries to enable them to understand and manage their groundwater resources for emergencies, drought resilience, and ultimately poverty alleviation.

Recognized internationally for its unparalleled capabilities in rapid and accurate water and mineral exploration, RTI was commissioned by UNESCO to pilot two advanced groundwater surveys for GRIDMAP of parts of Ethiopia and Kenya from 2012-2013. Following the successes of the survey conducted for UNESCO of the Upper Jerer-Fafen Basin in eastern Ethiopia, RTI has conducted this survey as GRIDMAP's first mapping exercise in Kenya. Governments in both countries are expected to scale up these pilot studies to the national level over the next few years.

Funding for this survey was provided by the Japanese Government as a support to drought-affected zones in Kenya. National consultations with Kenyan authorities took place in late 2011 to identify the priority region, and the County of Turkana was targeted. During consultations held between UNESCO and the former Kenyan Ministry of Water and Irrigation in May 2012, the exact boundaries of the survey area were delineated and approved by the Government at that time. UNESCO commissioned RTI to conduct the survey in July 2012.

This survey of groundwater is a significant step for Kenya and the County of Turkana, which is considered to be one of the country's poorest and driest areas. It is the first of its kind in Kenya to utilize advanced technology to explore for water, particularly at a time when discoveries of oil reserves have been recently made in the same area. Yet, the development of these strategic petroleum resources is still nascent, and economic benefits are not expected to trickle down to the Turkana people for some time. Meanwhile, the people of Turkana are still lacking basic services for water supplies and sanitation, and many still suffer from malnutrition and disease.

The survey is appropriate given the priority the government is giving to the Turkana region to develop it. Amid the drought and water scarcity afflicting this part of Kenya, the country is relying increasingly upon groundwater to satisfy rising water demand. According to the 2009 Census, 43% of rural and 24% of urban households rely on springs, wells, or boreholes as their main source of water. In Turkana County, rural water supply projects have led to considerable reliance on groundwater for pastoralists and displaced populations.

Meeting the demand for groundwater will require greater capacities in abstraction and long-term aquifer management. Yet, a lack of precise information on groundwater occurrence has consequences for local borehole drilling and regional aquifer management. Borehole drilling has become a risky business, with many contractors drilling haphazardly or without sufficient information to drill in the right areas. In Turkana County, two in three boreholes drilled are dry. Similarly, without access to reliable information, government technicians and groundwater consultants face greater difficulties in providing sound advice on groundwater development projects.

Insofar as the existing knowledge about groundwater in the region, the survey also comes at a time when new information about the resource is sorely needed. Boreholes that are dug dry come at a significant financial loss and frustrate local communities. Existing records about groundwater in Turkana are significantly outdated, fragmented across different ministries and is not sufficiently reliable to provide a sound basis for effective borehole drilling and overall sustainable management of the resource. This survey, along with its associated maps and tools, has been tailored to meet the needs of the Turkana context and the technicians working to address water scarcity by developing groundwater.

1.2. Study Objectives, Tasks and Deliverables

As agreed with the Government of Kenya, the advanced study has aimed to achieve three **key objectives**:

(1) To survey and assess the hydrogeology of northern and central Turkana County

(2) To identify and assess a maximum quantity of new clean groundwater resources for populations in the survey area, with particular focus on the communities of Lodwar, Lokichogio and Kakuma and Kalobeiyei.

(3) To assess the potential of groundwater for development, with a focus on both shallow and deep structures.

The survey aims to complete the following seven **main tasks**:

(1) To conduct the WATEX™ System technique in the exploration of hydrogeological resources of the study area. More specifically, this entails:

(a) To dentify and acquire multi-frequency and multi-seasonal remote-sensing imagery for the defined survey area, including from Synthetic Aperture Radar (SAR), Landsat, and Shuttle Radar Terrain Mission (SRTM) sensors.

(b) Pre-select and collect existing ancillary data of the defined survey area, including data and maps on rainfall, hydrogeology, geology, geomorphology, geophysics, seismicity, topography, pedology, land use and infrastructure.

(c) Process, geo-reference, layer, interpret and validate all remotely-sensed, ancillary and proprietary data into organized datasets.

(2) To develop and construct a GIS database that houses all raw and processed data, and includes an organized archived file directory and metadata on secure, portable hard drives.

(3) To develop and produce thematic digital maps: groundwater potential, soil and aquifer recharge.

(4) To develop and deliver RTI's proprietary Groundwater Exploration Navigations System (GENS) tool tailored to the study area, which assists users in navigating and locating groundwater resources in the field.

(5) To develop and publish a Technical Field Manual for Groundwater Targeting, a publication tailored for water well drillers, which will enable field technicians to explore and accurately identify groundwater resources in the study area and perform accurate drilling of wells and boreholes.

(6) To perform analysis and technical advice on the state of hydrogeological resources and the potential for managing groundwater in the study area.

(7) To organize a field training programme for a team of Kenyan experts in the site area.

The **key outputs** of the survey are:

(1) A set of high-resolution maps of the survey area: Groundwater target map (hydrogeological), Groundwater Recharge, and Soil Classification. RTI has developed a package of thematic, high-quality maps for UNESCO, including a hydrogeological map, soil map and aquifer recharge map. Other maps such as geological maps will be developed since they are a prerequisite for the afore-mentioned maps.

(2) A GIS Database of Hydrogeological Resources of central and northern Turkana County. The database contains GIS files (rasters and vectors) which can be used by technicians to map, query and manipulate the information delivered. The GIS database was delivered to UNESCO Nairobi Office in December 2012 and compiles the results of implementing the WATEX™© System.

(3) A Groundwater Exploration Navigations System (GENS). RTI develops Groundwater Exploration Navigation System (GENS) and has delivered to UNESCO two (2) units in December 2012 during a training course in Kakuma refugee camp. The GENS will be a practical tool that will allow field technicians and well drillers to easily navigate and locate groundwater by enabling field access to maps and coordinates that lead to high potential water sites, resulting in higher accuracy locating potential water sites than using maps. The GENS must enable beneficiaries to save time and resources and avoid long delays and costly un-productive well-drilling

(4) A Technical Field Manual for Groundwater Targeting, tailored to the northern and central Turkana County. RTI has delivered electronic and hard copies of Manual to UNESCO. The main purpose of the Manual will be to guide groundwater experts on best zones for groundwater productivity and recharge in the study area. Users of the Manual should be able to drill new productive wells more rapidly and minimize the loss of time and resources associated with drilling unproductive wells.

(5) Analysis and technical advice. Finally, RTI has provided UNESCO and the Kenyan Government with scientific analysis of the results of work performed, including expert advice and recommendations on the potential for improving groundwater management in the specific study area. Such analysis has been captured in this final technical report. Other more focused reports have been delivered to UNESCO during the course of the survey.

1.3. Study Area

The area of study (figures 1.1 and 1.2 below) covers a zone of 36,000 km² of northern and central Turkana County, Rift Valley Province as officially selected by the Government of Kenya (former Ministry of Water and Irrigation) on 24 May 2012. The southern boundary of the area is at 2.7°N latitude, while its eastern boundary is west of Lake Turkana at 35.8°E. The southwestern boundary is situated along the Uganda border, with a small portion of Uganda in order to account for critical watershed zones originating there. The northwestern boundary follows Kenya's border with South Sudan. The area's northern boundary follows at 4.6°N latitude at the "Maud Line" of the Ilemi Triangle.

The three main towns in the study area are Lokichoggio in the North-West near the border of South Sudan, Lodwar in the southeast corner of the survey area along the Turkwel River, and the town of Kakuma, which has grown to become the most densely populated area with the massive afflux of refugees from neighboring countries, with a total of almost 500,000 persons. The only good asphalt road in the study area is the Lodwar-Lokichogio road, which stretches from Lodwar, through Kakuma and Lokichoggio along a distance of 280 km. Kakuma, which is located at about 590 km northwest of Nairobi by direct flight, can be reached by car in two days through an unpaved road.

Figure 1.1. Location of the study area (red box) in northwestern Kenya. RTI, 2012.

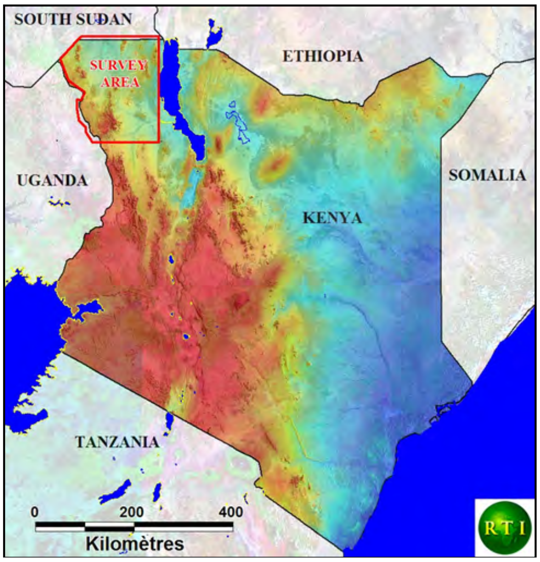


Figure 1.2. Close up of the study area (red box) in northern and central Turkana County, Kenya. RTI, 2012.

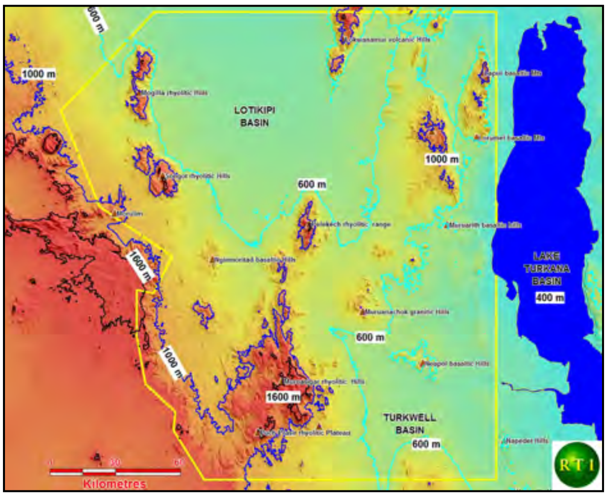
Description of Study Area

The survey falls on parts of the Lotikipi and Turkana Basins, watersheds that cover a surface area of 36,000 km² annotated by the red polygon as shown in Figure 1.2. This survey area is dominated by the Ugandan Escarpment which represents the western boundary of the rift system of Lake Turkana coastal plain which stretches all along the N-S direction in the East.

Topography of the area

The main prominent topographical features of the study are the Lake Turkana, which lies at an elevation of 400 m and the two major watershed basins of Lotikipi and Turkwel-Turkana. The Muriasingar-Pelekech volcanic range separates the two watersheds. Together with the Ugandan Escarpment to the west, these volcanic formations culminate over 1,600 m on the western margin of the Rift. A random dispersion of other minor volcanic intrusions punctuates the landscape.

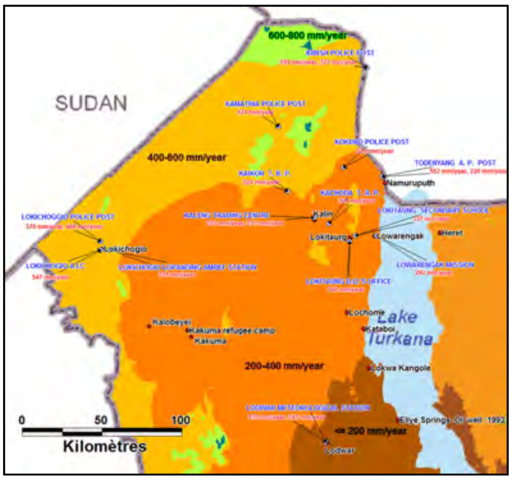
Figure 1.3. Topography map of northern and central Turkana County. Topographic isolines are shown on SRTM colored image treated and processed by RTI. RTI, 2012.



Climatic and pluviometric context

Rainfall in Kenya varies significantly across the country and throughout the year. East of the Rift Valley, two distinct rainy seasons occur. The “long” rains fall from March to May, and the “short” rains fall from October to November. National average annual rainfall is approximately 630 mm per year. The western semi-humid part of the country receives more than 1,600 mm annually, while the northern and eastern arid/semi-arid regions, which comprise about 80 per cent of Kenyan territory, receive a mere 200 to 400 mm annually. RTI has developed the rainfall map of northern and central Turkana County (Figure 1.4), based on 50 years of data (1960 to 2010) obtained from 14 meteorological stations in Turkana County. (Source: Kenya Meteorological Agency, supplied by JICA).

Figure 1.4. Rainfall map of northern and central Turkana County. Average annual rainfall values are indicated in black, average annual rainfalls calculated for a period 4 to 10 years are indicated in red text. Calculations may vary depending on the availability of the data derived from the 14 meteorological stations (names indicated in blue). RTI, 2013; Kenya Meteorological Agency data, 2012.



1.4. Methodology

To adequately map the sub-surface water resources of a remote and semi-arid area such as Turkana, which is characterized by large expanses of unexplored hydrogeological territory, a method that is reliable in achieving rapid and precise groundwater exploration is essential. It is for this reason and for the proven operational capabilities that UNESCO has commissioned the Contractor (RTI) to implement its proprietary WATEX™ System as the core component by which the survey and mapping of northern and central Turkana County has been driven.

Water for everyone, everywhere
watex

WATEX™: A state-of-the-art water exploration and mapping technology

Developed from years of research and development by RTI, the WATEX™ (short for “water exploration”) System is a proprietary technology that prospects and explores sub-surface water, soils and geology in order to enable and support effective hydrogeological investigations with optimal certainty. As an instrument of exploration, the WATEX™ is not a replacement for conventional hydrogeological investigations. Rather, it a powerful tool that helps to establish, or, in cases where prevailing science needs to be updated – to re-establish – the fundamental parameters of groundwater systems upon which hydrogeological investigations can be based and a more accurate understanding of groundwater can be achieved. The aim of the WATEX™ is to give the most reliable depiction, or model, of groundwater systems over very large areas within short periods of time and to deliver a package of tools and analysis so that, ultimately, decisions about managing the resource, such as where to drill a well or borehole, can be made with the greatest degree of certainty. In other words, WATEX™ helps to identify water hidden under the surface in order to unlock the potential of the resource for development.

WATEX™ achieves rapid, accurate mapping of groundwater potential thanks to its transdisciplinary and multi-technological design, which comprises a calculated mix of space-based remote-sensing and oil exploration technologies and conventional hydrogeological techniques. A particularly innovative feature of WATEX™ is the WATEX™ image processing component, which detects groundwater moisture in depths of 40 meters or more and enables accurate modeling of aquifers and fractures in shallow depths (0-100 meters). WATEX™ also maps deep aquifers from 100 meters to 4,000 meters with the integration of petroleum industry data. This integrated approach not only enables shallow and deep aquifer systems to be modeled and mapped together with high accuracy, it is also a cost-effective and time-saving way to survey hydrogeological resources at the large regional scale.

Operational, tested and proven

The WATEX™ is a peer-reviewed, proven technique for surveying and prospecting hydrogeological resources in a variety of climates. It has been recognized by UNESCO, US Geological Survey, the US Congress, the European Union as a unique method for mapping and identifying groundwater resources in large areas, rapidly and precisely. The process has been applied in Afghanistan, Darfur (Sudan), Chad, Angola, Iraq, and Ethiopia. In each case, the benefits of WATEX™ were recognized to have built a new large-scale vision of the resource where only little or unreliable information had existed, and to have made borehole drilling more effective – in all cases, the rate of successful drilling was improved to over 95%. Recognizing the unique capabilities of WATEX™, interest and demand for the technology as an unconventional yet reliable and practical tool for decision-making on water resources at both local and national scales is rising.

Implementation

For each regional study, the Contractor, RTI, implements the WATEX™ system and delivers results that are tailored to the client's needs. The key outputs of executing the WATEX™ System are a set of sophisticated, yet user-friendly, tools that provide new intelligence on groundwater resources and new capabilities in groundwater navigation and management.

Similar to most studies that RTI implements for its clients, the WATEX™ System has been used as the core component for the present survey (northern and central Turkana County). All maps, analysis, assessments and recommendations presented herein are the result of the application of WATEX™ System and the expertise provided by RTI.

Survey questions

The overarching objective of the survey is to locate quantities of groundwater in northern and central Turkana County that can be used safely for development concerns, such as drought mitigation, poverty alleviation and socio-economic development. With human development as the core concerns of the study, and also taking into account the significant geographic scope, the survey has been designed to answer practical questions for field practitioners and government officials who seek fundamental, yet crucial, information about the resource in order to best develop it into a viable, reliable supply for a variety of uses. The key questions that these stakeholders need answering entail the "where", "how much" and "how reliable" is the water in a given location.
The study is intended to be exploratory in nature and strives to provide new, practical and operational information for its users. As is customary with exploration, the scientific value of the survey is its advancement of basic hydrogeology of the Turkana Basin at the regional level and as a new baseline for continued hydrogeological investigations for local, national and regional levels for decades to come. The study does incorporate secondary sources of data if deemed reliable, such as well logs and existing maps. For the most part, however, the study focuses on raising the scientific bar to achieve a workable, practical new vision of groundwater resources in the area so that the impact on local populations can be delivered in a timely manner.

Taking into careful consideration the concerns for exploitation and management of the groundwater systems, the inquiry of the survey of groundwater resources of northern and central Turkana County is limited by, and therefore aims to answer the following set of scientific questions:

(1) **The physical location** of the occurrence of groundwater systems, including shallow alluvial aquifers, deep aquifer structure and conductive, water-bearing fractures. Where possible, parameters of aquifer occurrence such as extent, depth and geometry will be described.

(2) **Volume of water stored** in aquifer systems, estimated as potential storage, independent of recharge. Potential storage, measured as storage coefficient or specific yield, will be estimated for any large aquifer units, such as deep confined or unconfined aquifers that may be identified.

(3) **Rate of recharge**, or inflow to an aquifer system arising from precipitation, return flow from irrigation and flows from surface drainage. The survey aims to determine basic parameters of recharge for shallow alluvial aquifer systems and large deep aquifer structures. Where possible, directional flow of drainage and recharge will be mapped.

(4) **Groundwater inventory**, or the overall volume of renewable water available in the survey area is being studied. Where possible, a simulation of the total volumes for deep aquifer structures and shallow groundwater will be made.

(5) **Soil classification**, or the taxonomy of shallow soil types in the survey area is also being studied. The designation of soils will be made to aid in further study of agriculture potential.

The survey has collected other parameters, such as quality (physical and chemical properties), discharge and the impact of development and has considered them in the overall assessment. Where relevant, issues pertaining to these other parameters are highlighted in the assessment, particularly those that may concern human development. All parameters of hydrogeology collected by the survey are included in the final database delivered in GIS format.

Priority Zones (Areas of Interest, AOI)

In addition to the scientific inquiries mentioned above, the survey will give additional assessment of four areas considered to be of priority to key government and international stakeholders. These Areas of Interest (AOI) (see Figure 1.5), as decided upon by the Government of Kenya, include:

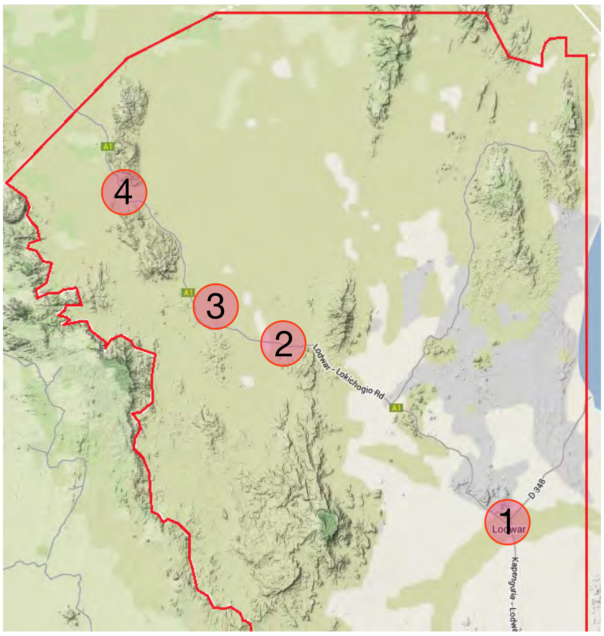
(1) Lodwar township and local surroundings

(2) Refugee Camp at Kakuma and local host community

(3) Proposed refugee camp site and local host community at Kalobeiyei

(4) Lokichogio township and local surroundings

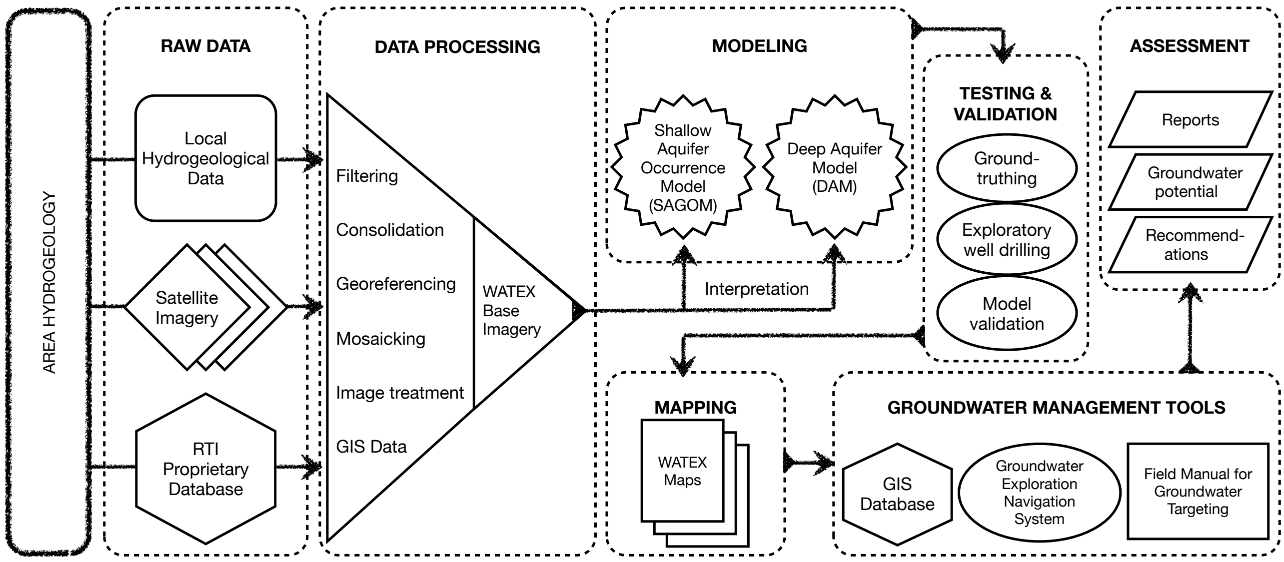
Figure 1.5. Location of four AOIs in the survey area. (1) Lodwar, (2) Kakuma, (3) Kalobeiyei, (4) Lokichogio. RTI, 2013.



Survey methods

In order to achieve the stated objectives of the survey, UNESCO, the Government of Kenya and RTI have agreed upon a process by which groundwater resources in northern and central Turkana will be studied. The process is captured in the flow diagram Figure 1.5, and each stage of the process is discussed in further detail below.

Figure 1.6. Methodology of the advanced survey of groundwater in northern-central Turkana. RTI, 2013.



Raw data collection

The overall methodology for the study began with the collection of reliable data inputs. These "raw materials" include unprocessed satellite imagery, secondary maps and data, primary field data and datasets from RTI's own proprietary database.

RTI has acquired multi-seasonal, multi-sensor untreated radar, optic and topographic imagery of satellites from a number of international civilian space programmes. In addition to remote sensing data, a significant number of hydrogeological data has been collected, mainly from academia, the Government of Kenya, UN agencies and non-governmental organizations. RTI has also procured un-interpreted seismic data and exploration reports from the oil industry and the National Oil Corporation of Kenya (NOCK). UNESCO procured primary vertical electrical sounding (VES) resistivity data in targeted locations. Other data was collected as a means to test the validity of the findings of the survey (discussed in "Testing and validation" section below).

In addition to the above, RTI and UNESCO collected valuable primary data directly from the field, including hydrology, hydrogeology, geology, stratigraphy, pedology and land use.

RTI has also drawn raw and processed datasets from its own proprietary, multi-field database of hydrogeological, geological, soil and petroleum resources from around the world. The sophisticated proprietary collection compiles images, data and maps, and is an unrivaled library of knowledge and interpretation, and includes GIS layers, digital elevation models, and data on drainage, rainfall, watersheds, soils, geology and morphology.

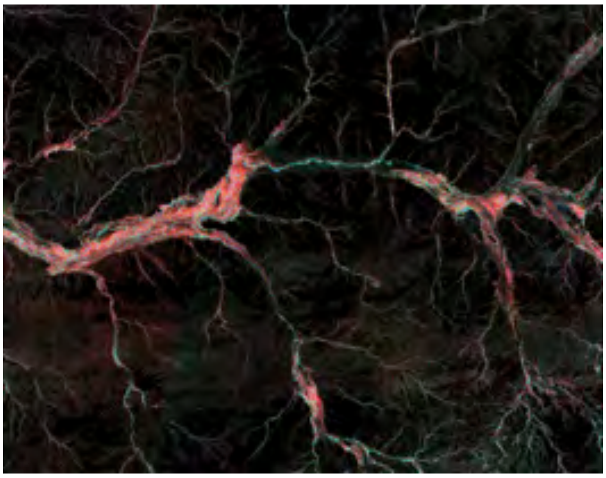
Data processing

The next stage of the study was to conduct the proprietary WATEX™ technique to process the raw data inputs into accurate interpretation of hydrogeological regimes in the study area, including groundwater, geology and soils. The main output of processing is WATEX™ base imagery, which was used during subsequent stages to conduct modeling and eventually mapping.

The WATEX™ processing entails the application of trade techniques developed and owned exclusively by RTI and protected by international law. The special method treats, georeferences, integrates, validates and interprets raw data inputs into a consolidated, accurate visual representation of groundwater, geology and soil regimes. In simplified terms, RTI uses special algorithms and processing methods to transform data into sophisticated images, called WATEX™ imagery (pictured in Figure 1.7 below).

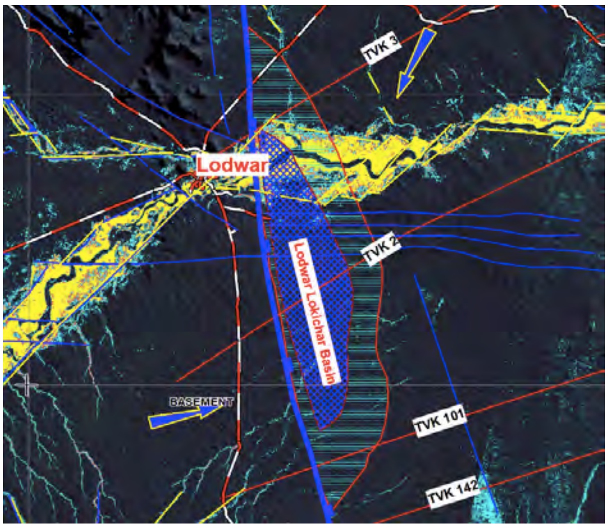
For **shallow groundwater** prospection, WATEX™ processes multi-frequency, multi-polarization radar imagery to detect the occurrence and extent of soil moisture 20 meters below earth's surface. Other optic and topographic imagery are also treated to create a new model of shallow aquifers and conductive fractures. This innovation allows shallow aquifers to be differentiated from other objects, such as dry soil, minerals and surface features. In previous studies in Sudan and Chad, models developed from this method demonstrated a certainty level of >90%, and a ground accuracy of six meters (RTI 2008).

Figure 1.7. Example of a WATEX™ base image. Bright areas show the occurrence of shallow groundwater. Dark areas are dry. RTI, 2010.



To prospect for **deep aquifers**, or water deeper than 100 meters, the WATEX™ technique combines base WATEX™ imagery with geophysical data interpretation. Magnetic, gravity, vertical electrical sounding (VES) resistivity and seismic (2-D and 3-D) data have been interpreted in order to evaluate the occurrence and other features of deep aquifer structures, such as basic geometry, the degree of confinement (aquiclude evaluation), and basement depth. The integration of WATEX™ base imagery also enables basic linkages with surface percolation to be evaluated. The resulting WATEX™ deep groundwater base image (Figure 1.8) is used later to model and map these aquifer regimes.

Figure 1.8. Example of a WATEX™ deep groundwater image. The image shows the inferred occurrence and extent of a deep aquifer structure. RTI, 2013.



The basic components of regional **groundwater recharge** are assembled by RTI in order to be interpreted and subsequently evaluated. RTI has developed a regional rainfall map with isohyets drawn from existing meteorological records. Regional watersheds and drainage were also mapped from DEMs derived from topographical radar imagery. Geology and stratigraphy is interpreted for percolation, and rates for permeability are assigned.

For the prospection and **classification of soils**, the WATEX™ technique processes raw optic, radar and topographic imagery to evaluate the extent and basic chemical response of soils no deeper than 50 centimeters from the surface. The result of this process is a set of WATEX™ base imagery of all soil types that occur in the survey area with a surface accuracy of 6 meters.

In addition to generating base imagery, the WATEX™ processing also entails the digitization, collation and filtering of all collected data into GIS formatting. RTI has ensured the "georeferencing" of data according to the latest revision of the World Geodetic System standard for cartography, geodesy and navigation (WGS 1984 datum in geographic coordinates because of the size of the regional survey). RTI developed a dual GIS system based on vectors and rasters. This is an essential step in processing since it allows for GIS mapping layers to be built, but also aids in database archiving later on. Also, multiple back-ups will be created throughout the conversion and processing.

The last stage of data processing involves the checking of data standards and preparing the data for modeling. RTI has cross-checked all data for consistency and standards and eliminated all remaining redundancies. RTI has held numerous consultations with UNESCO and the independent technical scientific committee on the preliminary findings will also be useful in refining the final products.

Modeling

The WATEX™ System enables unique capabilities in mapping complex groundwater systems with a high magnitude of certainty thanks to the implementation of two groundwater models, each with distinct concepts of groundwater that can be mapped independently but conjunctively – the Shallow Alluvial Groundwater Occurrence Model (SAGOM) and the Deep Aquifer Model (DAM). While no model can be 100 per cent certain, the goal of such models was to minimize the unknowns about the occurrence and extent of groundwater and to represent the actual systems as closely as possible.

The Shallow Alluvial Groundwater Occurrence Model, or SAGOM, is based on the base WATEX™ imagery for shallow groundwater and other data and represents unconfined aquifers occurring from surface to an approximate depth of 80-100 meters – the "low-lying fruit" of groundwater resources and a major resource for localized development. Figures 1.9 and 1.10 demonstrate examples of SAGOM visual representation of shallow groundwater and conductive fractures, respectively.

Figure 1.9. Example of SAGOM representation of shallow alluvial groundwater. Pixels represent 36 m2. Brightly colored pixels represent varying degrees of groundwater occurrence potential at that exact location. Dark pixels represent the absence or minimal groundwater occurrence at that location. RTI, 2013.

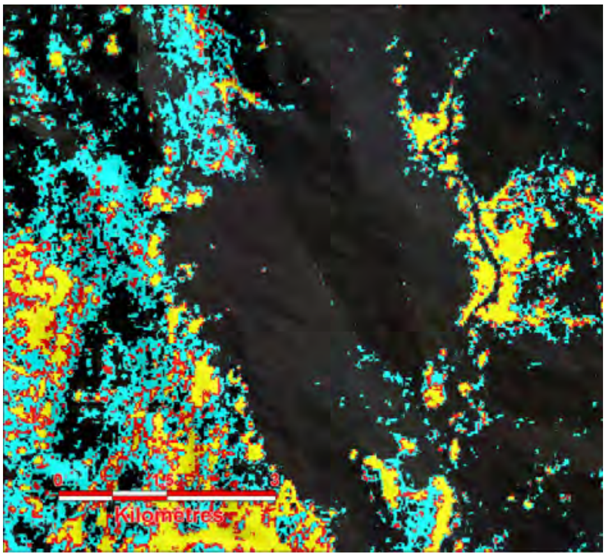
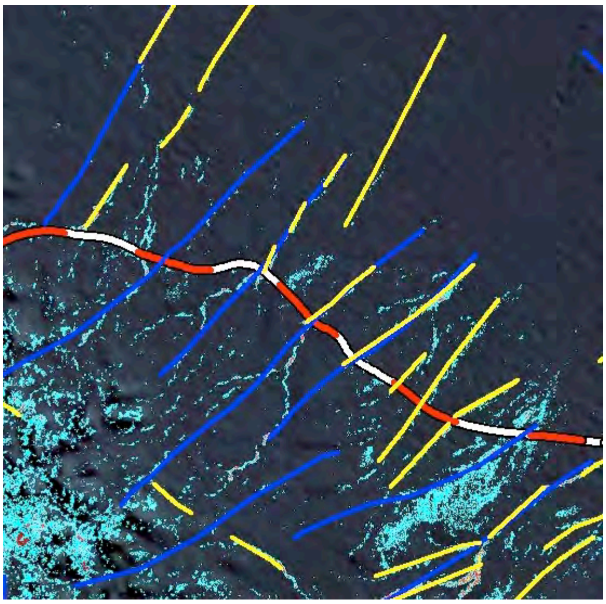
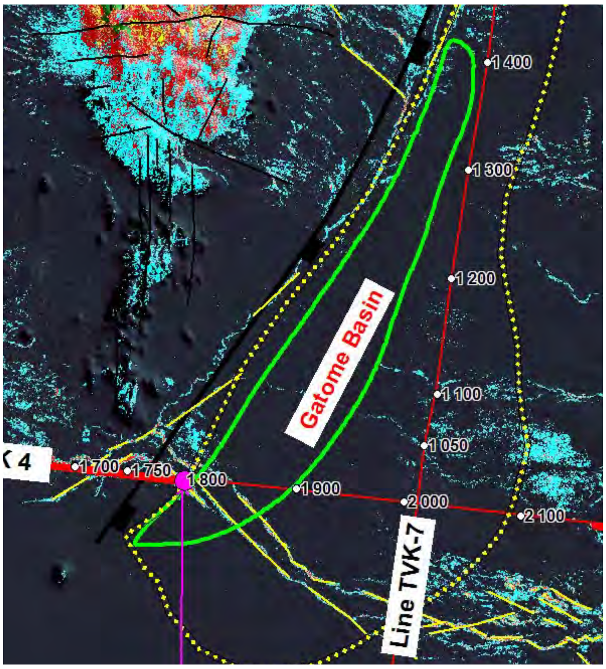


Figure 1.10. Example of SAGOM representation of conductive and non-conductive fractures. Conductive, or water-bearing fractures are assigned in yellow lines, while non-conductive or dry fractures are in blue. RTI, 2013.



The Deep Aquifer Model, or DAM, conceptualizes sedimentary basins occurring deeper than 100 meters. These large aquifers can contain vast quantities of water. Furthermore, the DAM was used to predict the existence of aquifers never documented before, offering the prospect of making major discoveries with strategic importance for Kenya.

Figure 1.11. Example of DAM representation of deep aquifer occurrence and geometry. RTI, 2013.



Testing and validation

An essential stage of exploration research for this study has been to test the level of accuracy, or skill, of the models in representing complex systems in the survey area. Several methods were employed to refine the preliminary models and to measure the closeness of the predictions of the two models to the reality observed in the field: ground-truthing, additional field sampling and exploratory borehole drilling.

A team of experts from RTI, UNESCO and the Government of Kenya conducted ground-truthing and additional field sampling. Data on geology, boreholes and wells were obtained through field missions across the survey area. UNESCO also collected additional VES resistivity readings for targeted areas. This additional ancillary data was a critical component in comparing and validating the original SAGOM and DAM models to observed phenomena.

A series of exploratory boreholes were drilled by UNESCO in targeted areas in the survey are in order to test and verify the predictions of the WATEX™ models. Four scientific boreholes were commissioned to prove the ability of the DAM model to identify deep structures, resulting in the positive confirmation of two large aquifers – the Lodwar Basin Aquifer and the Lotikipi Basin Aquifer.

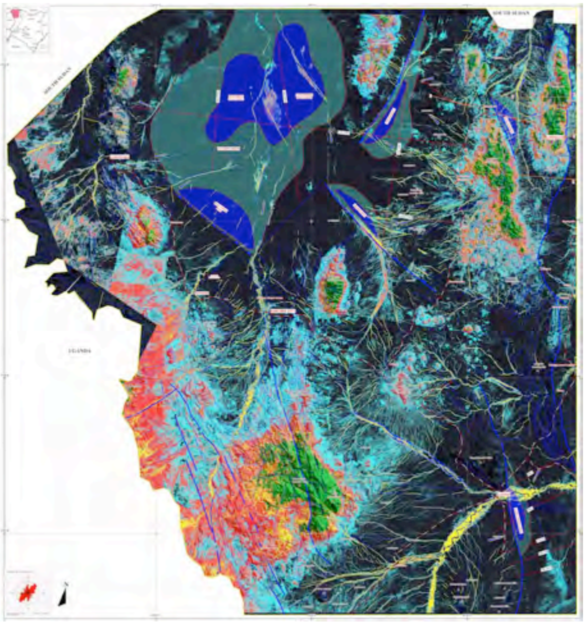
Statistical analysis was run on the SAGOM in order to test its validity and accuracy. Several samples of existing and new boreholes, amounting to over 700 boreholes in the survey area, were used to perform analysis of the SAGOM model. The analysis demonstrated that the SAGOM has had an accuracy of over 95% in predicting the occurrence of groundwater in the survey area.

Mapping

Following model validation and verification, a set of core maps was developed to depict groundwater occurrence and potential, vertical recharge and soil and vegetation classification. RTI utilized a mix of mapping software, which includes Pitney Bowes' MapInfo® and a proprietary GIS application to generate the three visual representations of these natural regimes and phenomena All three maps are developed with the same set of format and standards: a scale of 1:500,000, pixel resolution of 6.25 m x 6.25 m, legend, and key. Each is presented with a superimposed topographical relief background for three-dimensional effect, as well as relevant land features (airstrips, roads, administrative boundaries, villages and townships) along with appropriate data layers, legends and standard map formatting. The three core maps developed and delivered for this study are described below:

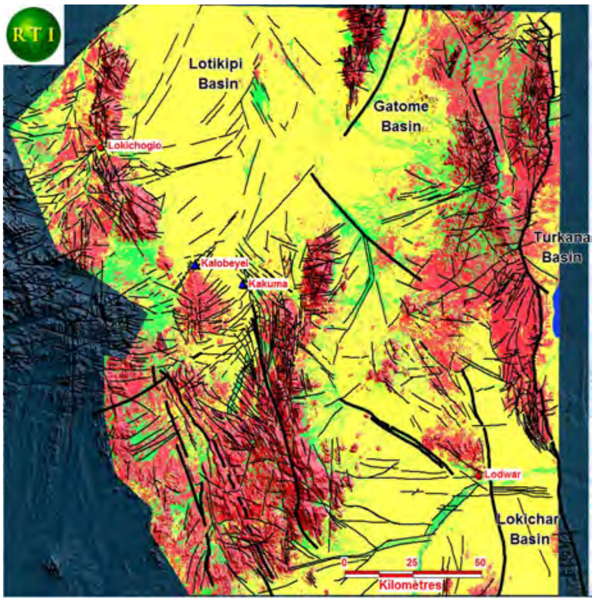
The High-Potential Groundwater Target Map of Northern and Central Turkana County provides an overview of all groundwater resources in the study area and indicates the proximity of water in relation to population centres and sub-catchment boundaries. It also shows the location and potential of both shallow aquifers (<100 m), deep aquifer structures (>100m) and conductive and non-conductive fractures. The map is a tool to understand how much water is in a given area and where to plan sites for boreholes and wells with a high level of certainty of success.

Figure 1.12. Groundwater target mapping. RTI, 2013.



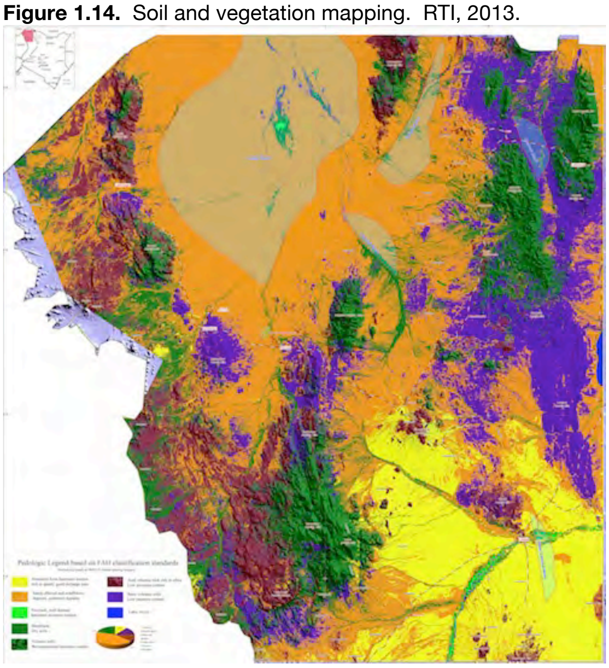
Regional trends in surface-aquifer recharge are mapped and presented as the **Groundwater Recharge Map of Northern and Central Turkana County**. This map depicts the groundwater recharge in the study area and indicates the location and rate at which rainwater seeps down through the soil into an underlying aquifer in relation to population centres and sub-catchment boundaries. It also depicts intergranular and impermeable aquiclude formations and fracture lineaments to give the rate of recharge in any given location. The map serves as a tool to identify the areas in the survey area where groundwater is most likely to be replenished and aids in understanding the relation between land-use practices and water quality and availability.

Figure 1.13. Groundwater recharge mapping. RTI, 2013.



The soil types of the survey area are classified and presented on the **Soil and Vegetation Map of Northern and Central Turkana County**. Soil is classified according to FAO and World Soil Classification standards, and indicates the location and type of surface soils (eg. arenosols, sandy alluvial deposits, and fluvisols) and humid vegetation (shrubland, wet moisture content) on the first 20 cm below surface. Soils are mapped in relation to population centres, major aquifers and sub-catchment boundaries. The map does not depict soil thickness, serves as a tool to aid in planning for agriculture and shallow groundwater investigations for irrigation purposes.

Figure 1.14. Soil and vegetation mapping. RTI, 2013.



Development of tools for groundwater management

The final maps, datasets and research have been integrated and developed by RTI into a suite of practical tools that users can use to manage and make decisions about the use of groundwater in the northern and central Turkana County. The package includes a GIS database, a set of RTI's proprietary Groundwater Exploration Navigation System (GENS) devices, and the Technical Manual for Groundwater Targeting.

The database archives all datasets and maps converted into GIS layers (MapInfo and ArcGIS compatible). The library contains files related to shallow and deep aquifers, boreholes, hydrochemistry, climate, slope and topography, drainage and sub-catchments, vegetation, geology and fractures, and land use features, and enables users to evaluate, interpret and present the groundwater information.

RTI has delivered two GENS devices tailored to the survey area. Each device is loaded with the county maps and information, and shows the user its location on the maps. Users of the GENS will be able to pinpoint groundwater from the surface and plan borehole drilling.

Figure 1.15. Groundwater Exploration Navigation System (GENS). Developed and trademarked by RTI. RTI, 2013.

RTI has also published the Technical Manual for Groundwater Targeting tailored specifically to the northern and central Turkana County. A practical guide for groundwater prospection, the Manual is written for water supply authorities, hydrogeologists and drilling contractors who need tailored advice on identifying sites for drilling boreholes. The Manual assumes that users have adequate expertise and qualifications to conduct localized hydrogeological assessments and understand requirements for borehole site selection. The manual is designed to provide an overview of areas with highest potential for groundwater prospection within the 36,000 km2 zone surveyed and provides advice on selected areas.

Figure 1.16. Technical Manual for Groundwater Targeting, Northern and Central Turkana County Edition, RTI 2013.

Assessment

The final stage of the survey methodology has been to conduct analysis on the potential of the groundwater resources in the survey area and provide technical recommendations. RTI has utilized the final maps and package of tools (discussed above) to analyze and develop key recommendations for policy makers. This report, along with the subsidiary annexes, is the core document which captures the results of this analysis. It summarizes the findings of the mapping programme and highlights key data on groundwater occurrence, such as groundwater availability, location, quality, recharge and highlight risks and potential development options. Strategic aquifers have been identified. The implications for borehole siting and drilling in the survey area have been discussed. As an overarching tool for planning, the report illustrates to hydrogeologists and policymakers the overall situation and potential of groundwater in this part of Turkana County.

Scientific peer review

The survey has been reviewed continuously throughout the entire process by an independent scientific panel – the Technical Scientific Committee (TSC). The Government of Kenya, Ministry of Environment, Water and Natural Resources mandated the establishment of the TSC to review, provide guidance for and validate the scientific processes and results of the full survey. Membership of the TSC consists of ten Kenyan experts of high scientific and technical qualification, which assumed the temporary role behalf of the Kenyan Government and the people of Kenya. The TSC was led by two co-chairs, Prof. Nobert Opiyo-Akech and Prof. Daniel Olago of the University of Nairobi. Other TSC members were represented by the Ministry, the Kenyan Water Resources Management Authority (WRMA), Kenya Water Institute (KEWI), and the Water Services Board. The results, endorsement and final recommendations of the TSC's work is captured in its final report.

1.5. Follow-up, continuity and sustainability

Although this survey, with its maps, analysis and recommendations, has generated new concepts for and a vision upon which groundwater resources of northern and central Turkana County can be better understood, the work performed is far from being the ending point for studying these regimes. Rather, the study is intended to serve as a new baseline upon which further investigations can be based and referred.

Recommendations for further scientific study have been offered in this report, with the aim of giving some direction to national hydrogeologists and groundwater experts as they seek to improve the understanding and management of these natural regimes.

Some options and scenarios for managing groundwater resources in the survey area have been offered in this study, but do not in any way intend to cover the entire range of options available. An intensive study of socio-economic potential of the groundwater resources mapped and assessed by this study will need to be conducted in order to achieve an appropriate management and response plan for the longer term.

One of the key recommendations coming out of this study is that this pilot survey be taken as a model for undertaking similar exploration and mapping of groundwater in other counties of Kenya as well as in other countries in the African region and beyond.

UNESCO and RTI have endeavored to build a cadre of skills and capacities within the Government of Kenya and other stakeholders in order to ensure the operationality and future sustainability of the products and tools delivered by this project. Central government and Turkana County officials, NGOs, local stakeholders have been trained to use and operate the package of maps and tools. The tools have been delivered and are being housed by the government officials in Nairobi (Maji House and Regional and County offices).

1.6. Structure of the Report

This final technical report presents a concise summary of the processes, observations, findings and messages resulting from the work of RTI to conduct this study. One aim of this report is to lend the reader a logical flow of ideas and direct the reader to a discussion of the main messages and ideas without getting lost in data and technical jargon. In that regard, this Technical Report has been organized into five core chapters. An annex of additional chapters and information has been published separately.

Following this introduction of context and methodology (Chapter 1), the report summarizes the key characteristics of regional hydrogeology in Chapter 2. The main outcomes of the WATEX™ method will also be presented. Chapter 3 gives a concise assessment of the potential derived from the hydrogeology for development. Chapter 4 is a report of the work of the UNESCO GRIDMAP team's independent review and validation of the models employed in this study. The chapter presents the results of statistical analysis of those tests. The final chapter, Chapter 5, articulates the study's main conclusions and proposes a set of recommendations for its follow up. The Annexes are an important ancillary volume of more detailed information, which allows the reader to delve deeper into components such as the survey dataset, the geological analysis, soil classification, and hydrology.

2. Hydrogeology of Northern-Central Turkana County

2.1. Introduction

This study takes an exploratory approach to surveying and describing naturally occurring resources at a large scale. The core methodology of this study has been described in the previous chapter. It entails methods of observing these systems both indirectly (WATEX System) and directly in the field, then modeling these systems so that they can be mapped with high certainty. RTI has processed an input dataset that includes raw satellite imagery and regional hydrogeological data to generate base exploration imagery (WATEX images). These images make up the building blocks of models of shallow and deep groundwater systems. The outputs of the models give an accurate depiction of groundwater in northern and central Turkana County, which can then be validated, mapped and assessed.

Objective of this chapter

This chapter aims to provide an overall description of hydrogeological regimes of northern and central Turkana County. The depiction of natural regimes presented herein are observed through interpretations and analysis of RTI's work to conduct the WATEX method for exploration and mapping groundwater and modeling those systems. This chapter provides the foundation for subsequent assessment of groundwater potential in the region, which is captured in Chapter 3.

The chapter is organized in such a way as to give the reader a narrative of the steps taken to process and interpret data, and gives the findings of each stage of the process. It follows a flow of logic, beginning with the raw inputs to WATEX processing and ending with the results of modeling. Following a summary of processing the raw datasets, the chapter describes the regional hydrology and geology that have been processed. The key outputs of WATEX processing – the WATEX base exploration imagery – are then explained prior to an introduction of the two core WATEX models for shallow and deep groundwater regimes. The chapter concludes with a summary of the results of implementing the models, which lays the ground for further assessment of potential later on in this report.

2.2. Raw data inputs

The key raw inputs of data include remote sensing data (eg. Landsat imagery, SRTM imagery, radar imagery), existing hydrogeological data in the form of reports, maps and databases, and primary data collected in the field. The survey undertook the WATEX processing and interpretation of these data, described in further detail in the Annex chapter "Dataset Report". This section walks the reader through the critical steps taken in order to conduct the full range of analysis.

Landsat imagery

Panchromatic optical and infrared imagery were obtained by RTI from the US Geological Survey (USGS) Landsat 7 Satellite mission (Landsat-7) for a coverage of the entire survey area. The imagery was generated from the Landsat-7 ETM+ sensor (Enhanced Thematic Mapper Plus), the most advanced sensor from the programme. Table 2.1 summarizes the image specifications.

Table 2.1. Categories of raw Landsat satellite imagery. RTI, 2013.

Category	Frequency/ Band	Spectral res. (µm)	Spatial res. (m)
Optical	1: Blue	0.450 – 0.515	30
Optical	2: Green	0.525 – 0.605	30
Optical	3: Red	0.630 – 0.690	30
Infrared	4: Near IR	0.760 – 0.900	30
Infrared	5: Mid IR	1.550 – 1.750	30
Infrared	6:Thermal	10.40 – 12.50	60
Infrared	7: Mid IR	2.080 – 2.350	30
Optical + Infrared	8: Panchromatic	0.520 – 0.920	15

All images were supplied by USGS through the Global Land Cover Facility website in a GeoTIFF format. RTI has assembled all imagery with ERDAS ERMapper software, then orthrectified and georeferenced them into UTM (Universal Transverse Mercator) coordinate system, in WGS84 datum. The path, row and date of the Landsat imagery are provided in Table 2.2.

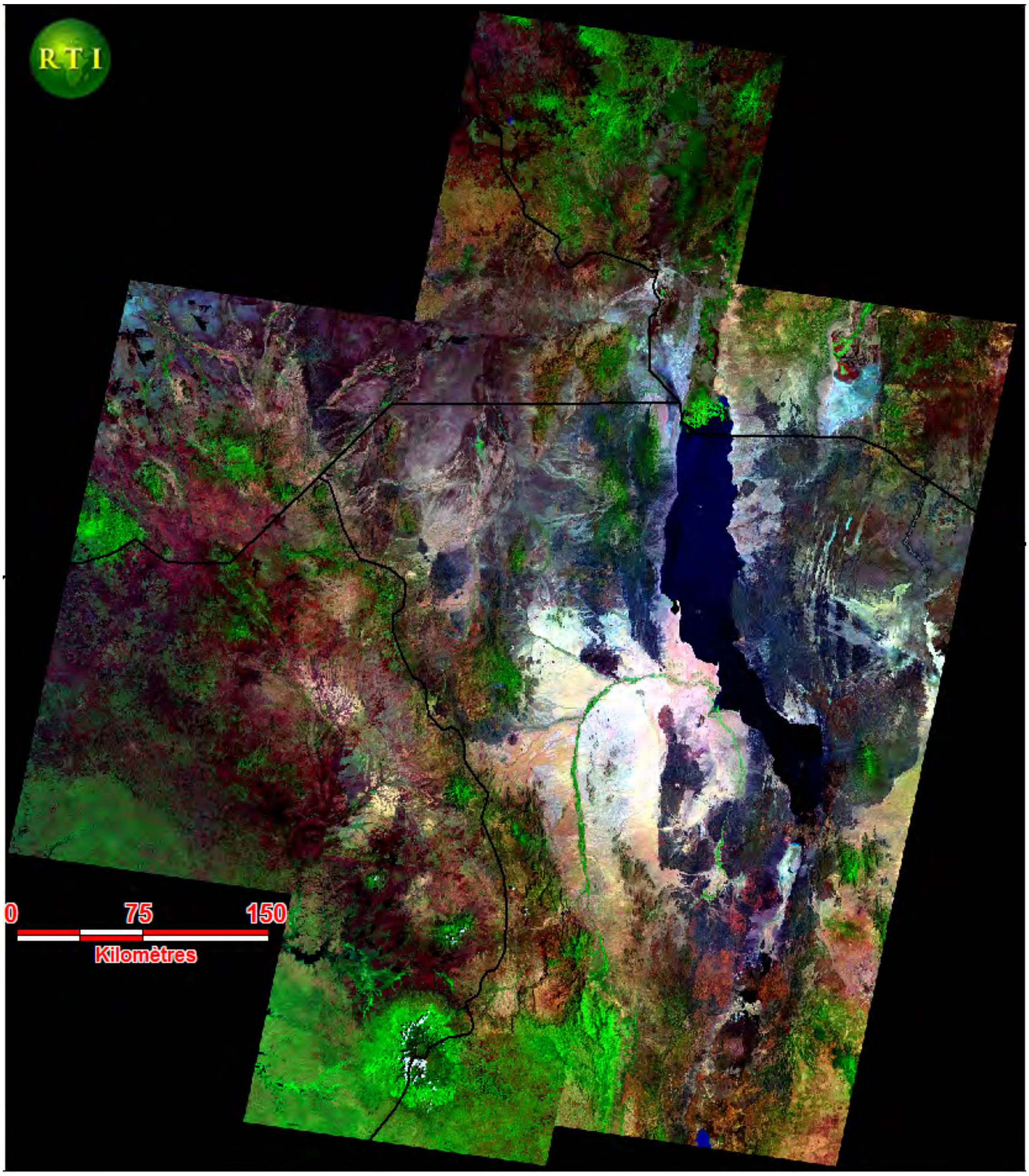
Table 2.2. List and date of Landsat-7 satellite imagery. RTI, 2013.

Path and row	Date
P169R059	27/01/2000
P169R058	27/01/2000
P169R057	27/01/2000
P170R056	05/02/2001
P170R057	05/02/2001
P170R058	18/01/2000
P170R059	05/02/2001
P171R057	27/01/2000
P171R058	27/01/2000

RTI processed Landsat 7 images using the 7 channels to extract four derived products, assembled into mosaics to cover the survey area:

(1) Landsat (7,4,2) and Landsat (3,2,1)
(2) NDVI mosaic for vegetation Index
(3) Sultan processed mosaic to enhance lithological/chemical signatures

Figure 2.1. Mosaic of Landsat imagery processed in 7.4.2. format showing enhanced lithological contrasts. RTI, 2013.



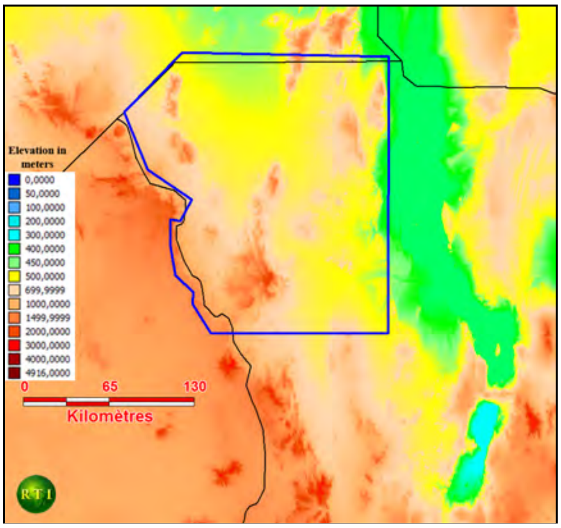
Shuttle Radar Topography Mission (SRTM)

The release of the Shuttle Radar Topography Mission (SRTM) global terrain model in 2003 provided access to slope and elevation data of unprecedented quality compared to other topographic information of the region. RTI has obtained SRTM imagery in order to process a model of terrain model with a pixel resolution of 90 m (5 m, 90% vertical accuracy).

Elevation grid (Digital Elevation Model)

The SRTM images have been assembled into a single mosaic in order to extract topographic isolines and slopes over an extended surface over the survey area. Such a product provides an accurate access to geomorphologic models and enables slope maps to be generated that can be used to determine watershed boundaries. RTI uses this to achieve and sustain a broad structural interpretation.

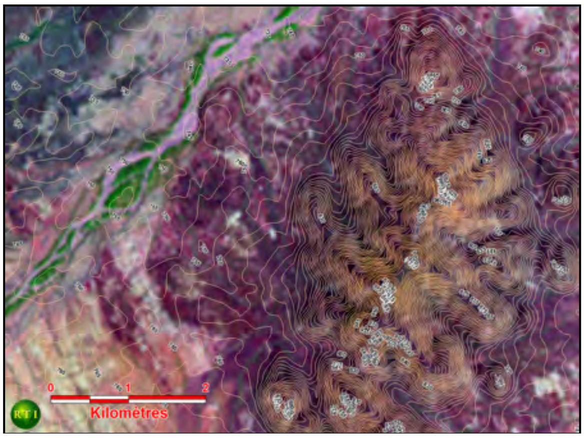
Figure 2.2. Elevation grid of the survey area. The elevations are generated by processing raw SRTM imagery. RTI, 2012.



Elevation isolines for topography evaluation

The elevation lines (isolines) were drawn (Figure 2.3) in order to analyze the precise topography of the study area. This SRTM derivative was also used to map out the drainage system more precisely, which cannot be achieved solely with Landsat as the intricacies of drainage patterns are not visible at some definitions. Elevation isolines were extracted from the elevation grid (Figure 2.2) with the Vertical Mapper module in MapInfo software with 5-meter intervals.

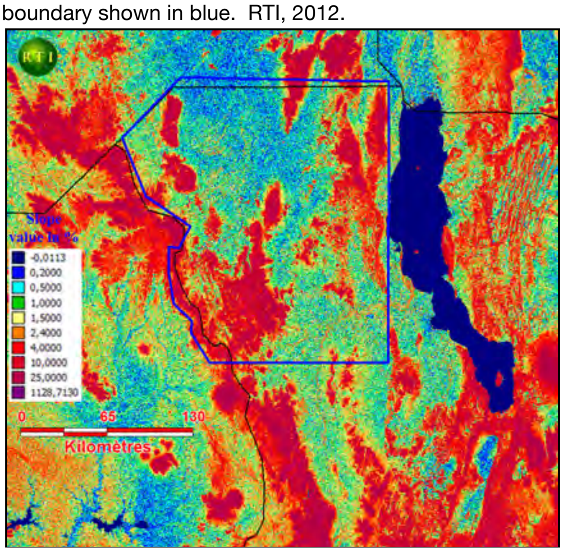
Figure 2.3. Close-up on the mosaic of Landsat with topographic elevation isolines superimposed. Interval is 5 meters. RTI, 2012.



Slope grid for structural evaluation

As an important factor of hydrogeology, RTI observed and interpreted regional structural geology with the aid of a slope grid (Figure 2.4). RTI generated a slope grid of the Turkana region by processing the elevation grid (above) with the Vertical Mapper module in MapInfo software. Such a tool shows the patterns and direction of fault lines and outcrops as distinct changes in slope. Slope is also a significant factor in the exploration for aquifers, as it indicates the inclination of the topographic surfaces and formations contributing to recharge and aquifer geometry. Slope was measured by the angle between inclination and the horizontal plane, and was expressed as a percentage, i.e. the elevation difference/horizontal difference between two points.

Figure 2.4. Slope grid of Turkana region. Study area boundary shown in blue. RTI, 2012.



Radar imagery

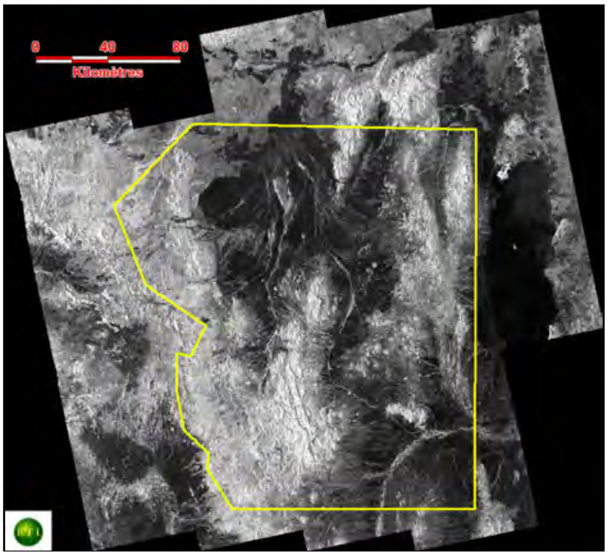
Another raw dataset input to the WATEX System is radar imagery. Conventional applications of radar are used to investigate groundwater only a few meters below the surface. Thanks to WATEX techniques, radar is processed to detect occurrence and extent of groundwater 20 meters below the surface, and enables the interpretation of shallow alluvial groundwater and conductive fractures from a range of 0-80 meters with a ground-surface accuracy of 6.25 meters thanks to secondary moisture effects. This is a significant capability in exploring and mapping groundwater.

RTI has geo-coded the raw radar images in UTM projection, WGS84 datum, then re-projected them in a geographic coordinate system, in latitude and longitude, always in the WGS84 global datum for compatibility in GIS.

In order to further treat and interpret the raw satellite imagery, RTI has assembled the images of each season to create three multi-seasonal mosaics at the regional scale. A first mosaic was constructed out of 22 images in single polarization (FBS: HH) with a pixel size of 6.25 meters acquired in the December 2009 to February 2010 season. The second mosaic was built with 21 images in single polarization (HH) with a pixel size of 6.25 meters acquired in the March 2008 and March-April 2010 seasons. The third mosaic was constructed out of 21 images in dual polarization (FBD: HH+HV) with a pixel size of 12.5 meters acquired from the May to July 2010 season.

RTI processed the three mosaics to generate a final multi-temporal mosaic, and applied radiometry balancing to adjust color contrasts. Figure 2.5. shows the final radar mosaic layer.

Figure 2.5. Example of regional mosaic of Spectral Aperture Radar imagery. Shown is mosaic of PALSAR, Dec 2009 – Feb 2010, single polarization. Study area boundary in yellow. RTI, 2012.



GIS Dataset Integration

The raw dataset of hydrogeology collected by the RTI entails chiefly borehole databases from various sources and field samples, plus a significant amount of observations made by the Contractor during the course of field mission taken in October 2012. Many databases of boreholes were obtained, though it is noted here that a significant amount of them were of varying degrees of reliability since none adhered to international standards for attributes for boreholes/wells, and therefore were of little use to the survey. Nonetheless, a compiled dataset of over 600 boreholes was collected. The final raw hydrogeology dataset (Table 2.3) discussed here comprises only those borehole databases that contained useful and relevant information (e.g. total depth, yield, static level, TDS and GPS coordinates). An example of a borehole database collected by the Contractor is shown in Figure 2.6. Figure 2.7 shows a water point documented by the Contractor in the field. The full set of raw data is discussed in further detail in the Annex.

Table 2.3. Summary of the dataset of raw hydrogeological data inputs selected. RTI, 2013.

Data	Date	Source
Borehole database	2008	Kenya Water Resources Management Authority
Borehole database	2012	OXFAM
Borehole database	2011	OXFAM, FAO [5]
Borehole database	2012	JICA
Borehole database	2012	UNHCR, Lutheran World Federation (LWF) [7]
Borehole database	2012	Blandenier [6]
Borehole database	2005	Turkana Rural Focus
Borehole database	2012	Catholic Diocese of Lodwar
Borehole database	2012	Kenya Ministry of Water and Irrigation
Borehole database	2012	Lokichogio Water Services Provider
Borehole field sample (water point)	2012	RTI
Recharge field observations	2012	RTI

Figure 2.6. Example of two datasets of borehole data. Boreholes are shown in blue (Oxfam) and yellow (FAO) points. Oxfam, FAO, 2012.

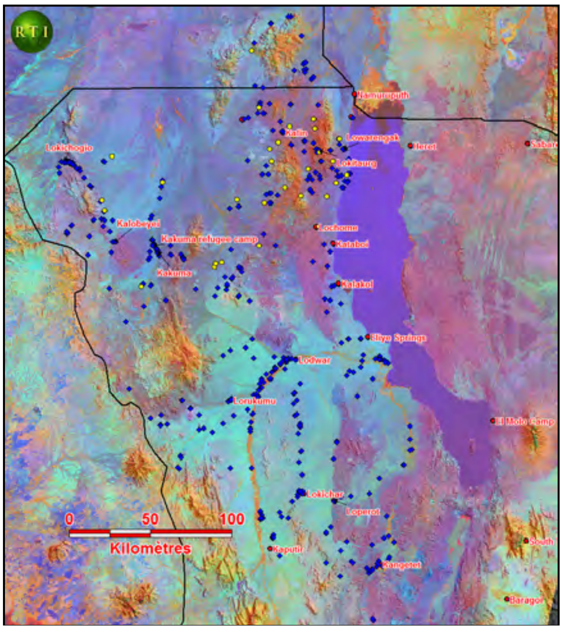
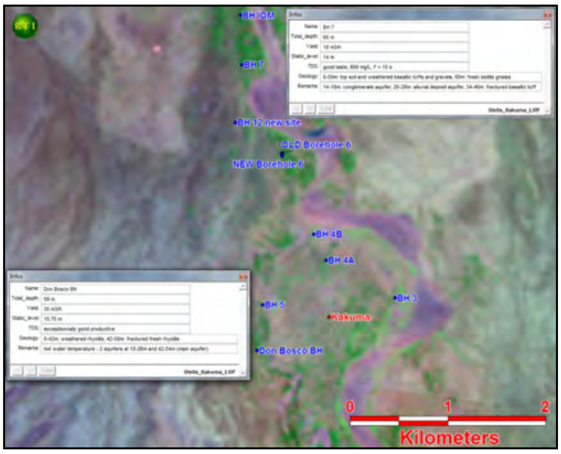


Figure 2.7. Example of GPS coordinates of boreholes taken and verified in the field by RTI in the Kakuma Refugee Camp area. RTI, 2012.



Geological data inputs

RTI collected a number of existing geological maps and primary field data to form the basis of geological exploration for the survey. Table 2.4 summarizes the geological dataset. Existing geological maps were collected from the Department of Mines and Geology of the Kenyan Ministry of Environment, Water and Natural Resources. These maps were published between 1958 and 1963, and were based on black and white aerial surveys between. The most recent and accurate geologic map was published in 1987 by BEICIP for the former Kenyan Department of Geology, Ministry of Natural Resources, shown on Figure 2.8. RTI has conducted ground-truthing of the maps to validate and check the maps in the field. Despite some residual inaccuracies of the BEICIP map, RTI has used it as the main reference for prevailing regional geology for the study.

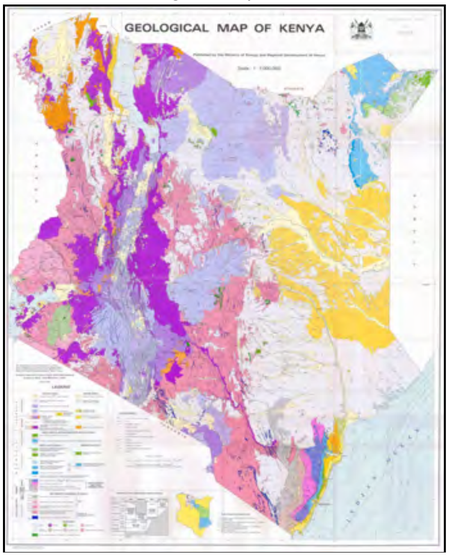
Table 2.4. Summary of the geology dataset. RTI, 2013.

Datum	Date	Source
Geological map of Kenya, 2nd Edition (1:3,000,000)	1962	Min. Environment, Water and Natural Resources
Geological map of Kenya, 1987 Edition (1:1,000,000)	1987	Min. Environment, Water and Natural Resources
Geological map of Karasuk area (1:125,000)	1958	Min. Environment, Water and Natural Resources
Geological map of Loiya area (1:125,000)	1959	Min. Environment, Water and Natural Resources
Geological map of Loperot area (1:125,000)	1958	Min. Environment, Water and Natural Resources
Geological map of Lorugumu area (1:125,000)	1959	Min. Environment, Water and Natural Resources
Geological map of Southern Lodwar area (1:125,000)	1959	Min. Environment, Water and Natural Resources
Geological map of the N.Turkana area (1:500,000)	1963	Min. Environment, Water and Natural Resources
Rock samples in the study area	2012	RTI
Mineral samples in the study area	2012	RTI
Soil samples in the study area	2012	RTI

Overall and as a whole, it was found that the maps provide a basic understanding of the main geology of the survey area. Nevertheless, when compared to georeferenced satellite images thanks to modern technology using the American Shuttle Data (SRTM data available since 2004 and Landsat images), RTI observed significant discrepancies between the existing maps and what the satellite images were demonstrating. For example, lithological boundaries were inconsistent by several kilometers. Moreover, the use of the Landsat 7 radiometric indication led to observation of geological formations that the maps did not cover, such as the outcropping Turkana grits formations observed in the field along the South-Western flanks of the basaltic Lothidok range and East of the Muruanachok granitic hills.

Such important information has aided in the discovery of previously unrecorded deep aquifer, such as the Lodwar Basin Aquifer System near Lodwar.

Figure 2.8. Geological Map of Kenya, 1987 Edition (1:1,000,000). Ministry of Environment, Water and Natural Resources, Geological Department, 1987.



Geological and structural context

A large part of the Kenyan geology consists of the Precambrian basement rocks and the Tertiary volcanics that have covered many of sedimentary basins, which are now considered to be potential basins for petroleum exploration. These basins are known to have evolved through the extension of tectonics, leading to continental rifting as a part of the major Gondwanaland breakup in the Late Paleozoic period, a trend that continued during the Mesozoic and Tertiary periods. The region underwent uplift and subsidence, intermittently, along major boundary faults of these basins even in the Miocene period. This movement was accompanied by the stupendous outpouring of the lava flows.

Pre-Cambrian Basement of the Turkana Basin

Lake Turkana belongs to the East African Rift System, which is developed on crust that exhibits a relatively simple history of successive rift and sag basins and was formed during the Paleozoic, Mesozoic and Early Tertiary periods. Precambrian granite and metamorphic rocks dominate the basement rocks of northern and central Turkana region of present-day Turkana County.

Cretaceous-Paleogene Rifting

An extensive rift system from Jurassic origin runs across central Africa, from Nigeria to Kenya, and has been reactivated during the Cretaceous period with episodic active rifting ending in some areas in the Early Tertiary. In northern Kenya, this rift system forms deep basins (6-8 km). The northwest trending Anza Graben terminates on the eastern side of Lake Turkana. The connection between the Anza Graben and the Sudanese Rift, which is inadequately studied, lies probably below the Lotikipi Plain and the Turkana Lake (Figure 2.9).

Figure 2.9. Map of the Cretaceous Rift System. BEICIP, 2001.

Tertiary Rifting

A new rifting episode succeeded the rifting event of the Cretaceous-Paleogene period. This mainly N-S trending rifting phase has been active since the Eocene and is responsible for the creation of a string of asymmetrical half-grabens. The basins are filled with 6-7 km of predominantly clastic sediments eroded from the basement and sedimentary source areas and deposited in fluvio-deltaic and lacustrine environments. The Turkana area shows a N-S trending rifting history that extends from the Paleogene to present day, which is likely to be superimposed on the Cretaceous-Paleogene rifting history of NNW-SSE direction.

A complex history of boundary fault propagation, activation, and deactivation (with some inversions by places) occurs. The basins are filled with basement-derived sedimentary rocks (dominantly sandstones and silts), volcanoclastics and lava flows. Each sub-basin has an independent geological history and facies correlations between them are difficult.

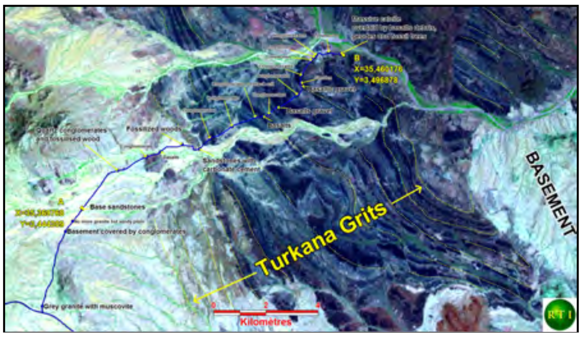
Volcanism

Volcanism is the most prevalent geologic component of the survey area. The phenomenon occurred in three distinct episodes: The first took place in the Early Oligocene (between ~40 and 30 Ma) prior to the initiation of widespread rifting in the Late Oligocene to Early Miocene (~25–20 Ma) and is locally visible in northern Kenya and southern Ethiopia. The second episode of volcanism was a more voluminous phase and took place between roughly 26 and 16 Ma. This magmatic and tectonic episode apparently propagated northward from Kenya into southern Ethiopia, where it is reflected in a volcanic pulse between 20 and 11 Ma), as well as southward into the Kenya and Western Rifts. The third phase of volcanism began in the Plio-Pleistocene (~3·5 Ma) and continues at present; recent magmatism occurs in several punctual areas.

These three volcanism events are spatially overlapping, but are characterized by lavas with distinct geochemical features. The basaltic cover has hidden under it a thick succession of Mesozoic and Tertiary sediments. This trend introduces implicit difficulties for mapping geologic and hydrogeologic features.

RTI has processed the radiometric signatures from Landsat 7 to identify specific morphologic signatures in order to overcome this obstacle. This led to the identification of Upper Cretaceous Turkana Grits formations found hidden under a thin basaltic debris layers as shown in Figure 2.10.

Figure 2.10. Exploration of the Upper Cretaceous sandstones and conglomerates (Turkana Grits). RTI, 2012.

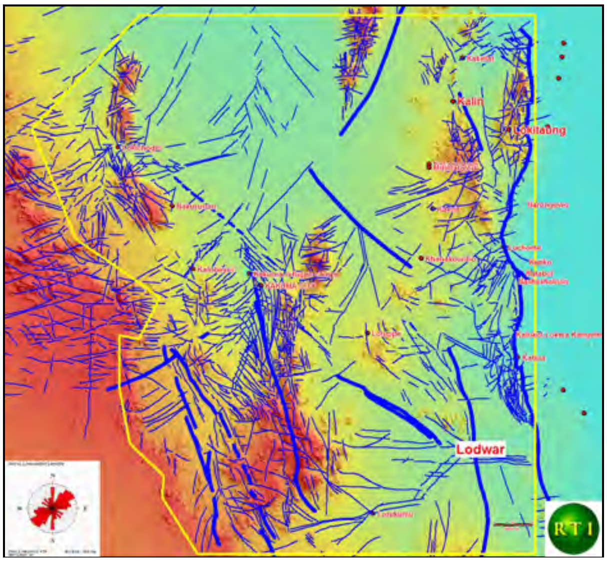


This continental formation is bearing fossilized tree trunks under dark basaltic flows, as observed by RTI and UNESCO in the field in October, 2012. This information introduces some substantial changes to the BEICIP map of 1987.

Fracturation and fissure evalation

RTI identified and mapped regional fracturation by interpreting the slope grid (derived from Landsat-7 and SRTM) and seismic echographies (Figure 2.11). Rifting in the survey area has been greatly influenced by several major North-South trending faults. Some of these major faults have had long periods of activity, or were reactivated. Displacement along the major faults have led to the development of predominantly lacustrine half-grabens or grabens, formed exclusively in a continental setting, which can generate deep aquifers locally.

Figure 2.11. Regional fracturation of northern-central Turkana County. SRTM color coding is also shown. RTI, 2013.



Other major N40°-60° elongated fractures are combined with N120°-N140° structural trends. The N120°-140° fractures play an important role in the delineation of deep basins west of Lake Turkana. In this area of Turkana County, the N-S structural direction manifests a "horse-tail" like fracture system just a few kilometers south of Kakuma, which can be interpreted as a shear-distensive system that has basalts injection along the main open fractures. This phenomenon was observed in the field near the Kakuma Refugee Camp.

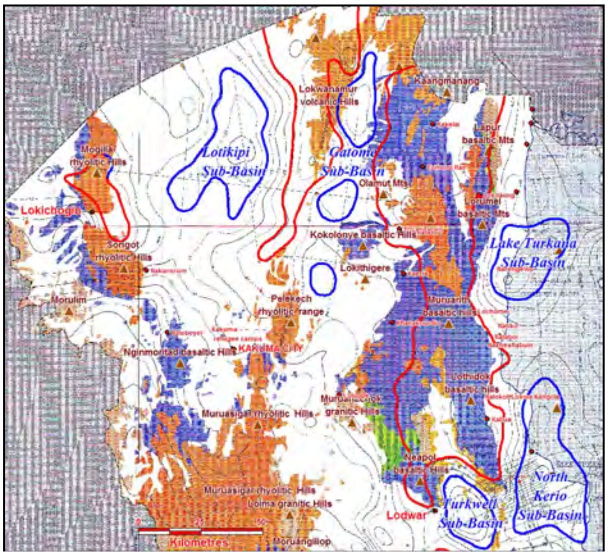
These major fractures are found to influence the creation of the main tertiary sedimentary basins, as was proven subsequently by interpreting seismic echographies. The major fractures were key markers for deep aquifers systems recorded in this survey.

Basement depth evaluation

A key raw input for evaluating basin dynamics was the Bouguer anomaly map published by BEICIP (Figure 2.12). A predominant feature shown by the map is the dense volcanic material covering much of the survey area, which posed a challenge to understanding regional basement trends in terms of sedimentary basins and basement proximity. Nevertheless, RTI was able to identify some interesting basinal trends, mapped as blue polygons superimposed on the BEICIP map: ie., the Lotikipi, Gatome, Lake Turkana, Turkwel and North Kerio basins. All of these basins were found to have Bouguer values over 70 Mgals.

RTI also mapped the shallow basement areas (red polygons on the BEICIP map) which returned Bouguer values under 60 Mgal: ie., the Mogila-Songot Hills area near Lokichoggio, the high axis area between the Lokwanamur and the Pelekech hills, the western banks of Lake Turkana, and the elongated highland area of the Lapur, Lorumel, Muruarith, Lothidok and Neapol Hills.

Figure 2.12. Regional basement depth evaluation. Interpretation of basinal values (blue polygons) and basement indications (red polygons) based on input from Bouguer Anomaly Map of the Turkana region. BEICIP, 2001.



The Uganda escarpment with outcropping granites appears with Bouguer values below 90 Mgal. In general, regions that are associated with large sedimentary basins tend to have thinner crust, whereas ancient orogenic belts appear to have somewhat thicker crust. Gravity highs (in red) are associated with higher density igneous and metamorphic rocks, while gravity lows (in blue) are associated with lower density sedimentary rocks.

2.3. Interpretation of regional hydrology and geology

Having processed the basic raw data inputs, RTI has extracted the relevant features of from derived data and imagery in order to interpret important regional hydrological and geological trends that influence groundwater potential.

Drainage regimes

The watersheds of the survey area (Figure 2.13), including the drainage systems and watershed sub-divisions, were mapped and assessed. This analysis enabled the amount of rainfall in each watershed and sub-watershed to be calculated.

RTI has identified two main watershed systems – the “western” and the “eastern” watershed systems – which together are comprised of ten minor watersheds (sub-watersheds). Each watershed unit has been assessed in terms of area coverage (km2). The Western system flows into the Lotikipi plain and is tributary to Lake Turkana and ultimately the Nile. The Eastern system flows into Lake Turkana. The Turkwel watershed goes far beyond the survey area, and extends over the Kenya highlands and Mt Elgon in Uganda towards the south. Their average slope is 0.56%, which is favourable to alluvial aquifers quality (clean desilted sandstone grains). A detailed analysis of the slopes of each river system offers specificities with important implications on the alluvial groundwater potential of each river. Table 2.5 gives the catchment areas for the key basins of the study area.

Figure 2.13. Regional drainage systems of northern-central Turkana County. RTI, 2012.

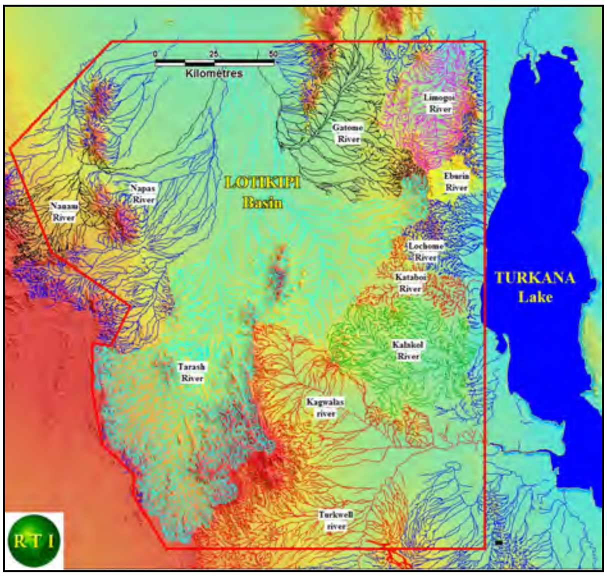


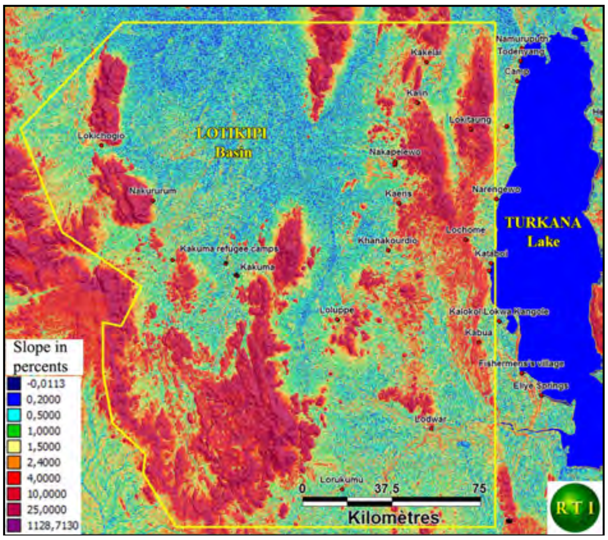
Table 2.5. Watershed systems and their catchment areas

Lotikipi Watershed system and Sub-watersheds	Area (km2)
(1) Tarash-Kakuma sub-watershed	5,168
(2) Nanam-Napas sub-watershed	1,313
(3) Lotikipi sub-watershed	14,000
(4) Kalobeiyei sub-watershed	770
Lotikipi watershed system (all sub-watersheds)	**21,251**
Lake Turkana watershed system and Sub-watersheds	**Area (km2)**
(1) Turkwel-Lodwar	16,516
(2) Kalakol	2,682
(3) Lomogoi	1,465
(4) Kataboi	769
(5) Lochome	423
(6) Eturin	336
L.Turkana watershed system	**22,191**

Watershed dynamics

It has been observed that the eastern slopes of the hills are steeper than the western sides, indicating the “half-graben style” of the structures detected by interpretation of seismic data covering the main structural incidents that characterize Lake Turkana basin.

Figure 2.14. Slope map of northern-central Turkana County. RTI, 2012.



Slopes in the region, as seen in the map derived from the SRTM data (Figure 2.14), remain steep (red) with high relief features, characterized by rugged topography.

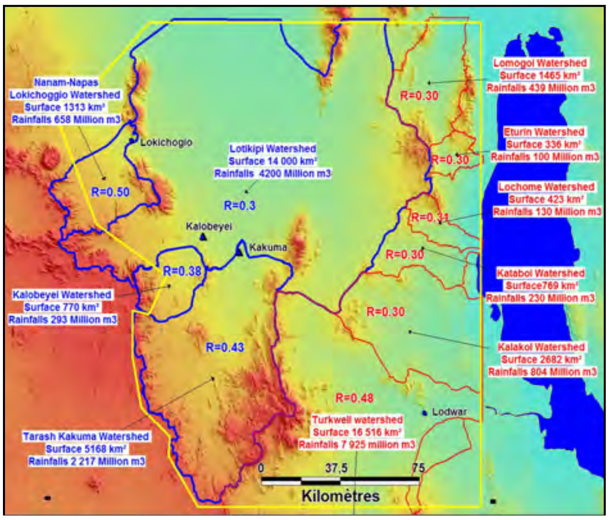
Shallow alluvial aquifers along the Tarash and the Turkwel rivers – watercourses that are controlled by fractures—are saturated and replenished locally. Such a feature is revealed as a bright signature exhibited on the base WATEX© imagery and which will dictate where boreholes and wells should be drilled. Well-sorted alluvial deposits can be anticipated because of comparable slopes lower than 0.56%, which imply good aquifer conductivities on all the alluvial aquifers associated with these river systems.

Watershed distribution and division

RTI has mapped the boundaries of watershed catchment areas within the study area, and calculated the total rainfall harvested per year, or catchment, prior to subtracting evaporation or runoff (seen in Figure 2.15). It is observed that the watersheds in the survey area are naturally oriented towards the four Areas of Interest (AOI): Lokichogio, Kalobeiyei, Kakuma Refugee Camp and Lodwar. The western watershed system and its four sub-watersheds replenishing the Lotikipi Basin (outlined in blue) have a cumulative rainfall harvest of 7.36 BCM/year. The eastern watershed system (outlined in red) replenishes Lake Turkana with a global input of 9.6 BCM/year.

In order to assess the productivity, or efficiency, of each sub-watershed, a ratio of rainfall to catchment area was determined (‘R Coefficient’).

Figure 2.15. Map of watersheds and sub-watersheds of northern-central Turkana County. RTI, 2012.



Watershed productivity

According to the calculations, the Lake Turkana watershed harvests some 2.21 BCM of rainfall/year and has an R ratio (efficiency rating) of 0.43. In comparison, the Lotikipi watershed harvests 7.36 BCM/year with an efficiency rating (R ratio) of 0.35. Such ratios suggest that the Lake Turkana watershed is more efficient than the complete basin (not enough rainfall on most of its surface. It must be stated that the watershed referred to as “Lake Turkana” is the designation given by RTI to describe system (red polygons in Figure 2.15) comprised of the six sub-watersheds near the lake, and do not mean the complete basin of Lake Turkana, which is out of the scope of this study.

One can notice the excellent performance of the Turkwel watershed with a ratio of 0.48 involving important water quantities (7.9 BCM/year). Such a fact can be understood by the size of this watershed that is fed well with rain by the Kenyan highlands upstream.

Overall, 17 BCM of water are harvested annually by the survey area (without subtracting evaporation and runoff).

Table 2.6. Surface area, rainfall rates and Rainfall:Area ratios of watersheds of northern-central Turkana County. RTI, 2012.

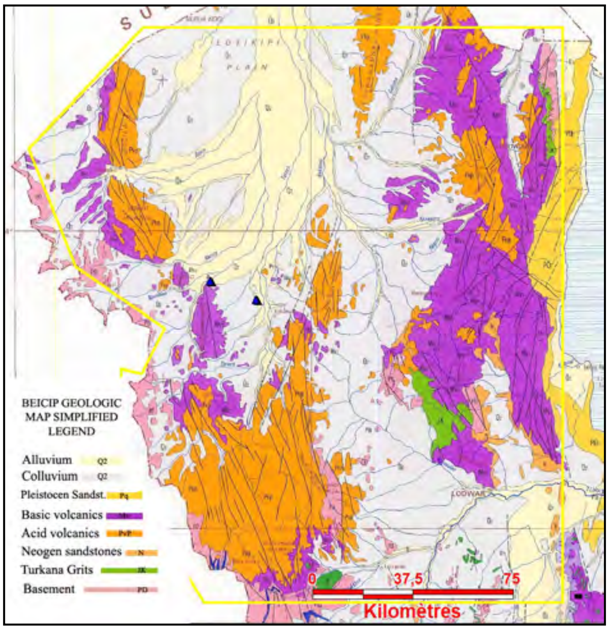
Watershed	(S) Area (km2)	(R) Volume rainfall (MCM/yr)	R / S ratio
(1) Tarash-Kakuma sub-watershed	5,168	2,217	0.43
(2) Nanam-Napas sub-watershed	1,313	658	0.50
(3) Lotikipi sub-watershed	14,000	4,200	0.30
(4) Kalobeiyei sub-watershed	770	293	0.38
Lotikipi watershed system (all sub-watersheds)	**21,251**	**7,368**	**0.35**
(1) Turkwel-Lodwar	16,516	7,925	0.48
(2) Kalakol	2,682	804	0.30
(3) Lomogoi	1,465	439	0.30
(4) Kataboi	769	230	0.30
(5) Lochome	423	130	0.31
(6) Eturin	336	100	0.30
L.Turkana watershed system (all sub-watersheds)	**22,191**	**9,628**	**0.43**

Regional groundwater recharge

The nature of the basement and sedimentary covers plays a crucial role in runoff, recharge and groundwater storage, including groundwater aquifer quality on the head of each watershed. Therefore, it was important to have a reliable geologic map as a result of remote sensing and fieldwork.

The BEICIP geological map of the western Turkana basin (Figure 2.16) was produced from a compilation of a number of geological documents (aerial photo and satellite interpretation, fieldworks, synthesis of regional geological studies, and compilation of previous geological maps).

Figure 2.16. Geological Map of Western Turkana Basin. The main geological formations are shown. BEICIP, 1987.



RTI has interpreted the map to identify the geologic formations that define and influence groundwater recharge in the study area. Those are:

- Crystalline Precambrian basement,
- Oligocene to Pliocene igneous rocks (acid and basic volcanics),
- Arkosic "grits" (Turkana Grits), and
- Paleogene and Neogene sandstones, with a large volcano-clastic component

The Lotikipi Plain in the North covers 30% of the survey area and is a broad depression approximately 110 km wide and is currently being filled by volcano-clastic and alluvial/lacustrine sediments. This subsiding basin is highly favorable to fresh groundwater storage, which has been carefully analyzed in this report.

Recharge Map

Having conducted a full assessment of the recharge potential of the predominant geologic formations, RTI has classified three categories of recharging, or aquifer-replenishing, areas across the survey area: (1) excellent vertical recharge rates (30-35%) due to presence of arenosols, Turkana grits and regolith, (2) good vertical recharge rates (15-30%) due to presence of fluvisols, and (3) low to moderate vertical recharge rates (< 15%) due to presence of aquicludes, basement, and volcanism. Combined with the assessment of regional fracturation, this information is important for understanding overall recharge potentials in any given location in the study area.

These trends have been represented in the Groundwater Recharge Map of Northern-Central Turkana County shown in Figure 2.17.

Figure 2.17. Groundwater Recharge Map of Northern-Central Turkana County. RTI, 2013.

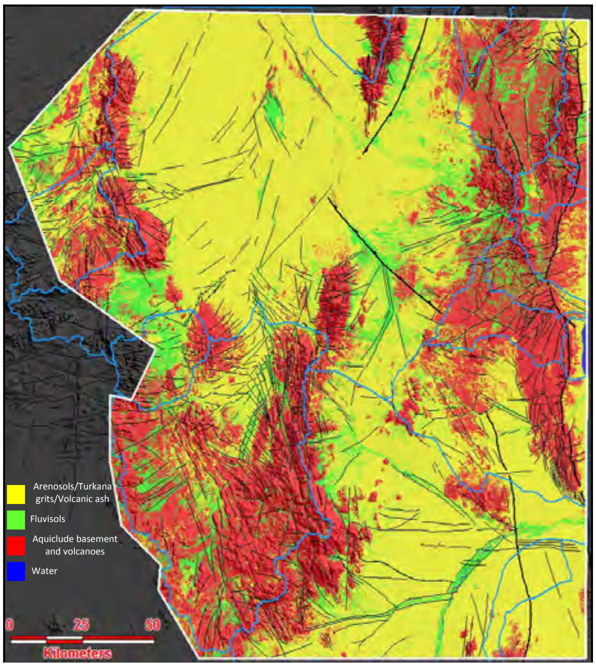
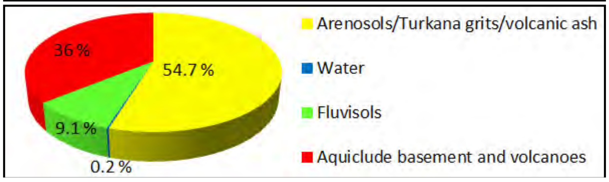


Figure 2.18. Legend of the Groundwater Recharge Map of Northern-Central Turkana County. RTI, 2013.

Recharge map legend.

Intergranular recharge		Alluvial deposits : gravel, sand silt clay. Excellent recharge rate due to high Silica content from weathered basement porosity : 15 to 30%
Intergranular recharge		1-Arenosols from basement erosion 2-Sandy alluvial and windblown deposits 3-Piedmont regoliths 4-Turkana grits Paleogen and neogen sandstones 5-Volcanic ash deposits Global porosity : 30 to 35% vertical recharge
Fracturation		Conductivity of alluvial, cemented Turkana grits and volcanoclastic deposits increased by fractures
Aquiclude		1-Basement 2-Basaltic flows and rhyolitic formations Low to moderate porosity due to weathering



Regional trends can now be extracted from the new Recharge Map. For example, most of the survey area is conducive to good groundwater recharge, with intergranular recharge zones covering 63.8% of the survey area. This can be explained by the close proximity of the basement in those areas, the presence of base Paleogene /Neogene sandstones and acid volcanic formations which have been eroded and transported by runoff and wind.

Such a context confers the survey area an exceptional groundwater recharge potential. This recharge potential is sustained by a dense fracture pattern, porosity levels of

12 to 30% and permeabilities of 20 to 500 mD. The volcanic hills and locally outcropping basement can be considered as aquicludes.

Recharge estimations

In the absence of reliable data on evapotranspiration and temperature for the survey area, it is nearly impossible to estimate the groundwater recharge rate of each individual aquifer in the survey area, in particular for the shallow alluvial aquifers (0-80m depth range), even in spite of the highly favorable character of the surface geology and the presence of numerous fractures that should reduce runoff and evaporation considerably. This appears to be the case of alluvial aquifers associated with the Tarash River, a seasonal river flowing northward through Kakuma, which drains an estimated 2.2 BCM/year.

Using the *rule of the thumb* method, we can globally consider the survey area covering 36 000 km² is harvesting globally 17 BCM per year. Some 63.8% of the survey area, which is permeable and favorable to vertical recharge, should retain 20% of the rainfall volume, or 2.16 BCM of water recharge. Another 36% of the survey represents the main aquicludes surface and should retain only 10% of the rainfall volume through the dense fracture pattern which represents only 612 MCM of water.

Therefore, we can conclude that the survey area harvesting annually 17 BCM of water has global annual recharge capacity of 2.77 BCM, which represents only 16.3% of the total rainfalls harvested on 36,000 km². This factor of 16.3% has been selected for each watershed and sub-watershed to compute their specific recharge capacity as shown on Table 2.7.

Figure 2.19. Alluvial plains near the Tarash River during the rainy season, December, 2012. The dry riverbed that stretches on the background is bordered by agricultural alluvial terraces. Notice a rhyolitic (volcanic) plug in the foreground. RTI, 2012.

Table 2.7. Recharge capacity potential of watersheds of northern and central Turkana County. RTI, 2013.

Watershed	(S) Area (km2)	(R) Volume rainfall (MCM/yr)	R / S ratio	Recharge capacity (MCM/yr)
(1) Tarash-Kakuma sub-watershed	5,168	2,217	0.43	361
(2) Nanam-Napas sub-watershed	1,313	658	0.50	107
(3) Lotikipi sub-watershed	14,000	4,200	0.30	685
(4) Kalobeiyei sub-watershed	770	293	0.38	48
Lotikipi watershed system (all sub-watersheds)	**21,251**	**7,368**	**0.35**	**1,201**
(1) Turkwel-Lodwar	16,516	7,925	0.48	1,292
(2) Kalakol	2,682	804	0.30	131
(3) Lomogoi	1,465	439	0.30	72
(4) Kataboi	769	230	0.30	37
(5) Lochome	423	130	0.31	21
(6) Eturin	336	100	0.30	16
L.Turkana watershed system (all sub-watersheds)	**22,191**	**9,628**	**0.43**	**1,569**

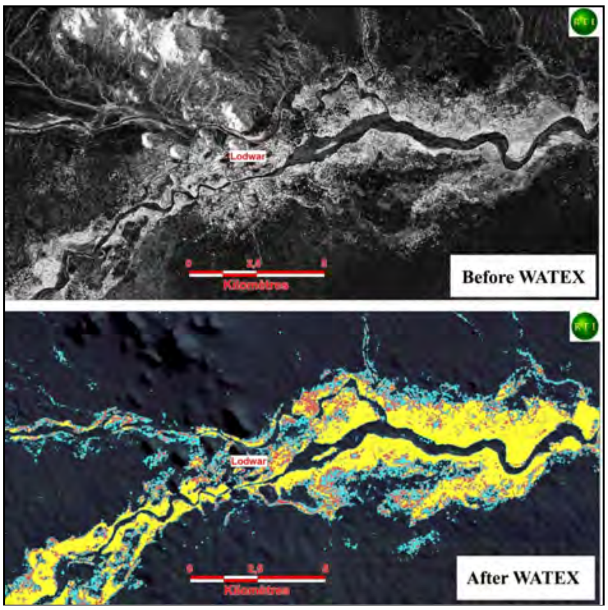
2.4. Generation of WATEX exploration imagery

This section summarizes a key stage in processing survey data – the WATEX processing. WATEX processing is an essential building block of the modeling stage that will ultimately inform the final maps and analysis. It integrates the interpretation of extracted features from the raw datasets (described above) with processed satellite imagery in order to generate new WATEX images that enable advanced capabilities in exploring groundwater. This method has been applied to identify and map water in a wide range of contexts and regions around the world since 2004.

Detection of shallow aquifers

RTI has applied the WATEX© process to the complete survey area in order to reveal buried aquifers. Figure 2.20 shows the area near Lodwar before and after processing. The top image is a raw, unprocessed radar image showing black and white responses, which are surface features. No groundwater is visible. The image below is a WATEX image of the same area after being treated by WATEX processing. All surface obstacles have been removed and the soil moisture at 20-40 meters depth has been revealed as a bright anomaly. Areas with dryness or minimal groundwater at 20-40 meters have also been shown as a dark signal.

Figure 2.20. Before and after WATEX processing. Comparison of raw unprocessed radar imagery (above) and a WATEX base image (below) of the same area. Bright, colored anomalies on WATEX base image are an indication of groundwater occurrence in shallow depths (0-80 meters). RTI, 2013.



WATEX© processing also removes bright features on the surface linked to soil roughness and enhances the most subtle moisture features that leads to modeling the potential of groundwater with high certainty and accuracy. The rugged landscape of volcanic hills that surrounds Lodwar has been eliminated from this image. The black areas are totally dry from surface to 80 m, but can hide other deeper potential aquifers underground revealed by discharges along fractures within basinal areas such as the Lokichar basin, Lotikipi plain and the Gatome Basin. Seismic lines have been used in this survey to detect these deep aquifers, as a complement of the radar imagery survey. WATEX base imagery provides a powerful tool for both exploration of regional groundwater, but also practical tool for planning the drilling of shallow wells with the greatest confidence.

WATEX method for hydrogeological investigation

The early phase of analysis involves mapping features which directly (or indirectly) affect the likelihood of finding large, renewable reservoirs such as the geologic context, the weathering processes, vegetation cover, watershed boundaries, slopes and river profiles to estimate energy level of transportation along *wadi* (i.e. riverbed) courses. All of these features can determine accretion or erosion impacts upon reservoir thickness and productivity and have been discussed in greater detail in former chapters.

Size and shape of WATEX bright anomalies

For alluvial aquifers, the assessment of the size of the radar anomaly is an indicator of the water storage volume. An aquifer with a sustainable production to support a community of 20,000 persons during a year implies the need to find a buried reservoir with an overall productivity of nearly 100,000 m3/year. Assuming permeable rocks with porosity of 10%, this is equivalent to a *wadi* reservoir of about 2,000 m long and 60 m wide, assuming a reservoir thickness of 7.5 m at an average depth of 10 to 15 m from the surface.

Accordingly, only WATEX© anomalies covering a minimum surface of 12 hectares (2,000 m x 60 m) must be considered in order to meet the above project goal.

At this stage of the WATEX© process, it is almost impossible to know if anomalies are associated with buried reservoirs versus surface moisture linked to clay or silts deposits. RTI applies additional analysis to be able to make that distinction.

Volume of upstream watershed drainage

Since each potentially suitable target must also be fed by an upstream watershed capable of supplying at least 1 MCM/year of water to the reservoir. The watershed surface area and average annual rainfall are used to estimate total yearly catchment, which is then corrected for evaporation, erratic runoff, and other water losses.

Geology of aquifer formations

Alluvial aquifer potential depends on the nature of sediments since the origin of these sediments determines the alluvial aquifers ability to reliably absorb and store sufficient water volumes. It is necessary to discriminate between “reservoir feeders” vs. “reservoir poisoners”. For example, basaltic rock types can create excessive clay and colloids that will reduce reservoir porosity and permeability, and are therefore referred to as “reservoir poisoners”.

Alternatively, “reservoir feeders”, such as quartzite and sandstone, can produce gravels that are ideal for storing large volumes of quality water storage. Intergranular and karsted aquifers quality depends on their geologic origin, structural history and diagenetic conditions through time. Thus, it is essential that the geological context be carefully mapped and understood.

Major fault structures

A linear river system controlled by graben-like structures is more likely to be old enough (ranging from several thousand years old to a million years old) to contain thick and multi-layered reservoirs, particularly if it sits downstream a well rain fed area.

Slopes and dips

For alluvial aquifers, the optimum riverbed slope is between 0.1% to 0.4% in order to ensure sufficient vertical recharge of alluvial aquifers within wadi courses. Very gentle slope or flat would result in a silt accumulation, compromising its ability to store sufficient water reserves.

Too steep of a slope might result in a reservoir prone to erosion of gravel bed that is essential for recharge during the rainy season. Most of the rivers reaching the Lotikipi Plain and the Turkana Lake, for example, have an average slope of 0.2%, thus confirming their great interest regarding their alluvial aquifers all along their course. The slope and the dip of intergranular and karsted aquifers will also control the recharge and transit time of the groundwater flows.

Once the five parameters listed above are satisfied, it is then possible to detect and make an overall assessment of the most promising alluvial aquifers. In order for these areas to be suitable for human settlement, RTI considers the implications of settlement near areas of existing cattle ranching, crop farming, and indigenous settlement. Sites that are close to roads, agricultural land and wood fuel sources are prioritized.

Environmental impact studies are essential for sustainability. Aquifers with high suitability are then examined to ensure close proximity to a suitable platform, since we recommends that new settlements be within 500 meters of at least one water point (The Sphere Project 2004). A more comprehensive survey of environmental drivers of groundwater quality in the region will be needed in the future.

Conductive fractures

An additional feature of the WATEX processing is its ability to detect fractures that store and convey water. Similar to alluvial groundwater, water-bearing fractures are detected by the WATEX process as a bright anomaly. The WATEX imagery captures this as a yellow line mapped on the region. Such fractures, in a sedimentary environment, are important indicators of deeper aquifers, but can be targeted by drillers to access shallow groundwater. Nevertheless, these fractures should lead to deeper and more prolific aquifers in specific geologic and structural context.

2.5. Hydrogeological modeling

The WATEX System enables unique capabilities in mapping complex groundwater systems with a high magnitude of certainty thanks to the generation of groundwater models. While no model can be 100 per cent correct, the goal of such models was to minimize the unknowns about the occurrence and extent of groundwater and to represent the actual systems as closely as possible.

RTI has implemented two hydrogeological models for this survey – one for shallow alluvial groundwater (SAGOM) and one for deep aquifer structures (DAM). Each model has its distinct concepts of groundwater that can be mapped independently, and layered conjunctively for GIS application and mapping. These models are based on the processed data and the WATEX base imagery, discussed previously.

Model limitations

As for every model, it is important to acknowledge the limitations of RTI's groundwater models. Both models – the SAGOM and DAM – are models of spatial distribution: They depict location and extent of water occurring below the surface. Though they aid in making certain judgments about potential yield of an aquifer, they do not predict precise yield quantities or other hydraulic attributes, which must be ascertained through long-term monitoring and well drilling. This means that while the models predict occurrence of groundwater at a given location and take certain parameters of geology into account, it does not predict the nature of water-bearing geological systems that may influence hydraulic performance or the performance of borehole drilling equipment. Users of the tools developed with the results of these models, such as the maps, database or GENS, are solicited to combine them with other maps and information on geology, soils and recharge in order to achieve a more complete hydrogeological assessment of a given area.

As is standard for technologies that are based in part on indirect observation methods and which presents information in GIS format, the WATEX System assumes the errors and limitations associated with those technologies. The models therefore are subject to the well-known array of limitations of remote sensing and GPS, such as the accuracy of satellite sensors, errors in processing and temporal variability.

As an imperfect model of complex groundwater systems, the WATEX models (SAGOM and DAM) recognize a difference between their predictions and reality. The imperfections and unknowns of the models are acknowledged as the various limitations compounded by technological and human error. This error in accuracy, or uncertainty, is an important measurement of the usefulness of the model.

Shallow Alluvial Groundwater Occurrence Model (SAGOM)

Model description

The objective of the Shallow Groundwater Occurrence Model (SAGOM) is to represent groundwater that is hydrologically connected to river channels or flood plains on the surface, and that which is, in general, stored unconfined in permeable geologic material from the surface to an approximate depth of 80 meters. The model also conceptualizes within the same depth range conductive fractures, or groundwater occurring in the fissures, joints, bedding planes and cavities of rock masses. Together, these shallow systems are available for development at the localized scale for a variety of uses such as small-scale irrigation, domestic and municipal water supplies and livestock watering. The shallow unconfined nature of this groundwater is characterized by downward, more direct recharge from rivers and drainage pans and connects them to surface ecosystems. However, these aquifers are often exposed to varying recharge and pumping rates. Shallow alluvial aquifer systems also tend to be susceptible to contamination and pollution.

RTI designed the SAGOM specifically to provide valuable information for assessing the groundwater potential of a given area and to serve as a tool for those planning projects that depend upon these systems, especially when no alternative water supply is available at the surface – a condition that is common in Turkana County.

The model describes the spatial distribution – the physical location and extent – of these systems. Location and extent are expressed as digital square pixels on the WATEX Groundwater Target Map. The pixel resolution is 6.25 meters wide by 6.25 meters long, representing a surface area of 39 m^2. Every pixel has been assigned a precise geographic address according to the Global Positioning System WGS84 format.

Groundwater occurrence potential classification

The model predicts the occurrence of groundwater at the exact location of each pixel and assigns a positive or negative value to each (Figure 2.21). Pixels with a positive value have a strong illumination and color, representing the occurrence of groundwater at that location. The different positive bright colors represent varying degrees of occurrence potential (Table 2.8). Pixels with a negative value have a weak illumination and dark or black color, representing the absence or minimal occurrence of groundwater at that location.

Figure 2.21. Example of close-up of SAGOM pixel radiance values and scales. RTI, 2013.

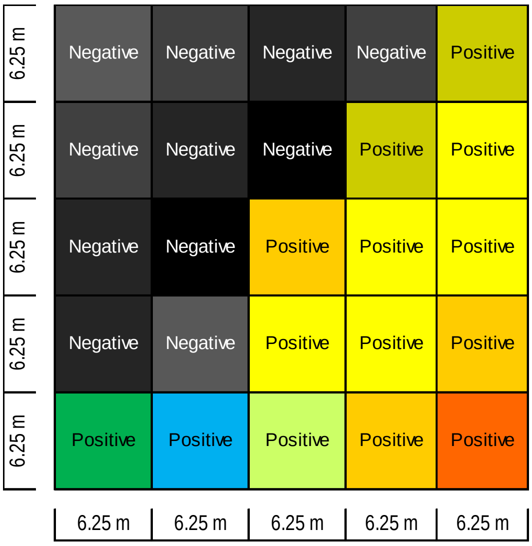


Table 2.8. SAGOM categories of shallow groundwater occurrence potential, 0-80 meter depth. RTI, 2013.

Pixel color	Groundwater occurrence classification
Yellow	Minimum of 90%. These pixels represent fracture discharges in alluvial sediments, or pure alluvial aquifers.
Red	75% probability of aquifer presence if combined with a conductive fracture.
Light blue	30% probability of aquifer presence if combined with a conductive fracture.
Green	25% probability of groundwater occurrence, located over hills and mountains. Wells in these pixels should only be drilled with the presence of a conductive fracture
Black / dark	0-5%, minimal occurrence potential, likely to be dry or have little potential for groundwater occurrence.

Figure 2.22. Example of SAGOM representation of shallow aquifers in the Lotikipi Plain. RTI, 2013.

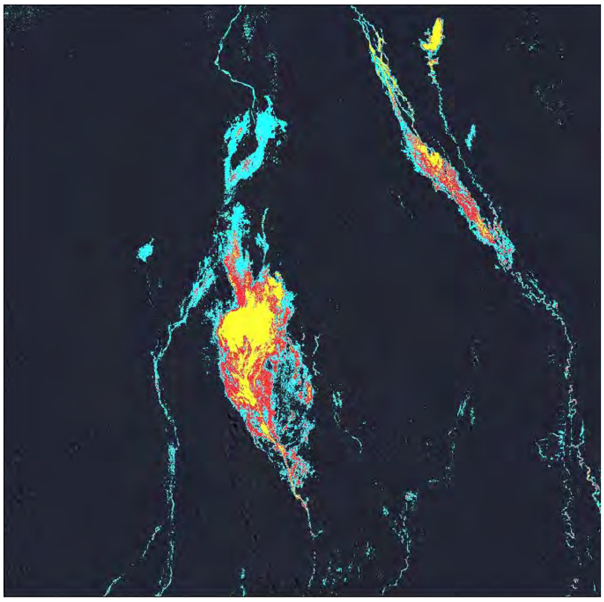
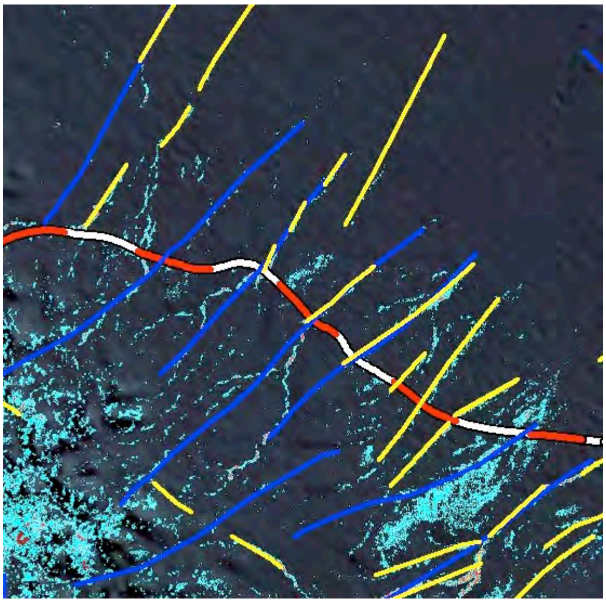


Figure 2.23. Example of SAGOM representation of conductive and non-conductive fractures. Conductive, water-bearing fractures are modeled in yellow. Dry, or low-conductive fractures are modeled in blue. RTI, 2013.



Model (SAGOM) results for shallow hydrogeology of northern-central Turkana County

Alluvial aquifers cover an cumulative area of 3,276 km2 and represent only 9.1% of the whole survey area. However, of these aquifers, the WATEX Process is able to distinguish which of these aquifers are productive and those which are not. It does this by determining, within the boundaries of the alluvial deposits, where are the most prolific alluvial aquifers. In Turkana, the Turkwel is the only perennial river as most of rivers runoff is quickly captured by fractures.

All the aquifers in northern and central Turkana County can be replenished by the normal course of the river by vertical recharge, but also by deep seated fractures especially along major structural corridors like in Kakuma, which structure the course of the river.

Figure 2.24. WATEX-SAGOM result of regional shallow alluvial aquifers in northern and central Turkana County. RTI, 2013.

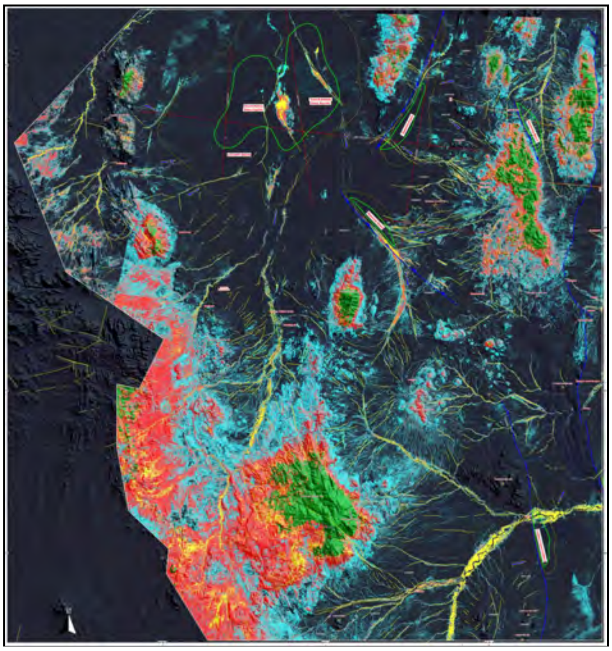
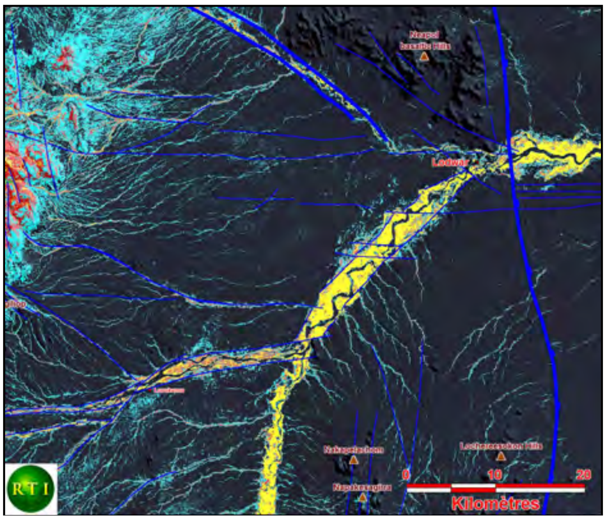


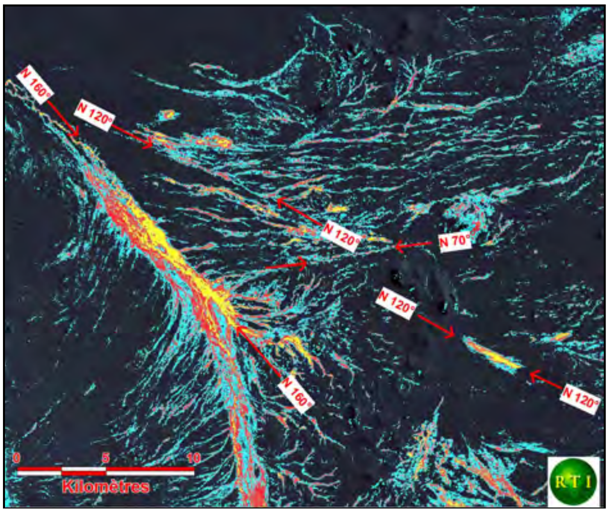
Figure 2.25. WATEX-SAGOM image showing shallow alluvial aquifers near the Turkwel River. Shallow alluvial aquifers are prolific (yellow and blue). RTI, 2013.



A linear river system controlled by graben-like structures is more likely to be old enough (several thousand years to million years) to contain thick and multi-layered alluvial aquifers, particularly if it sits downstream from an area that receives good precipitation.

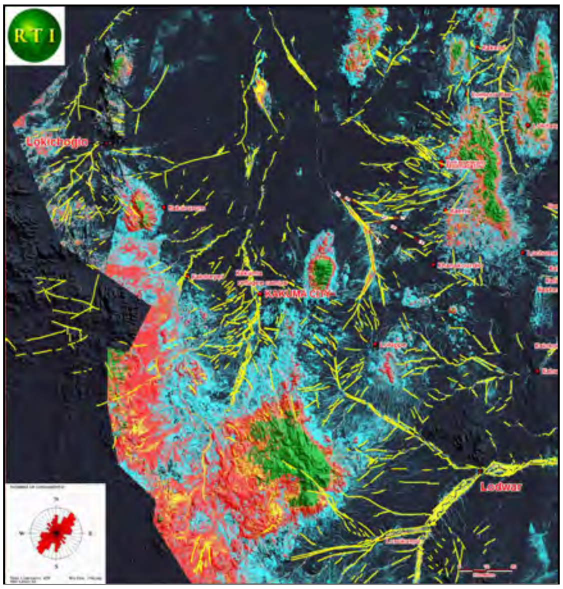
Moreover, when such rivers are connected upstream to a broad watershed fed by substantial rainfalls quantities in a favorable geologic context, with slopes higher than 2/1000, we can expect broad alluvial aquifers with good productivity even along river segments with poor radar response (dark), it means that an aquifer lays below 20 meters, which might be the case for the course of the Turkwel, upstream Lodwar.

Figure 2.26. WATEX-SAGOM results showing conductive fractures. Major conductive fractures 25 km northeast of Pelekech Hills are shown. The WATEX image shows 3 major structural directions enhanced by the effects of their discharge along N-160 and N70 fractur systems. RTI, 2013.



The SAGOM shows a main conductive fracture N160° that reveals deeper aquifers discharging. These aquifers were confirmed by seismic data. A shallow well through these conductive fractures will access freshwater almost from the surface, but drilling deeper should provide access to huge quantities of clean fresh water, in a more sustainable way.

Figure 2.27. Map of fracture systems of northern and central Turkana County. RTI, 2013.



As seen in Figure 2.26, the fractures which convey groundwater to the surface can be drilled with shallow wells and can be considered as water targets. Nevertheless, they also indicate the presence of deeper aquifers in a specific geologic and geomorphologic context and should indicate where to drill deep wells in order to access the main source of discharge that must be within deep-seated basins.

A general trend in northern-central Turkana County is that the conductive fractures with orientations of N160° and N120° should be more prolific than N70° fractures due to better orientations that are influenced by N-S shear distensive of the rift opening direction.

Deep Aquifer Model (DAM)

Model description

RTI's WATEX-based model for exploring deep hydrogeology, the Deep Aquifer Model (DAM), aims to represent groundwater regimes that are, in general, stored confined or semi-confined in permeable geologic material from 80-100 meters to an approximate depth of 3,000 meters or more. These systems are generally very large in volume and surface area than shallow alluvial aquifers, have a more consolidated geometry, are, for the most part, available for development at much greater scales, and can sometimes be classified as reservoirs with national and strategic importance. Such systems generally have multiple aquifer stratification. Each can be studied independently if sufficient data exists. In cases where the DAM records a previously undocumented aquifer, the DAM representation of the aquifer serves as the starting point for studying the characteristics of the aquifer system.

DAM was designed specifically to provide valuable information for assessing the groundwater potential of individual deep aquifer systems and to serve as a tool for those planning projects that depend upon these systems. The model describes the spatial distribution – the physical location and extent – of these deep systems. Location and extent are expressed as two-dimensional polygon shapes. However the exact geometry of the aquifer is given as an extrapolation of RTI interpretation. Every polygon has been assigned a precise geographic address according to the Global Positioning System WGS84 format.

Model (DAM) results for deep hydrogeology of northern-central Turkana County

RTI has run the WATEX model DAM for the survey area and has observed and assessed two categories of deep aquifer structures in the region: (1) shallow and deep basement aquifers and (2) Discharging fracture aquifers.

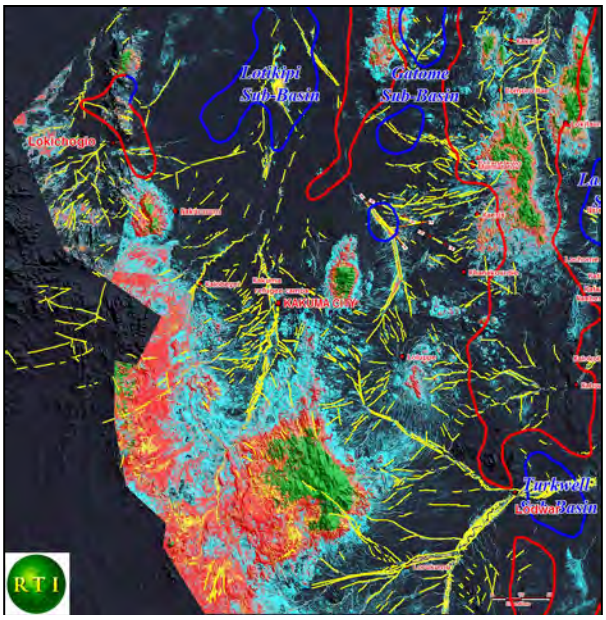
Shallow basement areas (less than 100 m deep) tend to retain more moisture than deep-seated basement areas for several reasons: Firstly, weathered basement rich in clay retain a lot of moisture detected by WATEX©. Secondly, shallow basement preserve river aquifers near the surface (less than 50 m) and are revealed by bright WATEX© signal (for example near the Turkwel River).

As a result in shallow basement areas, the radiometric values of the WATEX© image are higher than in deep-seated basement areas, which are darker.

Deep-seated aquifers located within a rift context are generally structured by deep-seated fractures. If the deep aquifer is active and recharged permanently, these deep-seated fractures tend to discharge to the near surface and can be detected on the WATEX© image.

A close look to the WATEX© target map indicates that the Lotikipi Basin and Lodwar areas could host deep-seated aquifers. This analysis is confirmed by gravimetric data as shown below (Figure 2.28).

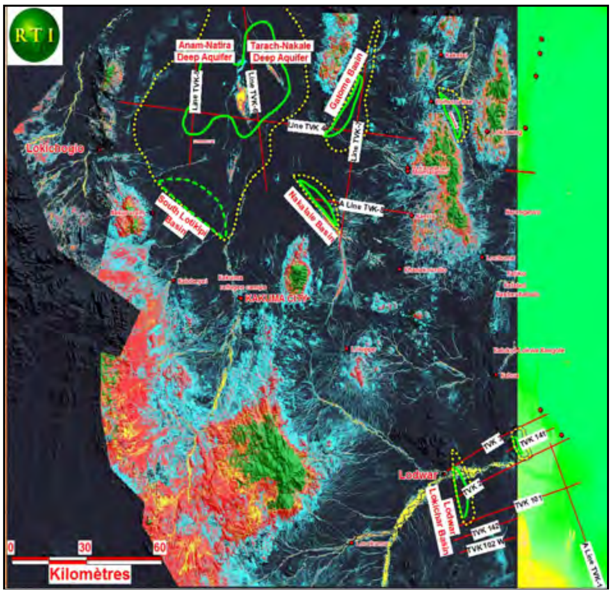
Figure 2.28. Deep seated basins of northern-central Turkana County. The image is a WATEX image overlaid by interpreted gravimetry data. Blue polygons are deep-seated basins. Red polygons correspond to shallow basement. RTI, 2013.



Confirmation of deep potential aquifers using seismic lines

The survey obtained data of 12 seismic lines located over the dark WATEX© area were bought to NOCK and interpreted by RTI.

Figure 2.29. Map of deep aquifer systems of northern and central Turkana County modeled by the DAM. RTI, 2013.



The interpretation of seismic lines (mapped in red lines in Figure 2.28) has revealed five deep-seated structures that could be important aquifers. These aquifers will be assessed further in the next chapters. UNESCO has implemented a scientific drilling campaign in 2013 in order to confirm the validity of the DAM model of these aquifers, thus confirming the existence of these aquifers, which have not been recorded before by prevailing science, thus constituting an important exploration discovery.

Table 2.9. Deep aquifer systems identified by the study. These aquifers have not been recorded by science prior to this study. RTI, 2013.

System	Comments
Lotikipi Basin Aquifer	Comprised of the Anam-Natira sub-system, Tarach-Nakalale sub-system and South Lotikipi sub-system
Nakalale Basin	Part of the eastern basin
Gatome Basin	Part of the eastern basin
Kachoda Basin	North East between Lapur Range and Pelekech Hills
Lodwar-Lokichar Basin	Lokichar Basin on the South-East of the survey area

3. Assessment of Groundwater Potential of Northern-Central Turkana County

3.1. Introduction

This study takes an exploratory approach to surveying and describing naturally occurring resources at a large scale. The core methodology of this study has been described in the previous chapter. It entails methods of observing these systems both indirectly (WATEX System) and directly in the field, then modeling these systems so that they can be mapped with high certainty. RTI has processed an input dataset which includes raw satellite imagery and regional hydrogeological data to generate base exploration imagery (WATEX images). These images make up the building blocks of models of shallow and deep groundwater systems. The outputs of the models give an accurate depiction of groundwater in northern and central Turkana County, which can then be validated, mapped and assessed.

Objective of this chapter

This chapter sets out the essential guidelines for individual classes of aquifers that will assist in assessing groundwater potential. It then provides a more detailed assessment of the groundwater potential specific to the four Areas-of-Interest (AOIs), which is intended to provide results directed to managers and technicians concerned with those areas. An attempt to provide an estimated inventory of regional groundwater resources is presented as a key indicator of development potential. It is intended that such a figure can help guide strategic decisions about developing the country at the regional and national scale. The chapter concludes by suggesting a few directions for groundwater extraction and recharge as well as some concepts for agricultural development based on the survey results.

3.2. Categories and specificities of aquifer potentials

RTI has assessed three categories of groundwater in northern and central Turkana County: shallow alluvial aquifers (0-80 m), conductive fractures, and deep-seated groundwater including deep aquifer structures (deeper than 80 m). It is important at this stage of assessment to give the major guidelines applied to each category.

Shallow alluvial aquifers

Alluvial aquifers at a depth range of surface to 80 m have a high-potential of aquifer occurrence (95% potential). Overall, this category of groundwater potential has a total regional area of 3,240 km². High-potential alluvial aquifers make up only 9% of all alluvial aquifers in the survey area.

With a conservative assumption of an average thickness of 5 m cumulated aquifer and a minimum porosity of 10%, this category of aquifer has a total storage capacity of 1,620 MCM, which represents an average of 0.5 MCM per 1 km².

Conductive fractures

Fissures and fractures in the region can be highly conductive and store and convey significant volumes of water. The fractures in this part of the Turkana Basin are a concrete expression of the shear-opening activity caused by the rift fault system. They convey significant groundwater quantities both horizontally and vertically underground, and discharge from deep aquifers towards the surface. With precise information on their location and conductivity – information provided by RTI in the base WATEX Groundwater Target Map – shallow boreholes and wells can be drilled successfully into the narrow faults and fractures with minimal risk. In addition to indicating shallow groundwater potential, fractures can also indicate the presence of deeper aquifers in a specific geomorphologic context.

Regardless of the plethora of conductive fractures identified by this survey (See Figures 2.11 and 2.27), to assess the total overall potential of groundwater of these fractures would be futile to predict since this would require field data from each individual fracture. The best guideline that can be given about fractures is that extraction efforts should focus on the fractures of the shear-distensive along the Rift Fault system having an orientation of 45°N, which will have significantly higher yields than those fractures oriented from 120° N to 160°N.

Deep-seated groundwater and aquifer structures

The potential of deep-seated structures were assessed. Previously unrecorded structures of the Eocene Age have been recorded in the course of this survey, which are several kilometers deep. For reasons associated with the economy and mechanical limitations of drilling boreholes in Kenya, this assessment has focused on assessing the hydrogeological value of only the shallowest 600 meters of the youngest (recent) sediments. Consisting of fluviatile, fluvio-deltaic and lacustrine sandstones, these Post-Middle Miocene sedimentary structures are present across the survey area. Red beds, volcanic levels and claystone are common.

Porosity of these structures is very high, between 20 - 35% in the best reservoir levels. A major risk to exploiting these deep-seated aquifer structures is the presence of more recent basaltic flows dating from the Plio-Pleistocene (~3·5 Ma) up to present day, and occur in shallow depths as outcropping plugs or inter-layered basaltic sheets. This report advises that when encountering such basaltic layers, well drilling should continue through basaltic formations in order to reach the high potential deep-seated aquifers below.

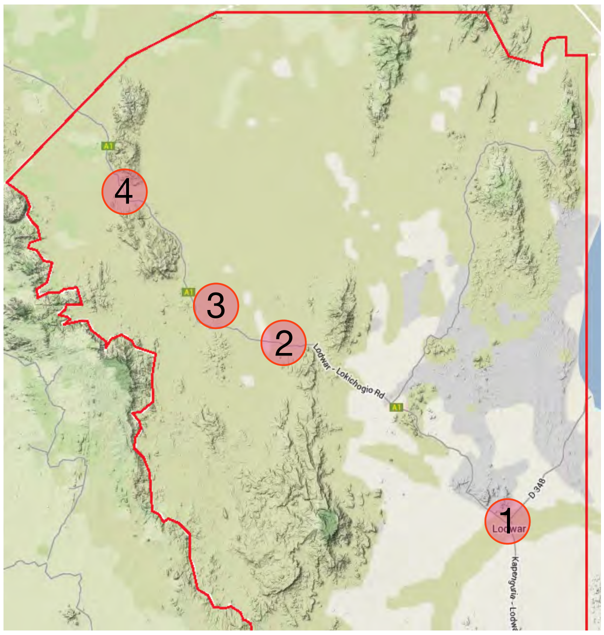
The deep-seated aquifers, evaluated down to 600 m along the lithologic column, are assessed to have a cumulated aquifer of 200 m or more and average porosities of 25%. This represents a total groundwater potential of 50 MCM per km², 100 times more than the shallow aquifers described before.

3.3. Assessment of groundwater potential

The potential of groundwater within the key areas of priority – the Areas of Interest (AOI) – prioritized by the Government of Kenya and UNESCO for this survey has been assessed. (See figure 3.1 for location of AOIs). Lodwar (AOI-1), is situated in the Turkwel River Basin, and envelopes a major urban center hosting a population of approximately 20,000 persons. Kakuma (AOI-2), Kalobeyei (AOI-3), and Lokichogio (AOI-4) are part of the large Lotikipi Watershed. Kakuma (AOI-2), with its three refugee camp components, is the most populated area in Turkana, hosting an average of 500,000 persons. Kalobeyei (AOI-3), selected for its potential location for a future refugee camp annex to Kakuma, currently has a population of approximately 2,000. Lokichogio (AOI-4), a second urban center in the survey area, is a significant post on the major corridor linking South Sudan and Kenya, hosting a large migrant population and nomads from Turkana.

Below, the assessment of groundwater potential begins with an examination of the parent watershed systems within which the four AOIs are hosted. The potential of each AOI is then assessed individually, including discussion on the local hydrogeological context and the potential of alluvial and other groundwater resources.

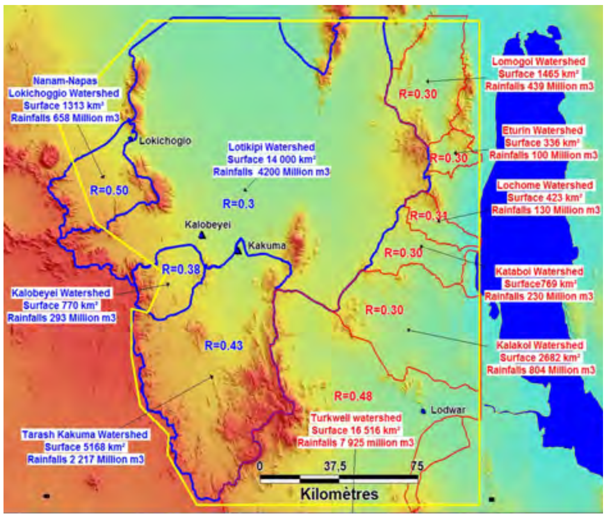
Figure 3.1. Location of four AOIs in the survey area. (1) Lodwar, (2) Kakuma, (3) Kalobeyei, (4) Lokichogio. RTI, 2013.



Assessment of parent watersheds

The four AOIs are situated in two distinct parent watersheds as shown Figure 3.2.

Figure 3.2. Watersheds tributary to Areas of Interest. The Lotikipi Basin watershed is labeled in blue, and the Lake Turkana watershed and sub-watersheds are labeled in red. RTI, 2013.



Lodwar (AOI-1) is situated in the Lake Turkana Watershed (red outline) which is divided into six sub-watersheds and has a total overall input to the Lake of 9.6 BCM/year (without removing runoff and evapo-transpiration).

Kakuma (AOI-2), Kalobeiyei (AOI-3), and Lokichogio (AOI-4) are situated within the large Lotikipi Basin Watershed (blue outline) of 21,251 km², which is divided into four sub-watersheds, and has a total overall contribution of 7.36 BCM/year (without removing runoff and evapo-transpiration).

The "R-Coefficient" of Rainfall—Surface ratio has been calculated for each sub-watershed, giving a measurement of efficiency of each. (More details of each watershed are discussed in the Technical Field Manual for Groundwater Targeting tailored to northern and central Turkana County.)

Table 3.1. R-coefficients of the watersheds tributary to the AOIs. RTI, 2013.

Sub-watersheds	R-S Coefficient (R)
Lotikipi Basin System:	
(1) Tarash-Kakuma sub-watershed	0.43
(2) Nanam-Napas sub-watershed	0.50
(3) Lotikipi sub-watershed	0.30
(4) Kalobeiyei sub-watershed	0.38
L. Turkana System	
(1) Turkwel sub-watershed	0.48

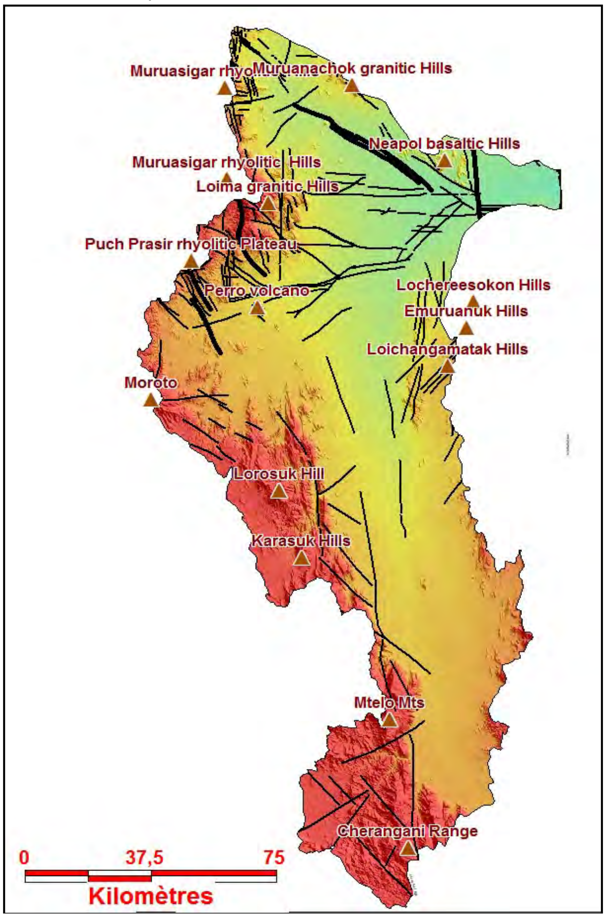
RTI has carefully scanned and processed each sub-watershed by the WATEX© process in order to detect the potential aquifers ready for drilling, taking into account, whenever possible, their specific conductivity, chemical content and recharge process. It is underscored here that the model presented herein is based mainly on indirect scientific approach and some existing borehole data. Therefore, further refinement of this model would necessitate additional field data generated by the drilling of new boreholes.

Groundwater potential of Lodwar

Hydrogeologic context

The Turkwel River Watershed is the largest within the survey area, extending far beyond its southern limits. The river originates in the Ugandan highlands at an elevation of 4,300 m near Mount Elgon, and flows down to 500 m elevation in Lodwar. The Turkwel River watershed receives some 7.9 BCM of water per year over a surface covering 16,516 km².

Figure 3.3. Map of the Turkwel sub-watershed. RTI, 2013

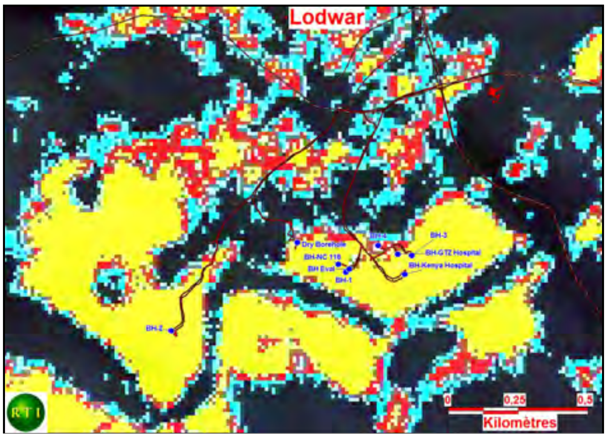


The tributary from Mount Elgon has been subtracted from this exercise because of the dam on the Suam River, which significantly diminishes the flow upstream. Most of the water flowing from the silica rich granitic highlands (Cherangani range, Karasuk and Loima Hills) channel enormous quantities of silica-rich sediments downstream, helping to produce prolific alluvial aquifers all along the Turkwel River. The area also has a shallow basement deeply incised by fractures which contribute recharge of runoff and infiltration. This is a favorable geologic environment for producing signifcant groundwater quantities downstream, through the Turkwel River Basin and its subsidiaries.

Moreover, the intergranular recharge zone covers most of the survey area, due to the proximity of the basement and acid volcanic formations, eroded and transported by runoff and wind. Such a context confers to the survey area an exceptional groundwater recharge potential.

As a consequence, one can anticipate the existence of alluvial aquifers increasing in density and occurrence as the river regime flows downstream, feeding deep aquifers in basinal areas. Given the high volume of water (7.9 BCM) that transits through this watershed each year, one can anticipate a minimum replenishment rate of 10%, which represents a recharge of 790 MCM each year. In Lodwar, there is almost no seasonal groundwater level variation in the boreholes below the alluvial deposits.

Figure 3.4. WATEX© image of the Lodwar area. The High Groundwater alluvial potential is coded in yellow. RTI, 2013.



The WATEX© image seen above (Figure 3.4) demonstrates that all the productive boreholes near Lodwar town correspond to the SAGOM model for high potential groundwater occurrence.

Most aquifers near Lodwar occur at shallow to moderate depths, often less than 50 m, within predominant alluvial sediments mixed with inter-volcanic layers within fractured geologic formations initiated by the shallow granitic basement around a radius of 4 km around the city.

Alluvial potential

Vertical recharge and underground flows near Lodwar is facilitated by the acid content (rich in silica), which corresponds to a very dark response on the WATEX© image outside of the the Turkwel valley. It is important to note that all of the existing boreholes which are unproductive or dry are located in these black zones.

If we consider a radius of 10 km along the Turkwel river, the estimated alluvial potential of Lodwar is averaging 20 MCM (for a surface offering a high groundwater potential of 40 km² with a water quantity of 0.5 MCM/km²).

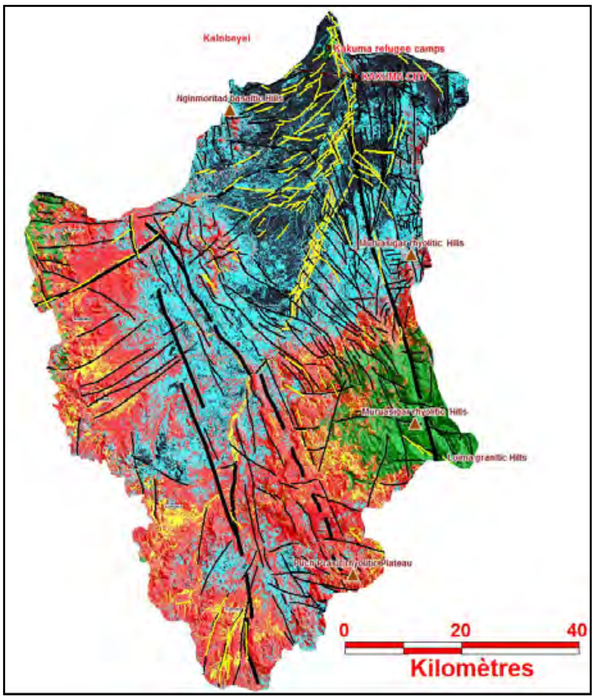
If we consider all the water quantities transiting through Lodwar, the estimated recharge capacity in Lodwar is averaging 1,292 MCM per year.

Groundwater potential of Kakuma

Hydrogeologic context

The Tarash-Kakuma sub-watershed is located on an area of highlands at an elevation, ranging from 1,400 m to 600 m. It receives a total of 2,217 MCM of water per year over a surface covering 5,168 km² (Figure 3.5). Most of the water in the watershed flows towards Kakuma town in a north-northeasterly direction from the silica-rich granitic escarpment of Uganda, the Puch Prasir rhyolitic plateau in the south and the Muruasingar rhyolitic hills southeast of Kakuma (the red and green areas in the map).

Figure 3.5. Map of the Kakuma sub-watershed. RTI, 2013



Structural style

The most prominent structural features of the area include the structuration of the Tarash River bed, which is controlled by a major North-South fracture that is recut by N45° and N160° (*en echelon)* fractures, observed as part of a "Horse Tail" shearing-distensive system. There are two rhyolitic volcanoes in the area: the Pelekech and Muruasigar Hills. The basement in the Kakuma area is relatively shallow, ranging from 100 m to 150 m. Significant volumes of water infiltrate downstream through the Tarash River and its tributaries, which converge at Kakuma. This condition likely helps to reduce the severity of floods during the rainy season in Kakuma.

The Kakuma area is expected to have minor groundwater potential in the shallow alluvial aquifer layers and high groundwater potential in the multi-layered aquifers found below 40-50 m deep within the volcanic layers and grits recut by fractures and reworked by rivers. Boreholes drilled in the Kakuma area should experience virtually no variations in seasonal water levels at depths below the alluvial deposits.

Geologic cross-sections near Kakuma

The assessment of the geologic context is represented in Figures 3.6, 3.7 and 3.8. The Kakuma Refugee Camp is situated in the center of a broad geosyncline (valley) between two distinct volcanic systems: the Ngimoritad basaltic hills in the West (light blue) and the Pelekech rhyolitic Hills in the East (light red). Within this valley-like structure, the Tarash Watershed drains all surface water towards Kakuma.

The Tarash riverbed itself is controlled by a shear-distensive fractures corridor, which is injected with hardened magma, known as rhyolitic plugs (labeled pink in Figure 3.7). These plugs protrude the surface, and are visible along the Lokichogio-Lodwar Road as west of Kakuma and within the Refugee Camp near the Tarash riverbed.

The basement, which can be reached at an average depth of 100 m, is overlaid by Turkana Grits (sandstones and conglomerates) and by weathered basalts and rhyolites layers intersected by deep-seated fractures. Rhyolitic plugs present a great challenge to well drilling operations in the Kakuma area, as their occurrence is not often visible or protruding on the surface.

Figure 3.6. WATEX© image of Kakuma area with geologic cross sections. The cross sections (red lines) (1) A-B from West to East and (2) C-D from South to North are situated along the course of the Tarash River, down to the Lotikipi Basin. RTI, 2013.

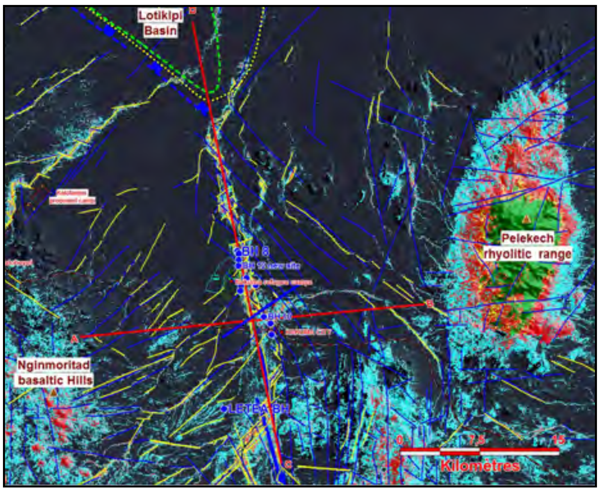
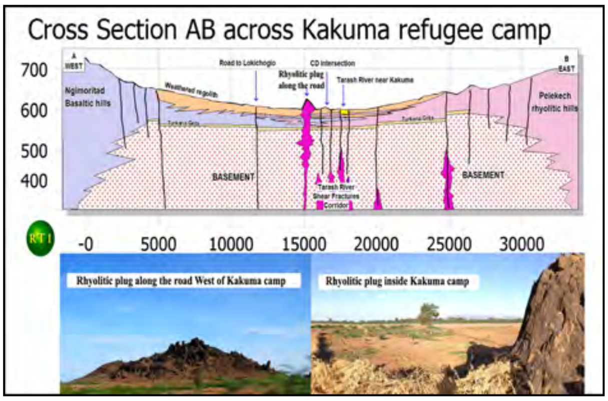
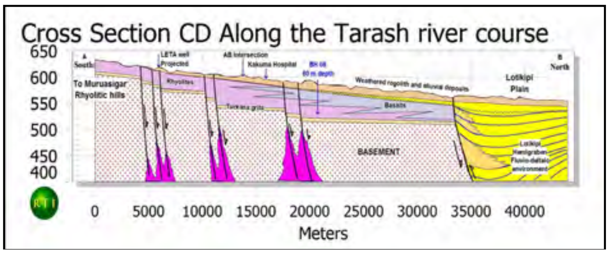


Figure 3.7. Cross section A-B from West to East across the Tarash valley in Kakuma. RTI, 2013. The geologic cross section A-B (approx. 35 km long) begins 15 km west of Kakuma and runs eastward through the Kakuma Refugee Camp and ends 15 km east of town.



The geologic cross-section C-D seen in Figurfe 3.8 is approximately 43 km long, begins about 15 km south of Kakuma town and ends about 30 km north of town along the Tarash River course. The existing LETA well, situated about 8 km south of Kakuma, encountered the basement at 35 m. UNHCR Borehole (BH08) intersected basalts and rhyolites down to 60 m without reaching the basement. The slope from point A (south) to B (north) is constant at an average rate of 0.2% slope, with the basement remaining shallow until it reaching a half-graben structure in the Lotikipi Basin area (Lotikipi South Aquifer, yellow) in the north. The location and existence of the half-graben was interpolated from seismic data and proven with UNESCO geophysical testing (VES) within the Lotikipi Basin.

Figure 3.8. Cross-section C-D from South to North along the Tarash valley in Kakuma. RTI, 2013.



Assessment for groundwater extraction

The aquifers reached by the boreholes within the vicinity of the Kakuma Refugee Camp are considered to be dynamic aquifers, with a general water flow oriented towards the north. The half-graben structure (in yellow) located in the north is filled with Plio-Pleistocene fluvio-deltaic deposits. Being steadily fed by the Tarash River course through vertical recharge, this half-graben structure is considered to be a renewable aquifer with high potential. The water level in this structure is estimated to be at a depth of 100 m or more. This structure can be confirmed by drilling deep boreholes approximately 20 km north of Kakuma BH08.

In the Kakuma area, most aquifers occur at a shallow to moderate depth, often less than 50 m. These aquifers are situated amongst inter-volcanic layers and within fractured geologic formations initiated by the shallow granitic basement.

Figure 3.9. Zoomed Watex© image of Kakuma showing all the GPS recorded boreholes drilled in Kakuma. RTI, 2013.

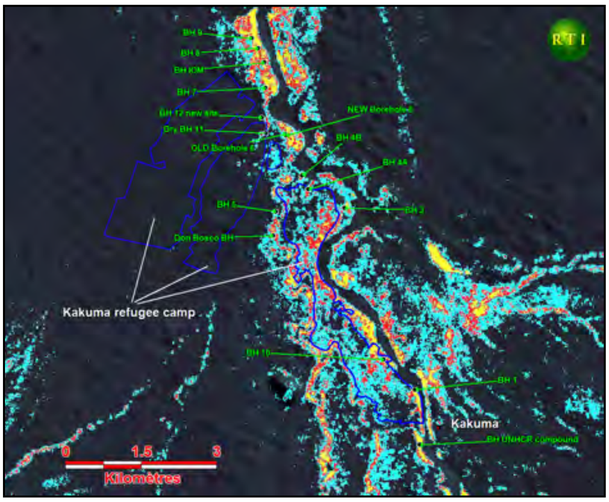


Figure 3.9 shows a WATEX© image zoomed in to the Kakuma Refugee Camp areas, denoted by blue polygons, which house more than 100,000 refugees today. Existing boreholes are in green. A strong evidence of the validity of the WATEX© Groundwater Map is that all of the productive boreholes are situated in the yellow areas (very high probability, >95%, of aquifer occurrence down to 80 meters), while all of the dry boreholes are located in the black zones (0% probability of aquifer presence).

Drilling wells and boreholes in the Kakuma area carries high risk due to the pervasive intrusive volcanic plugs, which are often not visible on the surface. In order to minimize risk, it is highly recommended to drill within the fracture corridor of the Tarash River which is a belt of 35 km long and 2 km wide along the course of the Tarash River, where conductive fractures (yellow lines) converge with high potential areas (yellow areas). Drilling outside of the corridor, even in yellow areas, carries a risk of difficult geology or low yields.

Alluvial and intra-basaltic layers potential

The intra-basaltic layers storage capacity is most likely higher than the alluvial storage capacity all along the course of the Tarash River. The Tarash fracture corridor should also contribute to the transit and the storage of a dynamic aquifer. This complex model is a serious obstacle to accurately evaluate the potential reserves available in Kakuma.

An alternative approach could be to consider that the average ratio between annual recoverable water quantities and the annual harvested rainfalls is 16.3% (See Annex, Hydrogology Report). Under such assumption, one can deduce the following:

If the total water transiting through the geosyncline of Kakuma area is 2.2 BCM/year, the estimated annual recharge (or available groundwater quantities available in Kakuma) is 361 MCM/year. Such a high volume has important consequences on the campsites management. Installation of well loggers on the main producing wells is absolutely necessary to monitor, on a daily basis, the water table, groundwater yield and quality variations to comfort and secure long-term assessment.

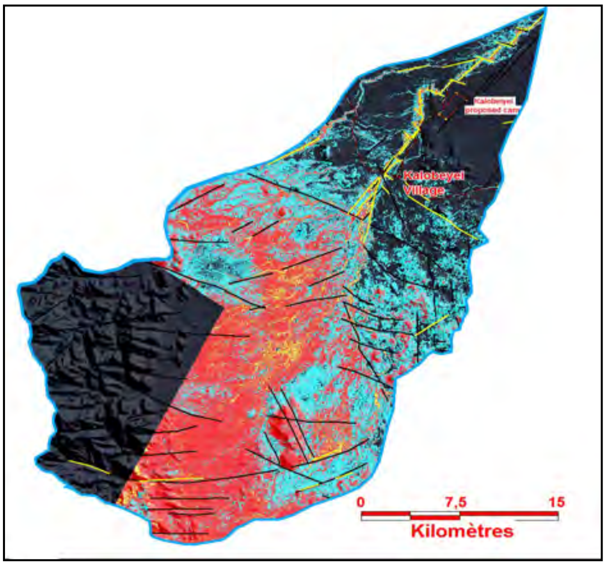
Groundwater potential of Kalobeiyei

Hydrogeologic context

Kalobeiyei (AOI-3) is situated within the Kalobeiyei sub-watershed which begins in the highlands at an elevation from 1,750 m and extends northward towards Kalobeiyei township down to 710 m. The AOI-3 receives some 293 MCM of water/year, which is drained over the catchment area of 770 km², making it around 10 times smaller in scope than the adjacent Tarash-Kakuma watershed. Most of the water is flowing from the silica rich granitic highlands of Uganda. The main groundwater resources in the hills, within the red areas, are hosted by conductive fractures with limited potential.

The most important aquifers for Kalobeiyei are hosted within the light blue and yellow area lying in the low plains of the Kalobeiyei River, within alluvial aquifers covering a shallow basement (less than 100 m deep).

Figure 3.10. Map of the Kalobeiyei sub-watershed. RTI, 2013



Geologic and structural context

The geologic context is similar to Kakuma, recent volcanic activities have covered the low plains of this watershed with basaltic and rhyolitic ash creating multi-layered aquifers recut by fractures and reworked by rivers, creating a complex pattern of aquifers from surface (alluvial) to the weathered basement.

Groundwater quality is affected by the alkaline volcanic context rich in sodium bicarbonate and locally affected by the presence of fluorine. The structuration of the Kalobeiyei River is dissected by N45° and N160° *en echelon* fractures.

Overall potential of Kalobeiyei

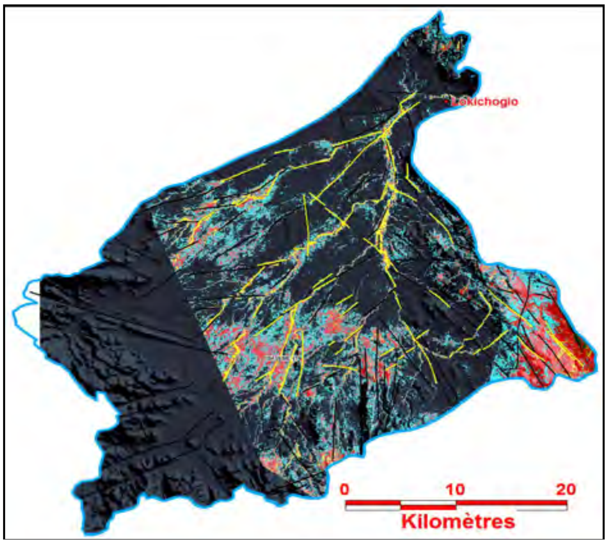
Taking into account the overall conditions, which are characterized by mild potential alluvial aquifers with intra-basaltic layers; taking also into account the total potential water transiting through the Kalobeiyei River (293 MCM/year); and using the regional vertical replenishment ratio of 16.3%, it can therefore be deduced that Kalobeiyei has an annual groundwater recharge and available groundwater quantity of 48 MCM of freshwater per year. Though this appears to be a relatively sizeable volume of water, the dispersion and distribution of shallow alluvial aquifers in the Kalobeiyei area make it less favorable to supporting an influx of population in the area, such as the proposed annex facility of the Kakuma Refugee Camp in Kalobeiyei.

Groundwater potential of Lokichogio

Hydrogeologic context

Lokichogio (AOI-4) is situated within the Nanam-Lokomoresi-Lokichogio sub-watershed, which begins in the western highlands at an altitude from 1,750 m and extends to the northeast down to 710 m. Situated in the lowest part of the watershed, Lokichogio is well positioned to benefit from the 658 MCM of water/year cultivated by the watershed over a total drainage area of 1,313 km² (which represents only 25% of the Tarash-Kakuma watershed surface). With an "R ratio" value of 0.5, this watershed is considered very efficient, as it receives a significant volume of water in proportion to its relatively small size. Most of the water is flowing from the silica rich granitic highlands of Uganda (not covered by the WATEX© image, and outside the survey area).

Figure 3.11. Map of the Lokichogio sub-watershed. RTI, 2013



Geologic and structural context

The most important aquifers for Lokichogio (AOI-4) are hosted within the light blue and yellow areas lying in the low plains of the Nanam-Lokomoresi River, within alluvial aquifers covering a shallow basement (less than 100 m deep). Volcanic activities have covered the low plains of this watershed with basaltic and rhyolitic ash creating multi-layered aquifers recut by fractures and reworked by rivers, creating a complex pattern of aquifers from surface (alluvial) to the weathered basement. Groundwater quality in the area is affected by the alkaline volcanic context rich in sodium bicarbonate and locally affected by fluorine.

Overall potential of Lokichogio

Taking into account the overall conditions of the area, which account for a total water potential of 658 MCM/year transiting through Lokichogio township, and using the regional vertical replenishment ratio of 16.3%, it can be deduced that the estimated annual recharge and potential available groundwater quantities available to Lokichogio is 107 MCM/year.

3.4. Inventory of groundwater potential of central-northern Turkana County

This study has attempted to provide a baseline assessment of the groundwater wealth in northern and central Turkana County. Such an assessment is now a critical imperative, given that "uncovering" these hidden resources is the first step to understanding the options for improving access to safe drinking water for the local populations affected by drought and water scarcity. This section discusses the results of this assessment, providing an inventory of groundwater resources available. This section also begins to consider what these resources mean for national development in Kenya, and concludes with offering a few development options.

Potential of regional shallow alluvial aquifers

Groundwater recharge of shallow aquifers

Having explored and mapped all shallow aquifers with a depth range of 0 – 80 m that occur in the primary watersheds of the study area, this study is able to make a sound estimate for the total recharge of these alluvial systems. It is recalled here that this study assumes that shallow aquifers in the region have an average thickness of 5 m cumulated aquifer and a minimum porosity of 10%. This means that shallow alluvial aquifers can store up to 1,620 MCM cumulatively with an average of 0.5 MCM per km^2. This was used as a guideline to evaluate the rate of recharge and is the dominant variable determining total potential of these shallow aquifers.

Using the "rule of the thumb" method, RTI has estimated that the survey area harvests a cumulative 17 BCM per year and accounts for permeability according to the following guidelines:

(1) 63.8% of the survey area is comprised of arenosols, Turkana grits and volcanic ash (54.7%) and of fluvisols (9.1%) which are very permeable and favorable to vertical recharge. This area should retain 20% of the rainfall, or 2.16 BCM per year;

(2) 36% of the survey area is comprised of low permeable basement and volcanic formations. These areas should retain only 10% of the rainfall through the dense fracture pattern, or only 612 MCM per year.

Therefore, the volume of surface intrusion in the survey area that is "available" for recharge can be calculated as 16.3% of the cumulative harvested volume of 17 BCM, or 2.77 BCM. As explained above, a factor of 16.3% has been selected for each watershed and sub-watershed in order to compute the specific recharge capacity of shallow aquifers regionally.

The above method has been applied to each specific alluvial system, and the figures for estimated recharge are given for the main systems in Table 3.2.

Therefore, the total potential recharge of shallow alluvial aquifers in the study area is estimated around 2.085 BCM. It is important to note that this estimate does not include recharge estimates for deep-seated aquifers, which is discussed below separately.

Storage capacity of shallow aquifers

As discussed prior, the shallow aquifers of Kakuma, Kalobeiyei and Lokichoggio are composed of complex multi-layered weathered volcanic formations and grits overlying a shallow basement. This complex and heterogeneous geologic context presents a challenge to estimating the potential storage of such aquifers at the regional scale. This study finds that localized studies need to be done for targeted alluvial aquifer units in order to achieve such an estimate.

Table 3.2. Estimated potentials of shallow alluvial aquifers of northern-central Turkana County. RTI, 2013.

Shallow Alluvial Aquifer Units (Superficial, intra-volcanic systems)	Surface area (km2)	Rainfall harvested (MCM/yr)	Recharge (MCM/yr)	Storage capacity (MCM)
Lotikipi Basin watersheds				
(1) Kakuma on River Tarash	5,168	2,217	361	-*
(2) Lokichogio on Napas River	1,313	658	107	-*
(3) Kalobeiyei	770	293	48	-*
Lake Turkana Basin watersheds				
(4) Turkwel-Lodwar	16,516	7,925	1,292	20**
(5) Kalokol	2,682	804	131	-*
(6) Katabol	769	230	37	-*
(7) Lochome	423	130	21	-*
(8) Eturin	336	100	16	-*
(9) Lomogoi	1,465	439	72	-*
		Total	**2,085**	-*

* Not estimated due to insufficient data of the complex inter-basaltic systems.
** Within a radius of 10 km of Lodwar town.

Potential of deep aquifers

The potential of the five structures identified by this survey are given below in Table 3.3. Annual recharge and total storage capacity are given.

Table 3.3. Estimated annual recharge and storage capacities of the deep aquifer structures of northern-central Turkana County. RTI, 2013.

Aquifer system	Recharge (MCM/yr)	Storage capacity (MCM)
(1) Lotikipi Basin	1,200	207,500
(2) Lodwar Basin	-*	10,000
(3) Gatome Half-graben	61	17,250
(4) Nakalale Half-graben	59	7,000
(5) Kachoda Half-graben	21	6,500
Total	**1,362**	**248,250**

* Estimate for recharge of Lodwar Aquifer is not given due to insufficient data on Turkwel River recharge dynamics.

Groundwater recharge of deep structures

As discussed in previous sections, the recharge potential of each deep structure is defined by the total harvested volume from rainfall that supplies them after removing runoff and evapotranspiration. The cumulative potential of annual recharge of all five deep structures is 1.36 BCM/year, representing a substantial volume that can be tapped into on an annual basis without considering the stored amount (see below). It is important to note that the rechargeable quantities correspond to 16.3% of the total rainfalls quantities in the region. This factor has been discussed in the previous chapter. It is also noted that the total estimate for recharge does not include an estimate for the Lodwar-Lokichar half-graben aquifer as the rate of recharge has not been determined since recharge is directly fed by the Turkwel River basin flows. This means that actual cumulative recharge for deep structures is expected to be greater than the findings of the survey.

Storage capacity of deep structures

The five deep aquifer structures discovered by this survey provide a significant prospect for Turkana County and the country as a whole. Estimated storage capacities of all five structures are given in Table 3.3. Factoring in only 200 m of water column, the five structures have an estimated cumulative storage volume of 248 BCM. Actual water columns may vary slightly when drilling is implemented. For example, UNESCO recorded 210 meters of water column for Lotikipi Basin Aquifer.

It must be underscored here that despite the prospect of significant volumes that these aquifers represent, extraction of water from these structures should be done with great caution in order to prevent over-exploitation. Development projects should take into account the relatively low recharge rate of 1.34 BCM/year, or 0.05% of the stored amount.

Confirmed deep aquifers

This study has modeled (DAM) and confirmed the existence by drilling exploratory boreholes of two previously unrecorded aquifers – the Lotikipi Basin and the Lodwar Basin. The key characteristics of these aquifers are given in Table 3.4 below. A discussion of important data observed also follows.

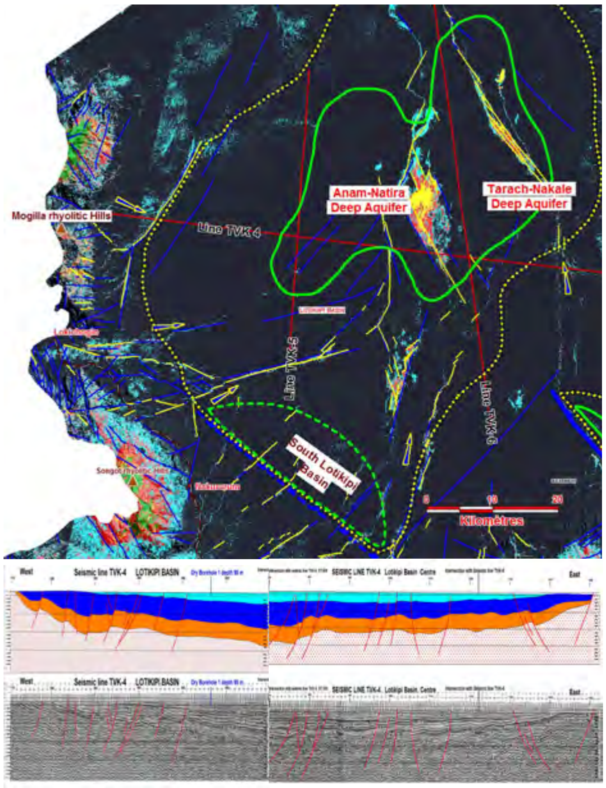
Table 3.4. Characteristics of confirmed deep aquifers. RTI, 2013.

Parameter	Lodwar Basin	Lotikipi Basin
Aquifer type	Sedimentary, unconfined	Major sedimentary, unconfined
Lithology	Clays, sands, sandstones	Paleo lake sediments
Dominant flow regime	Inter-granular	Inter-granular
Scale	Local	Regional
Surface area, km2	140	4,146
Storage, MCM/yr	10,000	207,000
Recharge, MCM/yr	Unknown	1,200
Abstraction, MCM/yr	0	0
Pollution vulnerability	Unknown	Moderate
Saltwater vulnerability	Moderate	Low
Depletion vulnerability	Low	Low
Dominant water use (in approximate order of volumetric use)	N/A	N/A
WRMA Type	Strategic	Strategic
WMRA Status	Unknown	Unknown

The Lotikipi Basin Aquifer

UNESCO confirmed the existence of the large Lotikipi Basin Aquifer System on 8 July 2013 by exploratory borehole (Figure 3.12). Drilled to a total depth of 330 meters, the well encountered three interconnected aquifer layers with a cumulative aquifer thickness of 202 meters, thus confirming the original hypothesis (DAM model) of the existence of a mature endoreic delta that consists from surface to 300 m of coalescent palaeo-channels rich in quartz gravels and sands.

Figure 3.12. Map and seismic cross-section of the Lotikipi Basin Aquifer, confirmed in July 2013. RTI, 2013.



The second layer of the aquifer was observed from 250 m to 300 m, with quartz-rich layers (Figure 3.13, top image) that significantly contribute to the lateral extension and vertical porosity of the aquifer and ensure good rates of recharge with porosity estimated at over 20%. The delta stems from the highlands south of Kakuma and extends towards the north of the basin. In the absence of test pumping, but based on field observation during borehole flushing and geologic cutting analysis, this aquifer layer is expected to produce high yields in the order of 100 m3/hour. The first two layers are modeled as light blue in the seismic cross section in Figure 3.12.

A distinctly different aquifer layer was observed at 300 meters. Analysis of the geological cuttings taken from 330 m (Figure 3.13, bottom image) has revealed fluvio-lacustrine, tuffs and brecciates. Seismic and gravimetry interpretation indicates a transition of seismic character to formation with very continuous horizons. This study has concluded that this layer of the Lotikipi Basin Aquifer is an ancient sedimentary formation that begins at 300 meters deep and has a minimum thickness of 500 meters (modeled in dark blue and orange on the seismic cross-seciton model). This paleo lake is expected to be the most water-saturated portion of the aquifer system and could store a volume even far greater than the shallower layers observed in the initial 330 meters. The water in this formation is likely to be much older than the shallower layers but may be less productivity than the shallower layers due to its reduced permeability caused by a different shale-to-sand ratio and possible carbonated cement. There is also a concern that water in this deep layer may be of lesser quality, but this can only be confirmed with deeper testing and dating.

Figure 3.13. Geologic cuttings taken from Lotikipi Basin Aquifer borehole. Samples were analyzed by RTI and University of Nairobi. Top image: Cuttings from 270 m, rich in unrounded centimetric quartz grains and fine sand, revealing a palaeo-channel from an endorheic delta. Bottom image: Cuttings from 320 m intersecting lacustrine formation and basaltic pumice cemented by limestone (carbonate rich sediments).

The Lotikipi Basin Aquifer System is a result of rivers flowing from the south, west and east which discharge into the north towards the Lotikipi Plains. These rivers, such as the Tarash and Epiketet Rivers and many other minor tributaries, contribute to the constant vertical recharge, which is a convincing sign of natural and constant sustainability. The presence of quartz grains down to 320 m associated with volcanic tuffs cemented by limestone is also very encouraging. The Lotikipi Basin Aquifer shows tendency to continue its drainage northward into the Ilemi Triangle, thus could be a transboundary aquifer. More exploration and mapping in the north is needed to confirm the discharge.

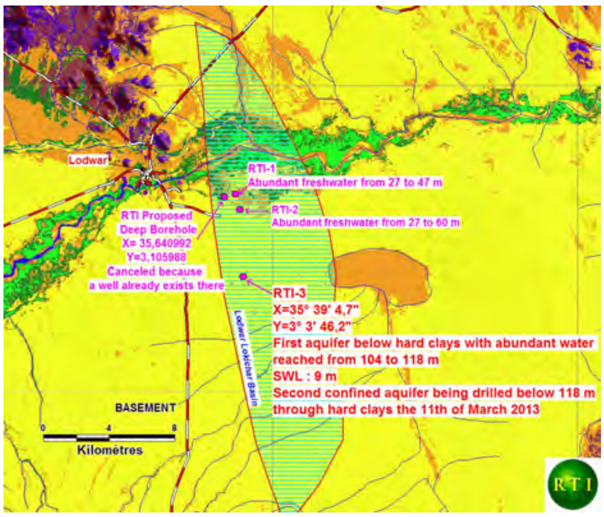
The Lodwar Basin Aquifer

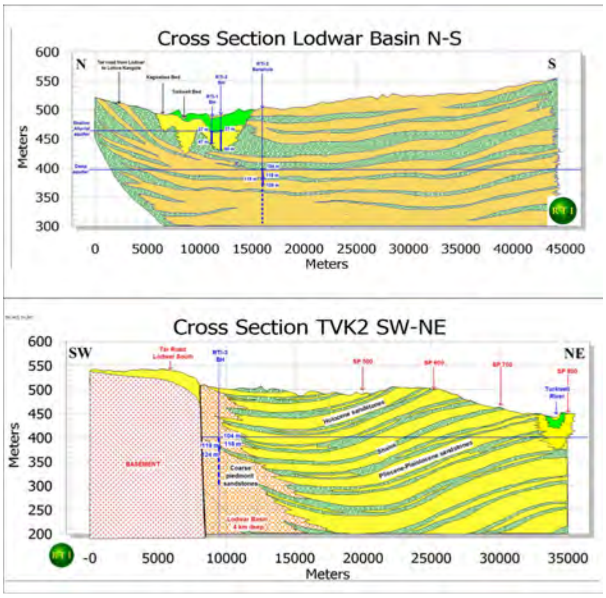
The Lodwar Basin Aquifer System was confirmed by UNESCO who drilled three boreholes located a few kilometers south of Lodwar town between January and March, 2013. The map of the aquifer and the three boreholes are shown in Figure 3.14.

The first two boreholes (RTI-1 and RTI-2) were drilled to 47 m and 61 m, respectively. Both encountered high-yield and potable freshwater, but were prevented from drilling deeper due to the high yield. The yield of RTI-2 was measured by UNESCO at 62 m3/hour, which stabilized at 27 m3/h. These first two boreholes, RTI-1 and RTI2, confirmed the alluvial deposits and thickness of the Turkwell alluvial system near Lodwar, and revealed high volume of good quality, which can be used for domestic purpose.

The third borehole was placed some 3 km south of the first two boreholes in an attempt to study a more isolated part of the aquifer. Dug to a total depth of 128 m, the borehole encountered two aquifer layers from 104-118 m and from 119-128 m, a cumulative water column 25 m. Cuttings from these layers (Figure 3.15) were assessed to be piedmont deposits of coarse sandstones from basement erosion and provide excellent aquifer conductivity. The borehole was tested to have initial yields of 40 m3/h at a depth of 120 m. A mixed sample from both aquifer layers, which is not a sufficient standard, assessed water quality to be slightly mineralized with presence of fluorine (Fl) and Na2CO3 at or slightly above acceptable limits.

Figure 3.14. Map and cross-sections of Lodwar Basin Aquifer, confirmed in March 2013. RTI, 2013.





The Turkwell alluvial system, shaded in bright green and yellow, demonstrates a potential contribution to the replenishment of the deep Lodwar Aquifer structure

Figure 3.15. Geologic cuttings taken from Lodwar Basin Aquifer borehole no. 3. Cuttings analyzed by RTI. Top-left: 104 m, fine sandstones. Top-right: 112 m, coarser sandstones. Bottom: 118-120m, coarse sandstones.

This study has concluded that the Lodwar Basin Aquifer is a large deep aquifer, covering a surface area of 374 km², with great hydraulic potential. Taking into account the lithology and hydraulic properties observed by a combination of WATEX methodology and the more recent field data, the presence of the aquifer and some of the geological and hydraulic properties have been confirmed and can now be estimated. Seismic interpretation by RTI demonstrates a potential for the aquifer to extend as deep as 4,000 m. However, in the absence of data supporting that hypothesis, it is safe to consider a cumulated water column of 100 m hosted in a formation with a porosity of 25%. Despite these limitations, it can be conservatively estimated that the Lodwar Aquifer stores a minimum reserve of 10 BCM of water.

Analysis of the new cross sections reveals a potential replenishment correlation dynamic between the Lodwar Aquifer and the Turkwel River, which flows directly above the aquifer. This dynamic, however, will require more intensive study to determine specific correlations.

In general, the Lodwar Aquifer will require further study and exploration in order to assess more fully the structure geometry, hydraulic scope and flow dynamics. This large aquifer will almost certainly consist of several overlaid aquifers which might differ in yield and water quality. Nevertheless, hydrothermalisation will be a limiting factor in such a structural graben.

Total renewable groundwater resources

The approach to estimating the total renewable groundwater resources accounts for the sum of total groundwater potential represented by both shallow and deep aquifers, both of which are discussed above. The approach does not account for possible quantities hosted by (conductive) fractures since more study is required to determine potentials of individual fractures.

Taking into consideration the total potential of high-potential shallow aquifers (considering the recharge of 2.085 BCM instead of the storage which cannot be estimated) and the total cumulative storage capacity of the five deep aquifer structures (245 BCM), the estimated total renewable groundwater resources storage of northern-central Turkana is 250 BCM for a total annual recharge of 3.447 BCM per year, which represents only 1.38% of the total storage volume.

Table 3.5. Estimated total renewable groundwater resources of northern-central Turkana County. RTI, 2013.

Aquifer system	Recharge (MCM/yr)	Storage capacity (MCM)
(1) Shallow alluvial systems	2,085	2,085*
(2) Deep-seated systems	1,362	248,250
Total	**3,447**	**250,335**

* In absence of localized data at the regional scale, a conservative estimate for the cumulative storage capacity of shallow alluvial assumes the same amount of annual recharge

3.5. Key groundwater development targets in northern-central Turkana County

This section reviews some options for regional and national development, beginning with the major implications and potential impact that these resources may have.

Implications for development

For a nation of 41 million inhabitants still at the throes of a deepening water crisis – 17 million Kenyans (43%) still lack access to freshwater and 28 million (68%) still do not have adequate sanitation – the groundwater resources surveyed in northern and central Turkana County are a critical resource. Now that the resource has been properly mapped and assessed, Turkana County, as well as its neighboring counties and the nation at large, can begin to tap into the resource and build new socio-economic opportunities. The 250 BCM of stored groundwater and 3.4 BCM of annual recharge, if developed safely and responsibly, offer new hope for the 20 million Kenyans still living in poverty and a country aspiring to become a leading economy in Africa.

While assessing the full socio-economic potential of the groundwater resources is beyond the scope of this study, some important insights can now be considered about the future possibilities that these "new" resources can support.

The Lotikipi Basin Aquifer

The large Lotikipi Basin Aquifer System – its existence confirmed by UNESCO in July 2013 – will no doubt play a vital role in the economic security of the country. Its annual replenishment of 1.2 km3 alone represents 6% of the nation's total renewable resources (20.2 km3/year). A freshwater reserve of 207 BCM, Lotikipi Aquifer equals the volume of Lake Turkana today, offering the prospect of becoming the "New Lake Turkana" since, unlike the actual lake that has alkaline water, its waters are fit for human consumption. As a major reservoir, the Lotikipi Aquifer also makes a significant contribution to Kenya's strategic water reserves by expanding in real terms the national dam capacity from 24 km3 to 224 km3 – a nine-fold (900%) increase.

Implications for national development

Table 3.5 gives estimates for a few key indicators of the development potential of the groundwater resources of northern and central Turkana County, providing a snap shot of the importance that these resources have for the national scale. If the annual recharge of these systems is considered, Kenya's total renewable water resources (20.2 km3/yr) increases by 17% to 23.6 km3/yr. These new findings mean that the share of water for every Kenyan increases from 492 m3/yr/pp to 575 m3/yr/pp, or an additional 83 m3/yr/pp.

As a measure of system viability, two different development options are considered. Columns 5 and 6 in Table 3.5 consider the scenarios of using the Turkana groundwater as a reliable, sustainable supply of water, for example, by exploiting only the annual recharge volumes so that the principle reserves are kept untouched. For the first scenario (Column 5), the objective is to sustain the normal rate of national water consumption (87 m3/yr/pp), including water for all economic sectors. Used in such a way, some 39.4 million people could be served every year. As a comparison, the second scenario (Column 6) considers the goal of sustaining only human life, ie. supplying 15 L per person daily over a year. It turns out that if the aquifers were utilized for humanitarian purposes, then over 625 million people could be served in a year.

A more drastic option would be to use the groundwater reserves in Turkana as strategic reservoir for national crises. The last column in Table 3.5 considers, as a measurement of aquifer longevity, how long it would take to deplete these resources if the whole nation depended on them (all 41 million Kenyans), assuming today's withdrawal rates and zero population increase). The study finds that as a strategic national reserve, the groundwater bodies in Turkana can serve the national population for up to 70 years before being depleted completely. The Lotikipi Basin Aquifer alone would be able to last up to 58 years during a severe water crisis. This is highly significant considering the trends that show that available water resources in Kenya are expected to diminish to 235 m3/year per person by 2025.

Table 3.6. Calculated development potential of groundwater resources of northern-central Turkana County. RTI, 2013.

Aquifer system	Recharge (MCM/yr)	% of total national renewable water [1]	Storage capacity (MCM)	Population served, annual (all sectors) [2]	Population served, annual (humanitarian) [3]	Duration of strategic reserve (years) [4]
Deep aquifer structures						
(1) Lotikipi Basin System	1,200	5.94%	207,500	13,793,103	219,178,082	58
(2) Lodwar Basin System	-	-	10,000	-	-	3
(3) Gatome Half-graben System	61	0.30%	17,250	701,149	11,141,553	5
(4) Nakalale Half-graben System	59	0.29%	7,000	678,161	10,776,256	2
(5) Kachoda Half-graben System	21	0.10%	6,500	241,379	3,835,616	2
Regional shallow alluvial aquifers	2,085	10.32%	2,085	23,965,517	380,821,918	1
TOTAL	**3,426**	**17%**	**250,335**	**39,379,310**	**625,753,425**	**70**

[1] Kenya's total renewable water resources = 20.2 km3/yr (FAO-Aquastat, 2005)
[2] Population that could be served by the groundwater system during one year, using only annual recharge volumes to satisfy total water withdrawals per inhabitant (87 m3/yr (FAO-Aquastat, 2005)
[3] Population that could be served by the groundwater system during one year, using only annual recharge volumes to satisfy annual basic life-sustaining needs per inhabitant (5.475 m3/yr, WHO Standards)
[4] Number of years the groundwater system would last if it supplied water to satisfy the consumption needs of the Kenyan national population (41 million, 2011). This is a measure of aquifer longevity, ie. how long it would take to deplete the aquifer during a period of severe prolonged water crisis.

Groundwater extraction targets

This section is presents a selection of key targets for extracting groundwater, extracted from the Technical Field Manual for Groundwater Targeting in Northern and Central Turkana County, which was designed to provide an overview of areas with highest potential for groundwater prospection within the 36,000 km2 zone surveyed and provides advice on selected areas.

In order to reduce the risk of negative drilling results, these advices need to be combined with a complete hydrogeological assessment of the selected area, as required by national WRMA regulations. Localized geophysical investigation techniques such as VES and resistivity testing are highly recommended prior to selecting sites and drilling boreholes in order to increase the probability of water presence and maximize actual production rates.

Two example targets for extracting groundwater are given below, one shallow alluvial and one for deep aquifer, both are highlighted in the Manual.

Shallow aquifer targets near Tarash-Kakuma

The overall potential for successful borehole drilling in the watershed is minor in the shallow alluvial aquifer layers and greater in the multi-layered aquifers found below 40-50 m deep within the volcanic layers and grits recut by fractures and reworked by rivers. Boreholes drilled in the Kakuma area should focus on the alluvial deposits near the Tarash river system, and are not likely to experience variations in seasonal water levels at depths below the alluvial deposits.

Optimum drilling sites should target the yellow conductive fractures and bright pixels. It is highly recommended to select sites in the system of fractures of the Tarash river fractures. Drillers should also account for the possibility of variations in groundwater quality resulting from the local alkaline volcanic context (rich in sodium bicarbonate) and traces of fluoride. Drilling in the Kakuma area carries high risk due to the pervasive intrusive volcanic plugs, which are often not visible on the surface. In order to minimize risk, it is highly recommended to drill within the fracture corridor of the Tarash River, where conductive fractures converge with high potential areas. Drilling outside of the corridor, even where high potential groundwater occurs, carries a risk of difficult geology or low yields.

Deep aquifer target in the Kachoda area

The alluvial bed of Lomogoi sub-watershed in the northern portion of the County offers several drilling possibilities when combining high potential areas indicated by the Groundwater Target Map with conductive fractures. The key target is the deep half-graben structure, Kachoda Basin Aquifer, identified by this survey and located approximately 20 km west of Lokitaung town along the main road to Lodwar. Still un-developed, the Kachoda Aquifer covers 130 km² and is replenished by the perennial Lomogoi River through its alluvial sediments ensuring vertical recharge increased by a dense fracture pattern. The water quality should be good. It might host

6.5 BCM of freshwater with a recharge capacity of 21 MCM/year.

The recharge of the aquifer is limited due to the presence of weathered basalts, but most likely sufficient to feed these alluvial aquifers, and the water quality should be good within fractured basalts.

A promising target is the half-graben-like structure near the major thrust fault oriented N160°. Drilling should penetrate down to a minimum of 250 m to explore the water column, if possible down to the basement most likely covered by Cretaceous sandstones. Such a discovery would ensure the agricultural development of this shrubland area.

Groundwater recharge targets

While managing groundwater recharge is not new in Kenya, only a few projects have been implemented. Managing groundwater recharge has many benefits, both to the groundwater systems (aquifers) and to those managing the resource (regularizing the supply). The conditions for recharge will depend on the goal of the project. The sites for recharge are too numerous to highlight here. However, some guidelines for managing recharge and water harvesting can be provided taking into account the specific recharge environment of the northern-central Turkana County. The reader should utilize the Recharge Map, in conjunction with the Groundwater Target Map and the Soil Map provided by the survey as a reference.

Managed aquifer recharge (MAR)

The survey area has some promising areas that can be targeted for managing and promoting the recharge of shallow and deep aquifers. The key guideline is to avoid sedimentary basin areas, and target fractures. Several good sites around the Tarash River basin near Kakuma give some examples. The horse-tail fracture system south of the basin also provides favorable conditions.

Harvesting surface water

In general, areas where surface water can be harvested should satisfy the conditions of (a) good groundwater recharge and (b) conducive topographic conditions, and (c) on the periphery of the extent of shallow basement areas, which is depicted by the edge of the red areas on the Groundwater Recharge Map. These areas are too numerous to point out here in the scope of the study, but in general, the northern and central Turkana County has very good potential for construction water harvesting schemes.

Agricultural development options

The new information produced by this study about existing water reserves and soil types, among other physical characteristics, provides a solid basis for more in-depth study of agronomical potentials in the northern and central Turkana region. Readers are solicited to review the Annex section on Soil classification as a core reference.

For this exercise, a zone is considered as having “good potential for agricultural development” where the basic conditions of water availability and good soils converge. The criteria do not exhaust other important factors such as logistics, agro-economics, pollutants, or political considerations, which would also influence selection. This section should not be perceived as policy recommendations, which would be based on much more intense study of agricultural development and irrigation potential; it is intended to stimulate further evaluation.

Four areas of good potential for agricultural development are highlighted:

(1) The riparian areas of the Turkwel River around in the vicinity of Lodwar town offer a good potential for agriculture given the high productive shallow alluvial aquifers and soils in the area.

(2) The area above the deep aquifer structure of Gatome also offers good potential given the expected good yield of this aquifer, which could likely sustain agricultural projects for food production and livestock husbandry.

(3) Similar to Gatome, the area above the deep aquifer structure of Nakalale is another area of good potential given the expected good yield of the aquifers which could likely sustain agricultural projects for food production and livestock sbandry.

(4) The large area in the center of the Lokitipi basin near the former seasonal marsh is of particular interest for grazing and ranching due to the great potential of groundwater reserves that the aquifer holds and because of the good soil conditions.

In the least, the seasonal flooding of the area could be harvested for spate irrigation.

4. Validation of Survey Groundwater Models

4.1. Introduction

This survey aimed to explore groundwater resources of northern and central Turkana County and develop maps with the highest level of accuracy of concept in order to help Kenyans make sound decisions about developing groundwater in the area. The challenge of such task – or of any modeler of groundwater – is to produce reliable maps that represent complex natural systems accurately and with minimal uncertainty. The WATEX System enables unique capabilities in mapping complex groundwater systems with a high magnitude of certainty thanks to the generation of groundwater models. While no model can be 100 per cent correct, the goal of such models was to minimize the unknowns about the occurrence and extent of groundwater and to represent the actual systems as closely as possible.

UNESCO's GRIDMAP team has conducted an independent validation of the two models in order to check the test the level of accuracy and skill in detecting and mapping groundwater. As discussed in Chapter 2, the two main groundwater models generate distinct concepts of groundwater regimes that can be mapped independently. The Shallow Alluvial Groundwater Occurrence Model, or SAGOM, is a representation of unconfined aquifers occurring from surface to 80 meters – the "low-lying fruit" of groundwater resources and a major resource for localized development. The main limitations of the models were also documented in Chapter 2, and are taken into account here.

The Deep Aquifer Model, or DAM, conceptualizes sedimentary basins occurring deeper than 100 meters. These large aquifers can contain vast quantities of water. Furthermore, the DAM was used to predict the existence of aquifers never documented before, offering the prospect of major discoveries with strategic importance for Kenya.

Objective of this chapter

In order to provide an independent review, UNESCO has drafted this chapter in order report on the results of the model validation. Due to the distinct nature of the two models, they must be tested separately. At a minimum, this chapter provides empirical evidence of the effectiveness and usefulness of the two models as applied to the study area.

4.2. Shallow Alluvial Groundwater Occurrence Model

The Shallow Alluvial Groundwater Occurrence Model (SAGOM) led to the precise mapping of 2.085 BCM of shallow alluvial aquifers across central and northern Turkana County. As described in further detail in Chapter 2, the (SAGOM) aims to represent groundwater that is hydrologically connected to river channels or flood plains on the surface, and that which is, in general, stored unconfined in permeable geologic material from the surface to an approximate depth of 80 meters. The model also conceptualizes within the same depth range conductive fractures, or groundwater occurring in the fissures, joints, bedding planes and cavities of rock masses.

RTI has designed SAGOM specifically to provide valuable information that is useful for assessing the groundwater potential of a given area and to serve as a tool for those planning projects that depend upon these systems.

Method of validation

The purpose of validating a groundwater model is to measure its ability to predict naturally occurring phenomenon. For spatial models such as SAGOM, accuracy should be measured in terms of the statistical closeness of a model's predictions to the observed reality. SAGOM predicts groundwater occurrence by assigning values to precise locations, expressed as digital pixels. The reality of groundwater occurrence can be observed as any groundwater point such as a known borehole, well or spring plotted on the same GIS system. The accuracy of SAGOM can therefore be obtained through a statistical analysis of how well SAGOM pixels and their occurrence values match the occurrence values of actual groundwater points.

Testing the accuracy of SAGOM involved the comparison of SAGOM pixels and their occurrence values to the location and occurrence values of actual groundwater points (eg. boreholes, wells, springs). The samples were plotted on the SAGOM model on the GIS (ie. Groundwater Target Map) and their location and groundwater occurrence values were analyzed in relation to the SAGOM pixels. A statistical analysis was conducted to determine accuracy and uncertainty of the model.

Samples

Four separate random samples of actual groundwater points, comprising a cumulative total of 797 groundwater points, mainly boreholes, were collected and analyzed separately. The overall sample aimed to include several samples, obtained independently by the Consultant (RTI) and UNESCO. The following parameters were collected for all samples: Name of groundwater point, client, GPS-longitude, GPS-latitude, type, status (dry, productive, functioning, etc.). Other parameters were also collected and taken into account, such as yield and comments on production. The full datasets of these samples can be found in Annex – Drilling Report.

Table 4.1. SAGOM validation sample size and description. UNESCO, 2013.

Sample Name	Sample Size	Description
1-RTI	628	Mix of primary and secondary data points collected by RTI. Primary data attributes confirmed directly by RTI. Secondary data attributes are assumed valid.
2-UNESCO	156	Data points from secondary sources collected by UNESCO. Attributes of GPS and occurrence status are assumed valid.
3-UNESCO	9	Data points collected and verified directly by UNESCO.
4-UNESCO	4	New boreholes drilled with the advice of the SAGOM model since from January to June 2013.

Tests of model accuracy

Accuracy of the SAGOM was measured by seeking answers to two statistical questions:

> *Test 1: How accurate is SAGOM in predicting groundwater occurrence?*
>
> *Test 2: How accurate is SAGOM in predicting both groundwater occurrence and absence?*

The validation of the SAGOM model entailed the answering of the above questions, through an analysis of the four independent samples. Figure 4.2 shows a mock-up of how SAGOM pixels are rated (positive or negative).

Figure 4.1. Example of close-up of SAGOM pixel radiance values and scale. Each block represents one pixel. (UNESCO, 2013)

6.25 m	Negative	Negative	Negative	Negative	Positive
6.25 m	Negative	Negative	Negative	Positive	Positive
6.25 m	Negative	Negative	Positive	Positive	Positive
6.25 m	Negative	Negative	Positive	Positive	Positive
6.25 m	Positive	Positive	Positive	Positive	Positive
	6.25 m	6.25 m	6.25 m	6.25 m	6.25 m

With this method, all 797 groundwater points were plotted in GIS onto the WATEX SAGOM image and juxtaposed so that they could be analyzed individually (Figure 4.3). The points were measured in terms of accuracy and given a score for their water occurrence and level of compliance with the WATEX SAGOM model.

Figure 4.2. Example of RTI Sample (1), showing juxtaposition of borehole samples to the SAGOM model. This example is near Kakuma. RTI, 2013.

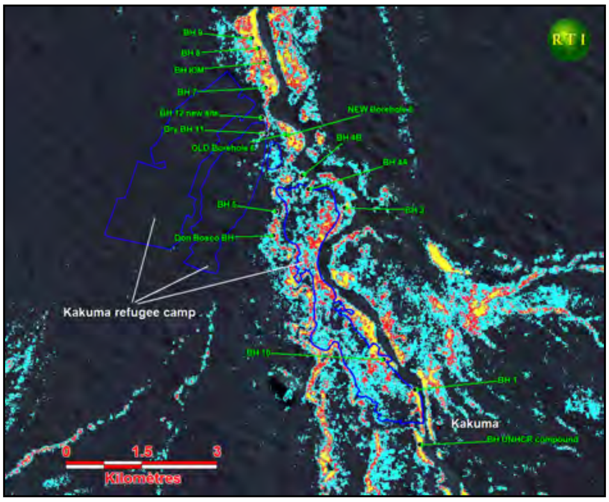


Figure 4.3. Example of UNESCO Sample (2), showing juxtaposition of borehole samples to the SAGOM model. UNESCO, 2013.

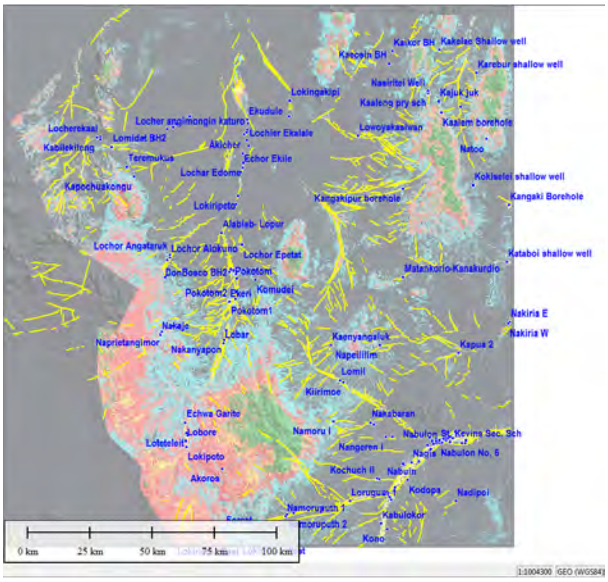


Figure 4.4. Example of UNESCO Sample (3), showing location of borehole samples taken in the field juxtoposed to the SAGOM model. UNESCO, 2013.

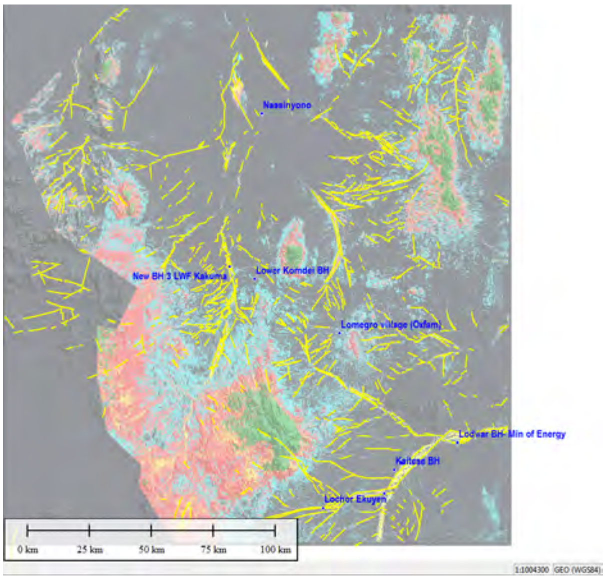
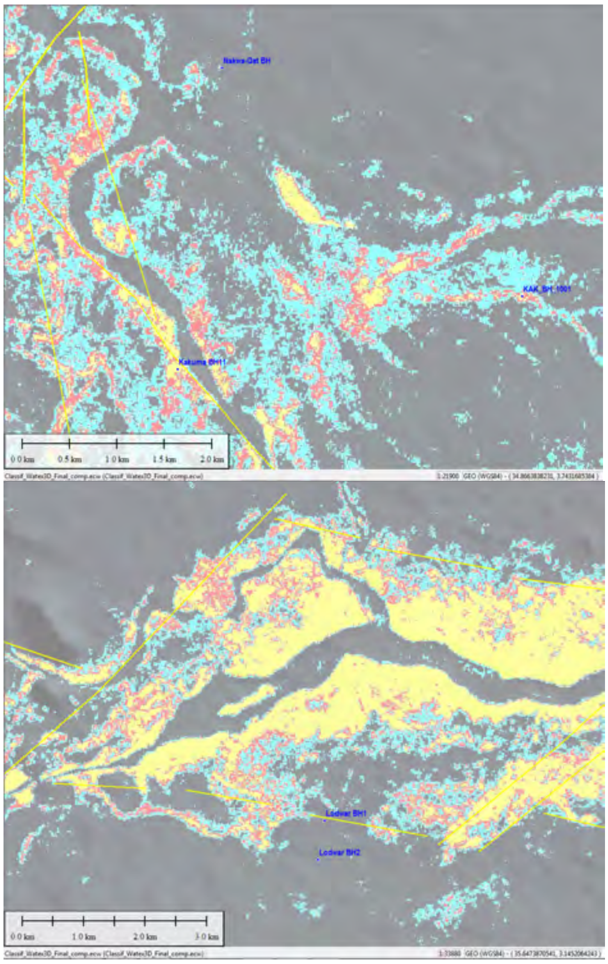


Figure 4.5. Examples of UNESCO Sample (4), showing the location of boreholes drilled by UNESCO and other partners in 2013. The top image is the Kakuma area. The bottom image is the Lodwar area. UNESCO, 2013.



Results of validation

Table 4.2 summarizes the results of UNESCO-run validation of the four samples against the two tests of accuracy. For the first test (*How accurate is the WATEX-SAGOM in predicting groundwater occurrence?*), the exercise resulted in a range of 94-100% accuracy in detecting shallow alluvial aquifers. It is worth noting that 100% of the boreholes drilled with the use of the WATEX Groundwater Target Map (based on SAGOM) have been drilled successfully, all tapping into shallow aquifers.

For the second test (*How accurate is WATEX-SAGOM in predicting both groundwater occurrence and absence?),* the exercise found the model accuracy to range from 70-100%. Though this points to less skill or certainty of the model when dry areas are considered, it is important to note that the goal of the SAGOM is to identify shallow groundwater. The sample may also be skewed since very few data were obtained on boreholes that were dry or unproductive, since this information is not easily shared.

Table 4.2. Results of the validation of SAGOM model. UNESCO, 2013.

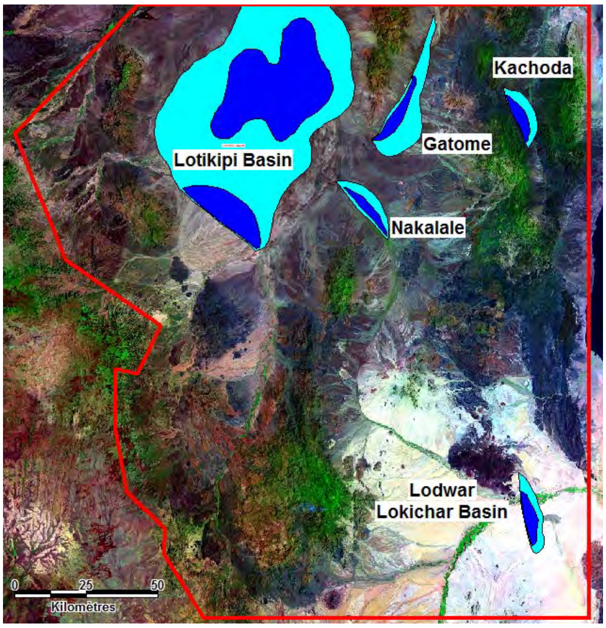
	Sample 1 Collected by RTI		Sample 2 Collected by UNESCO (Secondary sources)		Sample 3 Collected by UNESCO in the field		Sample 4 New boreholes drilled with the WATEX survey maps	
	Qty	%	Qty	%	Qty	%	Qty	%
SAMPLE ANALYSIS								
Sample size Total no. of water points (boreholes, wells and springs)	628		156		9		4	
No. of boreholes with groundwater occurrence	559	89%	146	94%	9	100%	4	100%
No. of boreholes with absence of groundwater	69	11%	10	7%	0	0%	0	0%
Test 1.: Level of model accuracy in detecting groundwater occurrence								
(A) No. of groundwater points with proven water occurrence (Total no. of PRODUCTIVE boreholes, wells and springs located in areas with positive WATEX response, eg. situated on a bright pixel)	395		94		9		4	
(B) No. of groundwater points which are situated on the positive response areas *Total number of NON-PRODUCTIVE and PRODUCTIVE boreholes, wells and springs located in areas with positive WATEX response (situated on a bright pixel*	421		97		9		4	
(C) Level of model accuracy (skill) in detecting the occurrence of water in positive response areas *Proportion (%) of productive boreholes, wells and springs to total number of non-productive/productive boreholes, wells and springs which are located in areas with positive WATEX response (situated on a bright pixel). Formula: C = A / B x 100*		94%		97%		100%		100%
Test 2. Level of model accuracy in detecting both groundwater occurrence and absence								
(A-1) Number of groundwater points with proven water occurrence Total number of PRODUCTIVE boreholes, wells and springs located in areas with positive WATEX response (situated on a bright pixel)	395		94		9		4	
(A-2) Number of groundwater points with proven absence of water Total number of non-productive boreholes, wells and springs located in areas with negative WATEX response (situated on a dark pixel)	43		7		0		0	
(B) Number of groundwater points which match the shallow groundwater model *Formula B = A.1 + A.2*	438		101		9		4	
(C) Anomalies Total number of boreholes, wells and springs whose water occurrence status (eg. Productive/non-productive) do not match the model (eg. Bright/dark pixel)	190		55		0		0	
(D) Level of model accuracy (skill) in detecting the occurrence and absence of water		70%		65%		100%		100%

4.3. Deep Aquifer Model

The implementation of the Deep Aquifer Model has enabled five major deep structures to be mapped and assessed by the survey. Given that these five structures were previously unknown to science, these findings are a very significant result for hydrogeology in Kenya, and for the people who will benefit from them. These structures represent a cumulative storage reserve of 248 BCM, and a great source of renewable water resources (1.36 BCM per annum).

The DAM aims to represent groundwater regimes that are, in general, stored in confined or semi-confined formations in permeable geologic material from 80-100 meters to an approximate depth of 3,000 meters or more. RTI designed DAM specifically to provide valuable information for assessing the groundwater potential of individual deep aquifer systems and to serve as a tool for those planning projects that depend upon these systems.

Figure 4.6. DAM regional model representation of five deep-seated structures in northern-central Turkana County. RTI, 2013.



Method of validation

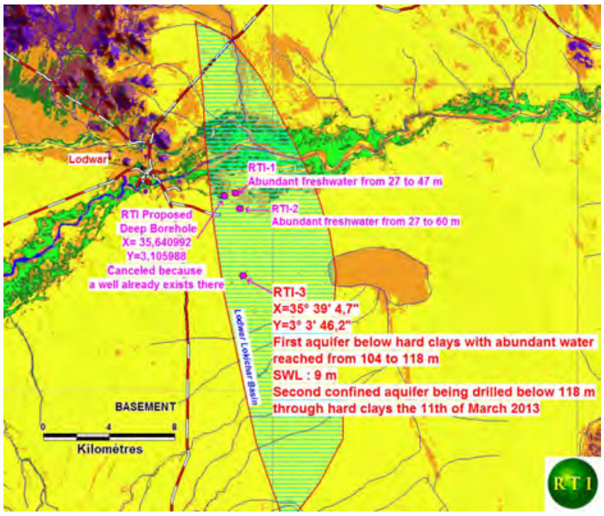
The aim of validating the DAM is to measure its ability to predict naturally occurring deep structures. The model describes the spatial distribution – the physical location and extent – of these deep systems. Location and extent are expressed as two-dimensional polygon shapes. However the exact geometry of the aquifer is given as an extrapolation of RTI's interpretation.

The accuracy of the DAM has been measured in terms of the statistical closeness of a model's predictions to the observed reality. Since the structures identified by the DAM are new to science, the only source of validation at this stage is the drilling of new exploratory boreholes into the newly recorded structures.

Samples

UNESCO has implemented a programme of drilling exploratory boreholes into two of the five deep structures identified by DAM: Lodwar Basin Aquifer and Lotikipi Basin Aquifer System. Unfortunately, the UNESCO project was limited and only able to drill deep exploratory boreholes for validation in these two systems, thus limiting the size of the sample. But in terms of the significance of these findings to science, this method of validation will suffice until additional boreholes can be drilled by scientists in order to refine the DAM models of these deep aquifers. The full datasets of these samples can be found in Annex – Drilling Report.

Figure 4.7. Location of exploratory borehole drilling in Lodwar. The red and green polygon is the DAM representation of the Lodwar Basin Aquifer (RTI). UNESCO, 2013.



Lotikipi Basin Aquifer: Confirmed, July 2013

One deep borehole was drilled by UNESCO from May to July 2013, down to a depth of 330 meters, penetrating three aquifer layers and a cumulative aquifer thickness of 202 meters. Three interconnected aquifer layers of the upper part of the Lotikipi Basin Aquifer were encountered, confirming the original hypothesis of the existence of a mature endoreic delta that consists from surface to 300 m of coalescent palaeo-channels rich in quartz gravels and sands.

Following the drilling of the deep borehole at Lotikipi Basin Aquifer, we can assess its surface area to be 4,146 km2 and a storage volume of over 200 BCM (equivalent to the volume of Lake Turkana). Recharge of the aquifer occurs in a zone of over 21,000 km2, which extends to as far south as Mount Elgon and the Ugandan border. More research is required to fully assess the potential of the aquifer to support specific development purposes.

Figure 4.11. Water production from the deep exploratory borehole at Lotikipi Basin Aquifer. UNESCO, 2013.

4.4. Conclusion

UNESCO has conducted a test the level of accuracy, or skill, of the groundwater models implemented by the contractor, RTI, to represent complex groundwater systems in the survey area. Testing and statistical methodology were applied to each model independently.

The overarching conclusion of this validation exercise is that the methods that RTI employed to model the occurrence of both shallow alluvial aquifers and deep-seated aquifers have great skill and accuracy. The statistics for productive boreholes matching the shallow alluvial groundwater model with a 94-100% rate strongly support this claim. Likewise, the confirmation of the deep Lodwar and Lotikipi aquifer systems provided by the exploratory borehole drilling conducted independently by UNESCO is irrefutable evidence of the ability of the Deep Aquifer Model to predict and identify these structures successfully. Therefore, the models implemented for this survey are accepted as valid and sound, and users of the maps and the analysis of this survey should use them with the highest confidence.

5. Conclusions and Recommendations

5.1. Introduction

The survey of hydrogeological resources of northern and central Turkana County aimed to undertake advanced exploration techniques in order to map and assess the potential of these resources in their current natural context. This report has attempted to summarize the findings of the assessment and provide a new baseline with which to underpin groundwater management in the short and long term. A set of maps and tools were developed, which have been delivered and accompany this report. The key findings of the survey are summarized here in this chapter. A broad set of recommendations is also given.

5.2. Key scientific findings

The following are the key findings of the study.

Physical location and depth

The study successfully explored, modeled and mapped all groundwater regimes of northern-central Turkana County. The WATEX© system has detected and confirmed the existence of shallow groundwater aquifers (between surface and 80 m) and deep aquifer structures (below 80 m) affected by dense fracture patterns linked to the evolution of the East African Rift. Shallow aquifers of the region, most of which occur in the first 80-100 meters in alluvial formations and in fractures, account for 2.085 BCM available water per year.

This study also recorded five large, deep-seated aquifer structures which had not been identified by science before: Gatome, Nakalale, Kachoda, Lodwar and the large paleo lake – Lotikipi Basin Aquifer. This study was able to confirm the existence of the Lodwar and the Lotikipi Basin Aquifers through exploration drilling. Table 5.1 summarizes the known characteristics of these two aquifers. All groundwater regimes are represented on the Groundwater Target Map delivered with this report.

Table 5.1. Characteristics of confirmed deep aquifers. RTI, 2013.

Parameter	Lodwar Basin	Lotikipi Basin
Aquifer type	Sedimentary, unconfined	Major sedimentary, unconfined
Lithology	Clays, sands, sandstones	Paleo lake sediments
Dominant flow regime	Inter-granular	Inter-granular
Scale	Local	Regional
Surface area, km2	140	4,146
Storage, MCM/yr	10,000	207,000
Recharge, MCM/yr	Unknown	1,200
Abstraction, MCM/yr	0	0
Pollution vulnerability	Unknown	Moderate
Saltwater vulnerability	Moderate	Low
Depletion vulnerability	Low	Low
Dominant water use (in approximate order of volumetric use)	N/A	N/A
WRMA Type	Strategic	Strategic
WMRA Status	Unknown	Unknown

Volume of groundwater storage

Contrary to intuition, large amounts of water are stored under the ground in northern-central Turkana County. In shallow depths near riparian systems, around 2 BCM of water is kept for short periods. The greatest quantities, however, are being stored in the five deep-seated structures identified by this survey. It is estimated that the region's deep aquifers, including the paleo-lake basin aquifer of Lotikipi, store a massive 248 BCM of water. Though these deep aquifers are sizeable, renewable reservoirs, they replenish at a rate of 1.34 BCM per year.

The large Lotikipi Basin Aquifer System – its existence confirmed by UNESCO in July 2013 – will no doubt play a vital role in the economic security of the country. Its annual replenishment of 1.2 km3 alone represents 6% of the nation's total renewable resources (20.2 km3/year). A freshwater reserve of 207 BCM, Lotikipi Aquifer equals the volume of Lake Turkana today, offering the prospect of becoming the "New Lake Turkana" since, unlike the actual lake that has alkaline water, its waters are fit for human consumption. As a major reservoir, the Lotikipi Aquifer also makes a significant contribution to Kenya's strategic water reserves by expanding in real terms the national dam capacity from 24 km3 to 224 km3 – a nine-fold (900%) increase.

Groundwater inventory

Taking into consideration the total potential recharge rates of both high-potential shallow aquifers and the five deep aquifer structures, the study estimates the total renewable groundwater resources of northern-central Turkana to be 3.447 BCM per year, which represents only 1.38% of the total storage volume (250 BCM).

Implications for national development

The importance of the findings of this study as a scientific advancement cannot be understated; both in terms of the potential impact of these findings may have on future human development and in terms of their contribution to hydrogeological science in Kenya and the region.

At the national scale, these groundwater systems raise Kenya's total renewable water resources from 20.2 km3/yr to 23.6 km3/yr, representing an increase of 17% to the nation's water share. In real terms, that translates into an additional 83 m3 per year per person in Kenya.

The groundwater in Turkana is sufficient to serve the basic and economic needs of over 39 million people every year. During a humanitarian crisis, the groundwater resources of the region could be enough to satisfy the basic needs (15 L/day) to over 625 million people.

Soil inventory

The study classified and mapped the soil types of northern-central Turkana County, offering a new baseline for study of soil health and opening up new possibilities for agricultural development in the region. The soils have been mapped on the Soil and Vegetation Map of Northern and Central Turkana County, delivered with this report. Sandy alluvial and windblown piedmont deposits make up 47% of the survey area, followed by shrub land with dry volcanic soils (20%). More details about soils can be found in the Annex-Soils Report.

Groundwater potentials of priority zones

Lodwar

The capital city of Turkana County, Lodwar, has a promising groundwater potential (1,292 MCM per year), and should be able to improve water access to its 17,000 inhabitants. In Lodwar, there is almost no seasonal groundwater level variation in the boreholes below alluvial deposits. Most aquifers near Lodwar occur at shallow to moderate depths, often less than 50 m, within predominant alluvial sediments mixed with inter-volcanic layers within fractured geologic formations initiated by the shallow granitic basement around a radius of 4 km around the city.

Lodwar is also now endowed with the deep Lodwar Basin Aquifer, with a confirmed estimated storage volume of 10 BCM, reachable within the first 200 meters. The aquifer has great potential for development in the area, although some questions about the water quality may need to be addressed depending on the intended use.

Kakuma

As of July 2013, 120,000 refugees are being housed at Kakuma Refugee Camp, and an additional 30,000 are expected to arrive to Kakuma by January 2014 (UNHCR). This study has assessed the renewable groundwater resources of the immediate area around Kakuma (10 km2) to be around 51 million m3/year. With current water consumption rates of the host community and refugee camp at 1.27 MCM/yr, supplied by merely seven functioning boreholes, the population is only withdrawing a mere 2.5% of the groundwater available to them. Therefore, the potential for augmenting water supply in Kakuma is very high. Best options for shallow boreholes (<100 meters) is to drill within the fracture corridor of the Tarash River identified by the study. Kakuma is also located 25 km south of the southern portion of the large Lotikipi Basin Aquifer (Lotikipi South), which could host large volumes of viable water for the camp and surrounding areas if confirmed by additional exploration and drilling.

Kalobeiyei

Kalobeiyei has been considered by some to be an optional site to which to relocate additional refugees from Kakuma, which is currently overwhelmed by the influx of refugees from South Sudan and other neighbouring countries. Unfortunately, this study observed very poor conditions to support a new population of refugees. The area's 48 MCM of freshwater per year is too fragmented and not viable enough. One opportunity for Kalobeiyei is to develop the Lotikipi South Aquifer, which lies 25 km to the east.

Lokichogio

Despite having 107 MCM of renewable groundwater available, the town of Lokichogio has few viable options available to develop groundwater for its 45,000 inhabitants. Some areas around the town could hold promising quantities of shallow groundwater, but carry risky conditions for drilling with the rhryolitic formations. The best option for Lokichogio is the large Lotikipi Basin Aquifer, which lies 25 km to the east.

5.3. Recommendations

Use of survey tools and maps

The Government of Kenya, as the rightful owner and custodian of the information and tools created by this project, should take measures to ensure that these information and tools are disseminated to the appropriate stakeholders. The GIS database of groundwater resources, the Groundwater Exploration Navigation Systems (GENS), the Field Manual for Groundwater Targeting and the set of maps should be disseminated to the appropriate stakeholders in order to maximize impact and sustainability.

Similarly, expand and build the cadre of skilled professionals who can utilize these tools. UNESCO and RTI have endeavored to build a cadre of skills and capacities within the Government of Kenya and other stakeholders in order to ensure the operation and future sustainability of the products and tools delivered by this project.

Continued research

This study has helped to establish a new vision of groundwater resources in northern and central Turkana County, however, we are only beginning to understand these regimes and their potential to support development aims. Much more research remains to be done to understand them adequately.

The temptation to develop these resources will be great. But, before any major development projects are to be planned, additional studies will be required to achieve a more comprehensive understanding of these resources and their full potential and vulnerabilities. Below are some suggestions for continuing research.

Expansion of WATEX approach to the national scale

The exploration and mapping approach taken by this pilot survey can be applied to other areas, even humid and tropic areas. The WATEX is an operational technology and can benefit areas where rapid baselines need to be established or where comprehensive assessments are needed. Given that this study has covered only half of Turkana County, the study could easily be expanded to cover the remainder of the County as part of a full county assessment. Likewise, this pilot could serve as a model for other studies in other counties in Kenya, and eventually be rolled out at the national scale. Such a study would help draw the Kenya's first hydrogeological map, which still does not exist today.

Assess socio-economic potentials of groundwater in Turkana

A few options for developing groundwater resources in the survey area have been offered by this report, but do not in any way intend to cover the entire range of options available. An extensive study of socio-economic potential of the groundwater resources mapped and assessed by this study should be preclude any major development projects in the county.

Deep hydrogeology in N-C Turkana County

This study was able to establish a baseline model of five previously unrecorded aquifer structures and confirmed the existence of and achieved a more refined model for two of the structures – Lodwar and Lotikipi Aquifer Systems. The importance of this scientific advancement cannot be understated; both in terms of the potential impact of these findings may have on future human development and in terms of their contribution to hydrogeological science in Kenya and the region. With a view to achieving a more complete and robust scientific understanding of these structures, a few specific recommendations for continuing research can be made:

(a) *Deep exploratory borehole drilling*:
A campaign to drill additional exploratory boreholes is needed to confirm and obtain baseline data for unconfirmed aquifers and to continue studying the confirmed aquifers. Each exploratory borehole should be drilled to a minimum depth of 300 to 400 meters, and should be coupled with proper testing for lithology, production, quality and dating/aging.

The following is a suggested programme for deep drilling and testing according to the needs for covering sufficiently the major aquifers of Turkana County.

(i.) *Kachoda Aquifer*: 2 x exploratory boreholes in order to confirm and obtain baseline data.

(ii.) *Gatome Aquifer*: 2 x exploratory boreholes in order to confirm and obtain baseline data.

(iii.) *Nakalale Aquifer*: 4 x exploratory boreholes located along seismic line TVK-8 (north-south) in order to confirm and obtain baseline data.

(iv.) *Lodwar Basin Aquifer*: 6 x exploratory boreholes should be drilled along the seismic lines TVK-3, TVK-2, and TVK-101 in order to study other portions of the aquifer system. This includes: 2 boreholes drilled on TVK-3 west-east northeast from Lodwar town with an interval of 20 km to study the northern and eastern portion; 2 boreholes drilled on TVK-2 spaced 15 km eastward from UNESCO-EXBH3 to study the central and eastern portion of the aquifer; and 2 boreholes drilled on TVK-101 west-east at an interval of 20 km to study the southern portion of the aquifer. If possible, 2 boreholes can be drilled to 600-800 meters to study the deeper portions of the aquifer.

(v.) *Lotikipi Basin Aquifer*: 19 x exploratory boreholes should be drilled along the seismic lines TVK4, TVK5 and TVK6 in order to study other portions of the aquifer system. This includes: 6 boreholes drilled along TVK-4 eastward from UNESCO EXBH-4; 5 boreholes drilled along TVK-5 to study the southern portion of the aquifer that is in closer proximity to Kakuma and the refugee community; and 8 boreholes along TVK-6 (north-south). All boreholes should be spaced by 10 km from one another. At least 2 of the 19 boreholes should be drilled to 600-800 meters in order to study the palaeo-lake in the deeper lacustrine formation.

(vi.) *Other aquifers*: At least 2 boreholes will be needed to study aquifers that will be identified with future surveys of Turkana County. For example, there will be need to drill near the Lokichar Basin area.

(b) *Gravity and magnetic surveying*:
Currently, only low-resolution gravimetry data exists for Turkana County (and the rest of Kenya). Therefore, it is highly recommended to conduct a low-altitude aerial gravimetry/magnetic survey at the county scale, which will offer a much better resolution and understanding of the dimensions and geometry of the basins in Turkana. Achieving an improved evaluation of basin geometry will assist in delineating the zones for land management and aquifer conservation, as well as improving estimates for aquifer storage and recharge.

(c) *Seismic surveying*:
Additional seismic shot lines (2D) with greater density than those lines shot by Shell Company in 1992 (eg TVK4 and TVK5). Note: The Bolen Company, which is currently exploring for oil in Lotikipi and around Lokichogio, may be planning or implementing the above-mentioned seismic and gravity surveying.

(d) *Hydrogeological assessment and modeling:*
Modeling and assessment of individual aquifers is required to study flow and recharge dynamics as well as achieving a more robust estimate of production. This hydrogeological study will evaluate the aquifer for sustainability, suitability for potable supply, and possible measures for supply enhancement. The study will help provide a water supply more resistant to drought, and through cooperation with local, national, regional, and international entities, further develop the capacity of scientists and engineers in groundwater assessment and development.

Build national drilling capacities

The skills and capacity of the Kenyan borehole drilling industry are inadequate for carrying out reliable and sound exploratory drilling, and need to be supported to improve the level of capacity and service. The industry is short in terms of skilled professionals and in terms of equipment, which is outdated. The impact is felt when many drilling projects do not succeed due to lack of capacity. A major campaign should be launched to build the capacity of the industry as a whole, and reduce the inefficiencies in the market.

Short-term development projects in Turkana County

While it is out of the scope of this report to offer any advice on ambitious, large scale projects to exploit groundwater in Turkana, a few suggestions can be made for actions can be undertaken with little risk to the groundwater systems that have been mapped and implemented in the short term while additional research is being conducted.

Immediate water supply to local communities

It is highly recommended to develop and equip the exploratory boreholes drilled by UNESCO (Lotikipi BH and Lodwar BH2) to provide immediate and long-term water supply for local communities. UNESCO's discussion with local stakeholders suggest that the development include installing wind and/or solar driven high-volume pumps, with an elevated tower steel tank (capacity 200 m3), distributed to multiple points in different locations to avoid destruction of rangeland at the borehole and disruption of grazing routes. A series of three submersible pumps should be installed in the boreholes, one for each aquifer layer.

Furthermore, hundreds of shallow boreholes (80-100m) can be drilled immediately across central-northern Turkana County. Priority of boreholes can be given to the areas identified by the Turkana Government and other stakeholders. WRMA will need to coordinate and regulate the proliferation of boreholes by various partners.

Aquifer Management

In addition to drilling additional boreholes to augment water supplies, a few suggestions can be made about managing the groundwater resources mapped by this survey.

Firstly, Kenyan authorities should establish a limit on abstraction rates for both the Lotikipi and Lodwar Aquifers. WRMA can establish the rates for abstraction for normal and emergency situations.

Secondly, Kenyan authorities are recommended to gazette the land above the aquifers in order to protect them from harmful activities. For example, the recharge zone of Lotikipi Basin Aquifer (4,146 km2) can be gazette to ensure that its water quality is conserved.

Thirdly, establish a modern aquifer monitoring system to monitor the Lotikipi and Lodwar aquifers. Modern logging equipment can be installed in the UNESCO boreholes at Lotikipi and Lodwar in order to monitor the state of the aquifers and collect additional data.

Annex
(Published Separately)

Summary of reports

A. Drilling Report

Provides a summary of the data samples used to validate the WATEX groundwater models, including the exploratory boreholes drilled by UNESCO and the regional samples collected.

B. Dataset Report

The report describes the set of data that are collected, processed and generated as the main body of scientific information during this survey. Primary data, such as raw imagery and other acquired data are discussed. The report also discusses the secondary data, or WATEX-derived products that are developed by RTI and used for advanced stages of interpretation and modeling. The final GIS database is also described. It then describes the final, complete dataset, or GIS database of the survey.

C. Geologic Report

The report describes the geologic data collected and observed in the field during ground-truthing, which was used to interpret and analyze geological formations. These data were essential in assessing groundwater potential in the region.

D. Geophysics Report

The report presents the geophysical data, such as seismic and resistivity (VES) and results of interpretation and analysis conducted by the Contractor (RTI).

E. Hydrology Report

The report presents the hydrological data collected and analyzed for the study. It includes data for climate and all WATEX-derived products such as drainage and watershed dynamics.

F. Soil Classification Report

The report discusses how pedological resources were interpreted and analyzed in order to generate an accurate map of soil classification.

Kenya, like other countries grappling with recurrent drought and water scarcity, is relying increasingly upon groundwater to satisfy rising water demand. Some 43% of rural and 24% of urban households now depend on a spring, well, or borehole as their main source of water. In Turkana County, one of Kenya's driest and poorest regions, rural water supply projects rely considerably on groundwater to meet the needs of pastoralists and displaced populations.

Meeting the demand for groundwater will require greater capacities in abstraction and long-term aquifer management. Yet, a lack of precise information on groundwater occurrence has consequences for both local borehole drilling and regional aquifer management. Borehole drilling has become a risky business, with many contractors drilling haphazardly or without sufficient information to drill in the right areas. Two in three boreholes in Turkana are drilled dry. Similarly, without access to reliable information, government technicians and groundwater consultants face greater difficulties in providing sound advice on groundwater development projects.

As a response to regional drought and the knowledge gap on groundwater, UNESCO commissioned this study of hydrogeological resources with a view to improve the effectiveness of groundwater projects in Turkana County. As part of the regional initiative GRIDMAP, UNESCO commissioned Radar Technologies International to implement this study with the innovative technology, the WATEX™ System, which integrates remote sensing, petroleum industry interpretation and conventional hydrogeology to achieve more precise maps of deep and shallow groundwater reserves. This report summarizes the findings and outcomes of the study, and outlines important recommendations for the sustainable exploitation of these precious resources in Turkana County and the nation of Kenya. The report is part of the overall package of practical tools developed for this project, which includes maps, GIS database, a field manual for groundwater targeting, and tailored advice for decision makers and technicians.

This report and the associated tools are intended to provide a new vision for groundwater in Turkana, and help form the basis for future studies of the resource in Kenya.

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