SSIGL 7

NATIONAL GUIDELINES

For Small Scale Irrigation Development in Ethiopia

Groundwater Study and Design

November 2018

Addis Ababa

MINISTRY OF AGRICULTURE

National Guidelines for Small Scale Irrigation Development in Ethiopia

SSIGL 7: Groundwater Study and Design

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First Edition 2018

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FORWARD

Ministry of Agriculture, based on the national strategic directions is striving to meet its commitments in which modernizing agriculture is on top of its highest priorities to sustain the rapid, broad-based and fair economic growth and development of the country. To date, major efforts have been made to remodel several important strategies and national guidelines by its major programs and projects.

While efforts have been made to create access to irrigation water and promoting sustainable irrigation development, several barriers are still hindering the implementation process and the performance of the schemes. The major technical constrains starts from poor planning and identification, study, design, construction, operation, and maintenance. One of the main reasons behind this outstanding challenge, in addition to the capacity limitations, is that SSIPs have been studied and designed using many ad-hoc procedures and technical guidelines developed by various local and international institutions.

Despite having several guidelines and manuals developed by different entities such as MoA (IDD)-1986, ESRDF-1997, MoWIE-2002 and JICA/OIDA-2014, still the irrigation professionals follow their own public sources and expertise to fill some important gaps. A number of disparities, constraints and outstanding issues in the study and design procedures, criteria and assumptions have been causing huge variations in all vital aspects of SSI study, design and implementation from region to region and among professionals within the same region and institutions due mainly to the lack of agreed standard technical guidelines. Hence, the SSI Directorate with AGP financial support, led by Generation consultant (GIRDC) and with active involvement of national and regional stakeholders and international development partners, these new and comprehensive national guidelines have been developed.

The SSID guidelines have been developed by addressing all key features in a comprehensive and participatory manner at all levels. The guidelines are believed to be responsive to the prevalent study and design contentious issues; and efforts have been made to make the guidelines simple, flexible and adaptable to almost all regional contexts including concerned partner institution interests. The outlines of the guidelines cover all aspects of irrigation development including project initiation, planning, organizations, site identification and prioritization, feasibility studies and detail designs, contract administration and management, scheme operation, maintenance and management.

Enforceability, standardization, social and environmental safeguard mechanisms are well mainstreamed in the guidelines, hence they shall be used as a guiding framework for engineers and other experts engaged in all SSI development phases. The views and actual procedures of all relevant diverse government bodies, research and higher learning institutions, private companies and development partners has been immensely and thoroughly considered to ensure that all stakeholders are aligned and can work together towards a common goal. Appropriately, the guidelines will be familiarized to the entire stakeholders working in the irrigation development. Besides, significant number of experts in the corresponding subject matter will be effectively trained nationwide; and the guidelines will be tested practically on actual new and developing projects for due consideration of possible improvement. Hence, hereinafter, all involved stakeholders including government & non-governmental organizations, development partners, enterprises, institutions, consultants and individuals in Ethiopia have to adhere to these comprehensive national guidelines in all cases and at all level whilst if any overlooked components are found, it should be documented and communicated to MOA to bring them up-to-date.

Therefore, I congratulate all parties involved in the success of this effort, and urge partners and stakeholders to show a similar level of engagement in the implementation and stick to the guidelines over the coming years.

H.E. Dr. Kaba Urgessa
State Minister, Ministry of Agriculture

SMALL SCALE IRRIGATION DEVELOPMENT VISION

Transforming agricultural production from its dependence on rain-fed practices by creating reliable irrigation system in which smallholder farmers have access to at least one option of water source to increase production and productivity as well as enhance resilience to climate change and thereby ensure food security, maintain increasing income and sustain economic growth.

ACKNOWLEDGEMENTS

The preparation of SSIGLs required extensive inputs from all stakeholders and development partners. Accordingly many professionals from government and development partners have contributed to the realization of the guidelines. To this end MOA would like to extend sincere acknowledgement to all institutions and individuals who have been involved in the review of these SSIGLs for their comprehensive participation, invaluable inputs and encouragement to the completion of the guidelines. There are just too many collaborators involved to name exhaustively and congratulate individually, as many experts from Federal, regional states and development partners have been involved in one way or another in the preparation of the guidelines. The contribution of all of them who actively involved in the development of these SSIGLs is gratefully acknowledged. The Ministry believes that their contributions will be truly appreciated by the users for many years to come.

The Ministry would like to extend its appreciation and gratitude to the following contributors:

- Agriculture Growth Program (AGP) of the MoA for financing the development and publication of the guidelines.
- The National Agriculture Water Management Platform (NAWMP) for overseeing, guidance and playing key supervisory and quality control roles in the overall preparation process and for the devotion of its members in reviewing and providing invaluable technical inputs to enrich the guidelines.
- Federal Government and Regional States organizations and their staff for their untiring effort in reviewing the guidelines and providing constructive suggestions, recommendations and comments.
- National and international development partners for their unreserved efforts in reviewing the guidelines and providing constructive comments which invaluably improved the quality of the guidelines.
- Small-scale and Micro Irrigation Support Project (SMIS) and its team for making all efforts to have quality GLs developed as envisioned by the Ministry.

The MOA would also like to extend its high gratitude and sincere thanks to AGP's multi development partners including the International Development Association (IDA)/World Bank, the Canada Department of Foreign Affairs, Trade and Development (DFATD), the United States Agency for International Development (USAID), the Netherlands, the European Commission (EC), the Spanish Agency for International Development (AECID), the Global Agriculture and Food Security Program (GAFSP), the Italy International Development Cooperation, the Food and Agriculture Organization (FAO) and the United Nations Development Program (UNDP).

Moreover, the Ministry would like to express its gratitude to Generation Integrated Rural Development Consultant (GIRDC) and its staff whose determined efforts to the development of these SSIGLs have been invaluable. GIRDC and its team drafted and finalized all the contents of the SSIGLs as per stakeholder suggestions, recommendations and concerns. The MoA recognizes the patience, diligence, tireless, extensive and selfless dedication of the GIRDC and its staff who made this assignment possible.

Finally, we owe courtesy to all national and International source materials cited and referred but unintentionally not cited.

Ministry of Agriculture

DEDICATIONS

The National Guidelines for Small Scale Irrigation Development are dedicated to Ethiopian smallholder farmers, agro-pastoralists, pastoralists, to equip them with appropriate irrigation technology as we envision them empowered and transformed.

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ACRONYMS

AGP	Agricultural Growth Program
API	American Petroleum Institute
ASTM	American Society for Testing Materials
CAD	Computer Aided Design
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EC	Electrical Conductivity
ET	Evapotranspiration
GIRDC	Generation Integrated Rural Development Consultant
GIS	Geographic Information System
GW	Ground Water
MOANR	Ministry of Agriculture and Natural Resource
MOWIE	Ministry of Water, Irrigation and Electricity
NGO	Non-governmental Organization
PVC	Poly Venile Chloride
SAR	Sodium Absorption Ratio
SSID	Small Scale Irrigation Development
SSIGL	Small Scale Irrigation Guideline
SSIP	Small Scale Irrigation Project
SSIS	Small Scale Irrigation Scheme
TDS	Total Dissolved Salt
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
USSL	United States Salinity Laboratory
UTM	Universal Traverse Mercator
VES	Vertical Electrical Sounding
WTF	Water-table Fluctuation
WWDSE	Water Works Design and Supervision Enterprise

PREFACE

While irrigation development is at the top of the government's priority agendas as it is key to boost production and improve food security as well as to provide inputs for industrial development. Accordingly, irrigated land in different scales has been aggressively expanding from time to time. To this end, to enhance quality delivery of small-scale irrigation development planning, implementation and management, it has been decided to develop standard SSI guidelines that must be nationally applied. In September 2017 the Ministry of Agriculture (MoA) had entrusted Generation Integrated Rural Development Consultant (GIRDC) to prepare the National Small-scale Irrigation Development Guidelines (SSIGLs).

Preparation of the SSIGLs for enhancing development of irrigated agriculture is recognized as one of the many core initiatives of the MoA to improve its delivery system and achieve the targets in irrigated agriculture and fulfill its mission for improving agricultural productivity and production. The core objective of developing SSIGLs is to summarize present thinking, knowledge and practices to enable irrigation practitioners to properly plan, implement and manage community managed SSI schemes to develop the full irrigation potential in a sustainable manner.

As the SSIGLs are prepared based on national and international knowledge, experiences and practices, and describe current and recommended practice and set out the national standard guides and procedures for SSI development, they serve as a source of information and provide guidance. Hence, it is believed that the SSIGLs will contribute to ensuring the quality and timely delivery, operation and maintenance of SSI schemes in the country. The SSIGLs attempt to explain and illustrate the important concepts, considerations and procedures in SSI planning, implementation and management; and shall be used as a guiding framework for professionals engaged in SSI development. Illustrative examples from within the country have been added to enable the users understand the contents, methodologies presented in the SSIGLs.

The intended audiences of the SSIGLs are government organizations, NGOs, CSOs and the private sector involved in SSI development. Professionally, the SSIGLs will be beneficial for experienced and junior planners, experts, contractors, consultants, suppliers, investors, operators and managers of SSI schemes. The SSIGLs will also serve as a useful reference for academia and researchers involved and interested in SSI development. The SSIGLs will guide to ensure that; planning, implementation and management of SSI projects is formalized and set procedures and processes to be followed. As the SSIGLs provide information and guides they must be always fully considered and applied by adapting them to the local specific requirements.

In cognizance with the need for quality SSIGLs, the MoA has duly considered quality assurance and control during preparation of the guidelines. Accordingly, the outlines, contents and scope of the SSIGLs were thoroughly discussed, reviewed and modified by NAWMP members (senior professionals from public, national and international stakeholder) with key stakeholders in many consultative meetings and workshops. Moreover, at each milestone of SSIGL preparation, resource persons from all stakeholders reviewed and confirmed that SSIGLs have met the demands and expectations of users.

Moreover, the Ministry has mobilized resource persons from key Federal, National Regional States level stakeholders and international development partners for review, validation and endorsement of the SSIGLs.

Several hundreds of experienced professionals (who are very qualified experts in their respective fields) from government institutions, relevant private sector and international development partners have significantly contributed to the preparation of the SSIGLs. They have been involved in all aspects of the development of SSIGLs throughout the preparation process. The preparation process included a number of consultation meetings and workshops: (i) workshop to review inception report, (ii) workshop on findings of review of existing guidelines/manuals and proposed contents of the SSIGLs, (iii) meetings to review zero draft SSI GLs, (iv) review workshop on draft SSI GLs, (v) small group review meetings on thematic areas, (vi) small group consultation meetings on its final presentation of contents and layout, (vii) consultation mini-workshops in the National States on semi-final versions of the SSIGLs, and (viii) final write-shop for the appraisal and approval of the final versions of SSIGLs.

The deliberations, concerns, suggestions and comments received from professionals have been duly considered and incorporated by the GIRD Consultant in the final SSIGLs.

There are 34 separate guidelines which are categorized into the following five parts concurrent to SSI development phases:

Part-I. Project Initiation, Planning and Organization Guideline which deals with key considerations and procedures on planning and organization of SSI development projects.

Part-II. Site Identification and Prioritization Guideline which treats physical potential identification and prioritization of investment projects. It presents SSI site selection process and prioritization criteria.

Part-III. Feasibility Study and Detail Design Guidelines for SSID dealing with feasibility study and design concepts, approaches, considerations, requirements and procedures in the study and design of SSI systems.

Part-IV. Contract Administration and Construction Management Guidelines for SSI development presents the considerations, requirements, and procedures involved in construction of works, construction supervision and contract administration.

Part-V. SSI Scheme Management, Operation and Maintenance Guidelines which covers SSI Scheme management and operation.

Moreover, Tools for Small Scale Irrigation development are also prepared as part of SSIGLs.

It is strongly believed and expected that; the SSIGLs will be quickly applied by all stakeholders involved in SSI development and others as appropriate following the dissemination and familiarization process of the guidelines in order to ensure efficient, productive and sustainable irrigation development.

The SSIGLs are envisioned to be updated by incorporating new technologies and experiences including research findings. Therefore, any suggestions, concerns, recommendations and comments on the SSIGLs are highly appreciated and welcome for future updates as per the attached format below. Furthermore, despite efforts in making all types of editorial works, there may still errors, which similarly shall be handled in future undated versions.

UPDATING AND REVISIONS OF GUIDELINES

The GLs are intended as an up-to-date or a live document enabling revisions, to be updated periodically to incorporate improvements, when and where necessary; may be due to evolving demands, technological changes and changing policies, and regulatory frameworks. Planning, study and design of SSI development interventions is a dynamic process. Advancements in these aspects are necessary to cope up with the changing environment and advancing techniques. Also, based on observation feedbacks and experiences gained during application and implementation of the guidelines, there might be a need to update the requirements, provisions and procedures, as appropriate. Besides, day-by-day, water is becoming more and more valuable. Hence, for efficient water development, utilization and management will have to be designed, planned and constructed with a new set up of mind to keep pace with the changing needs of the time. It may, therefore, be necessary to take up the work of further revision of these GLs.

This current version of the GLs has particular reference to the prevailing conditions in Ethiopia and reflects the experience gained through activities within the sub-sector during subsequent years. This is the first version of the SSI development GLs. This version shall be used as a starting point for future update, revision and improvement. Future updating and revisions to the GLs are anticipated as part of the process of strengthening the standards for planning, study, design, construction, operation and management SSI development in the country.

Completion of the review and updating of the GLs shall be undertaken in close consultation with the federal and regional irrigation institutions and other stakeholders in the irrigation sub-sector including the contracting and consulting industry.

In summary, significant changes to criteria, procedures or any other relevant issues related to technological changes, new policies or revised laws should be incorporated into the GLs from their date of effectiveness. Other minor changes that will not significantly affect the whole nature of the GLs may be accumulated and made periodically. When changes are made and approved, new page(s) incorporating the revision, together with the revision date, will be issued and inserted into the relevant GL section.

All suggestions to improve the GLs should be made in accordance with the following procedures:

I. Users of the GLs must register on the MOA website: Website: www.moa.gov.et
II. Proposed changes should be outlined on the GLs Change Form and forwarded with a covering letter or email of its need and purpose to the Ministry.
III. Agreed changes will be approved by the Ministry on recommendation from the Small-scale Irrigation Directorate and/or other responsible government body.
IV. The release date of the new version will be notified to all registered users and authorities.

Users are kindly requested to present their concerns, suggestions, recommendations and comments for future updates including any omissions and/or obvious errors by completing the following revisions form and submitting it to the Ministry. The Ministry shall appraise such requests for revision and will determine if an update to the guide is justified and necessary; and when such updates will be published. Revisions may take the form of replacement or additional pages. Upon receipt, revision pages are to be incorporated in the GLs and all superseded pages removed.

Suggested Revisions Request Form (Official Letter or Email)

To: ---
From: ---
Date: ---
Description of suggested updates/changes: Include GL code and title, section title and # (heading/subheading #), and page #.

GL Code and Title	Date	Sections/ Heading/Subheading/ Pages/Table/Figure	Explanation	Comments (proposed change)

Note that be specific and include suggested language if possible and include additional sheets for comments, reference materials, charts or graphics.

GLs Change Action

Suggested Change	Recommended Action	Authorized by	Date

Director for SSI Directorate**:** ________________________**Date:** _________________

The following table helps to track initial issuance of the guidelines and subsequent Updates/Versions and Revisions (Registration of Amendments/Updates).

Revision Register

Version/Issue/Revision No	Reference/Revised Sections/Pages/topics	Description of revision (Comments)	Authorized by	Date

1 OBJECTIVE AND SCOPE OF THE GUIDELINE

The ultimate objective of this guideline is to standardize the hydrogeological investigation practice; methods and procedures to meet internationally accepted qualities in shallow groundwater studies targeted to be used as irrigation source in conjunction with surface water for gravity and pressurized Small Scale Irrigation Projects (SSIPs) in Ethiopia. It is intended to have independent guideline for SSIPs by filling the gaps of the previous guidelines prepared by different bodies for irrigation projects of different magnitudes/scales.

The guideline is further targeted to provide and follow:

- The necessary approaches and/or methods, instrumentations and technical knowledge to locate, investigate and extract groundwater resource so that current and future generations can depend on this resource in conjunction with surface water for irrigation to enhance the quality of life.
- Best practices in the field of Hydrogeology and assisting the professionals in the field in conducting an appropriate investigation and generating a hydrogeological report that meet a generally accepted minimum standard.

The scope of this guideline is to outline the desirable quantity and quality of shallow groundwater resource investigations required for safe and economical design and construction of SSIPs in Ethiopia.

In this regard groundwater is taken as a priceless resource lying beneath most of the earth’s land surface. Reliance on groundwater has increased greatly because of population shifts to areas where surface water is often not adequate. Similarly, substantial increases in groundwater withdrawals have occurred recently in almost every country of the world.

The vulnerability of groundwater to overuse and water quality degradation was not widely understood until recently. In the future, as much attention shall be given to water quality preservation and resource conservation as to the resource development.

Ideally, before groundwater is developed in a basin, an investigation of the groundwater resources should be made. In practice this rarely occurs; instead, a study is usually initiated either after extensive development with a view toward further development or after over development when a problem threatening the water supply or irrigated agriculture appears imminent. Investigations are seldom concerned with simply locating groundwater supplies. More commonly the concerns involve evaluating the quantity and quality of groundwater resources already known to exist or determining the impact of human plans or activities on the quantity and quality of groundwater.

Another cause of poor hydrogeological practice in an area’s groundwater investigation is the absence of an established and generally accepted guideline through which hydrogeological investigations and reports are evaluated. And this poor hydrogeological practice leads to inaccurate results, unfounded recommendations, and poor design of facilities or programs which finally results in depletion, contamination and misuse of groundwater resource. Therefore, there is a need to establish guideline against which hydrogeological investigations and hydrogeological reports are to be evaluated.

Groundwater potential evaluation for irrigated agriculture in Ethiopia is newly being practiced and is done by well programmed and integrated investigation techniques. Indirect and direct groundwater exploration methods are applied. The indirect methods of groundwater exploration currently under practice in the country include detail geological, geomorphological and structural mapping at large scales; geophysical surveys, hydrological study, and water points inventory with water quality survey. The only direct method of the investigation is drilling and testing works of mapping/test wells.

An assessment of the groundwater resources of an aquifer system involves developing of a quantitative understanding of the flow processes which operate within the aquifer. Three features must be considered:

- How water enters the aquifer system,
- How water passes through the aquifer system and
- How water leaves the aquifer system.

The investigation is carried out mainly in two phases comprising phase I (Detail Reconnaissance) and phase II (Feasibility). Each phase will have investigation stages and related activities and in general extended to:

- determine the hydraulic properties and the dimensions of each unit in the geologic section;
- determine the source and amount of recharge to each aquifer;
- determine the amount and location of discharge from each aquifer;
- determine the quality of the water from each aquifer
- determine the effects of withdrawal of water from each aquifer
- determine the effects on surface water of changes in recharge and discharge of groundwater
- determine the direction of water movement
- determine the effects on groundwater of the changes in surface water
- determine the source(s) and fate of contaminants;

The work process in groundwater potential study and design is as shown in the activity flow chart of figure1-1.

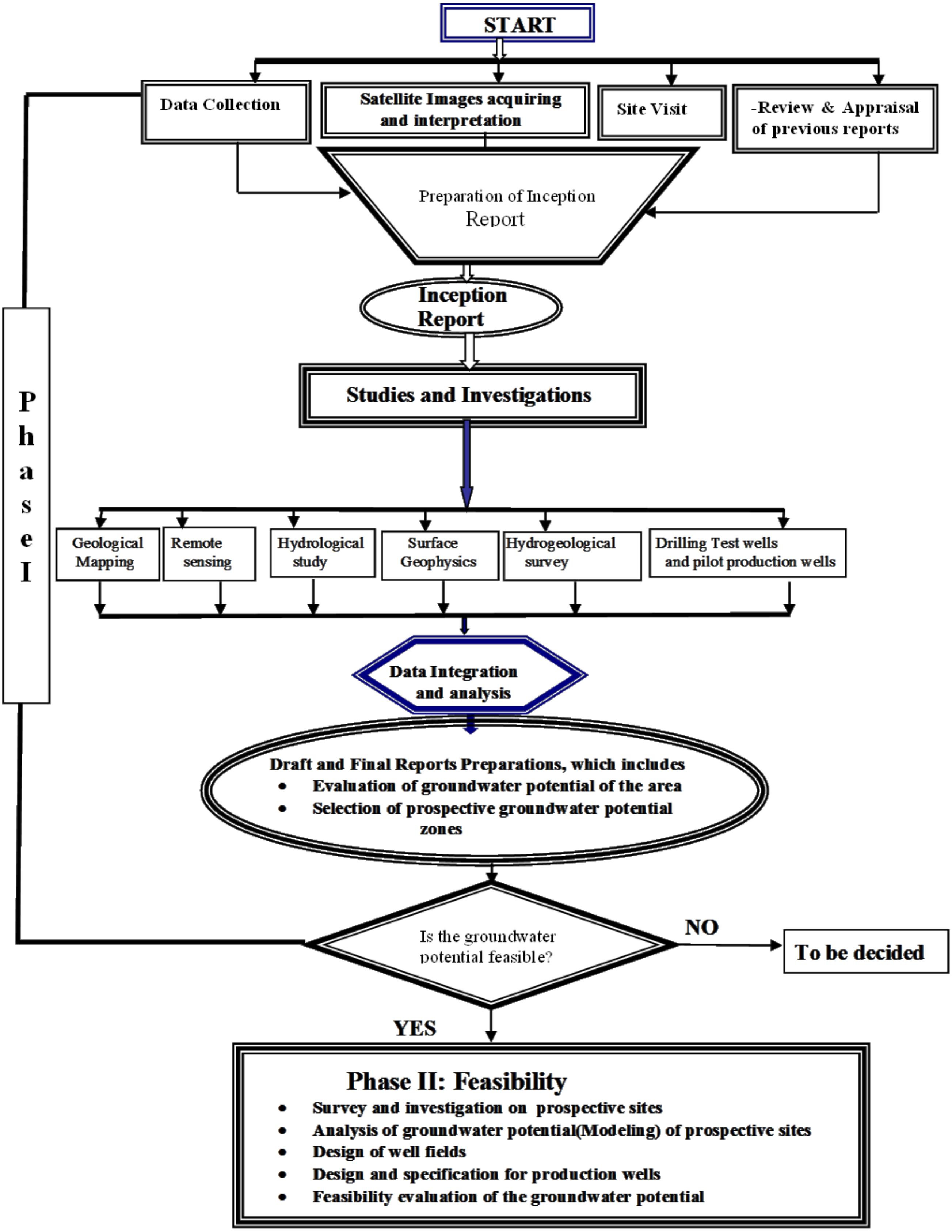


Figure 1-1: Work flow and groundwater study methodology

2 PHASE I (DETAIL RECONNAISSANCE)

2.1 INCEPTION STAGE

2.1.1 Data types, sources of data and graphical representation

2.1.1.1 Data types

Generally the main data types which have important role in the hydrogeological study and to be considered in the area of groundwater investigations are listed below:

Geologic maps

- Grain size areal distribution in superficial / surficial deposits (alluvium, talus, lacustrine, wadi deposits, colluvial etc, deposits),
- Aerial photographs and satellite images are reviewed to develop preliminary base maps for geological and geomorphological mapping
- Regolith thickness and fractures in volcanic rocks, in addition to fractures, attention should also be paid to the characters of individual flow units and interflow formations
- Fractures, regolith thickness and structural discontinuities in basement rocks
- In carbonate rocks, mapping of various solution (karst) features and springs are of special importance
- Geomorphological investigations include delineation and mapping of various landforms and drainage characteristics

Hydrogeological data

- Depth to water table
- Inventoried existing water point data with geographic coordinates
- Well pump test data such as well discharge, transmissivity, storativity
- Static water level data in boreholes and time of measurement
- Well completion reports such as well lithologic logs , year of construction
- Remote sensing data
- Topographic maps
- Hydrogeological Maps

Hydrologic data

- Hydro meteorological data
- Water Budget data
- Precipitation data
- Evaporation data
- Stream flow data, including measurement of gain and loss of stream flow between gauging stations
- Surface inflow and out flow
- Consumptive use
- Change in surface storage
- Change in soil moisture
- Change in groundwater storage
- Subsurface inflow and out flow
- Groundwater level fluctuation data/ groundwater monitoring data

Geophysical Data

- VES data
- Magnetic data
- Satellite geophysical data

  - ➢ the DMT can be easily acquired within a short time
  - ➢ and for reasonable costs, even in large unexplored areas.

- Moreover, this method does not require any physical measurements or personal exploration in the field

- Profiling data
- Well resistivity log data
- Gravity survey data
- Groundwater penetrating radar survey data

Chemical Data

Surface water & groundwater quality data as

- Field Test data (p^H, EC, TDS, ---)
- Physio-chemical Laboratory test data
- Bacteriological test data
- Isotopic Laboratory Test data (useful to understand groundwater recharge sources and mechanism of recharge)

2.1.1.2 Data sources

- Ministry of water , Irrigation and Electricity
- Geological Survey of Ethiopia ,
- Universities,
- Water Well Drilling Enterprises and Private Drilling Companies,
- NGO's,
- Publications on groundwater resource development program like research papers and articles.
- The internet.
- Professionals working in the area

2.1.1.3 Graphic processing and presentation of data

In order to present hydrogeological point data in a few representative concise diagrams, certain logical groupings are necessary. Most point data generated during hydrogeological investigations can be accommodated within these groups.

Group 1: Hydraulic properties of the aquifer(s), such as hydraulic conductivity, transmissivity, storativity.

Group 2: Time-dependent data, such as groundwater abstraction; groundwater levels; water quality.

Group 3: Specialized hydro chemical diagrams for detailed chemical interpretations such as Wilcox diagram and any relevant graphic representation can be used.

Layouts for graphs to depict variables within each of these groups may vary from one presentation to the next. There are, however, three basic rules to be considered when constructing displays.

These are:

- The displays must be clear, concise and legible/readable,
- They should contain only relevant data,
- Displays should be provided with the necessary headings and labels to ensure that they will be meaningful entities on their own.

2.1.2 Relevant data collection, review of previous studies and analysis

Collection and review of available data and previous studies are very important being the basis for data gap identification, developing and devising methodology and volume of works.
The data to be collected includes but not limited to the following;

- Remote sensing data
- Geological studies
- Geomorphological studies
- Hydro-geological studies
- Well completion reports
- Pumping test results of drilled wells
- Water quality data
- Geophysical survey
- Hydrological data
- Meteorological data

Location of potential aquifers is only the first stage in the development of groundwater resources. Already available geological & hydrogeological mapping are very helpful for the exploration work. In Ethiopia geological mapping at scale of 1: 250,000 cover 94 % and hydrogeological mapping at the same scale is at about 90 % of the country. The whole country is mapped geologically & hydrogeologically at 1:2,000,000 scale which only shows or gives very general condition of water resources potential. After relevant data collection, the next step to proceed with the groundwater exploration program is making review of existing data and information followed by generation of additional data by remote sensing techniques. Image interpretation in groundwater studies includes the mapping of linear features with an inferred hydrogeological significance. Lineaments can represent faults, dykes and contacts, which in turn all can be related to fracture zones with sufficient hydraulic conductivity to be of value for groundwater exploration. Maps prepared by the results of remote sensing methods would be evaluated, checked and amended as necessary by geological mapping of linear features with an inferred hydrogeological significance.

The geological mapping for house hold irrigation shall focus on superficial deposits grain size areal distribution, relative thickness and lateral extent, weathered and fractured zones in volcanic as well as in basement rocks.

The result of the mapping would be to produce a map at the appropriate scale for the size of the area (1:100,000 or 1:50,000 based on the current national practice of geological and hydrogeological mapping projects) where the main geological elements of successions and structures were shown. However, the scale of geological and hydrogeological mapping can be made larger at operational level based on the complexity of geology and hydrogeological settings.

Before the commencement of the field work, all pertinent existing data will be compiled from respective offices and organizations and the following data types will be analyzed and interpreted at the office.

- Hydrogeological maps,
- Aquifer parameters,
- Geological maps,
- Geomorphologic maps
- Satellite imageries (SPOT, Landsat etc)
- DEM
- Topographic maps(Scale 1:50,000 and 1:250,000)

- Hydrological data
- Meteorological data
- Water quality data

2.1.3 Preliminary site visit

A preliminary site visit is carried out in the study area at least for two weeks in order to familiarize the area of study, preliminarily verify the aerial photos and imagery interpretation as well as all pertinent data and information verification helpful to enhance the conceptual understanding of the groundwater system of the area and helpful to redefine appropriate methodologies and workable schedule. During field visit the geologist, hydrologist, Hydrogeologist and geomorphologist shall visit the recharge and discharge zones that have been identified at office level within delimited groundwater basin boundary.

2.1.4 Preparation of inception report

Subsequently, all gathered hydrological, climatological, hydrogeological, geological information and data is reviewed and preliminary analysis done together with the outcome of the field visit. The main outputs of the Inception stage includes but not limited to the following:

- Review and analyses of previous studies and data
- Preliminary determination of the extent of potential aquifers and its geometric configuration
- Preparation of different possible conceptual groundwater models of the study area.
- Identifying data gaps and preparing revised methodology (as indicated in the work flow chart in fig1-1) and volume of work for the next stage (Survey and Investigation stage of Phase I).
- Specification and bill of quantities for the drilling and pumping testing of mapping/test wells.
- Preparation of revised work program for the subsequent stage and phases.

2.2 SURVEY AND INVESTIGATION STAGE

2.2.1 Geological and geomorphological study

Groundwater inevitably occurs in geological formations. Knowledge of how these earth materials formed and the changes they have undergone is vital to the hydrogeologist. The geology of Ethiopia is basically heterogeneous and the geologcal knowledge is prerequisit to understanding the distribution of geological materials of varying hydraulic conductivity and porosity. A groundwater study of an area necessarily includes a review of previuos geologic studies. A geologic study begins with the collection, analysis, and interpretation of existing topographic maps, aerial photographs, geologic & hydrogeologic maps and logs, water point data and other pertinent records.

In an area of limited geologic knowledge, a detailed geological study must be made along with the groundwater study. The hydrogeologist is concerned with the distribution of earth materials as they affect the porosity and the hydraulic conductivity of the earth materials.

Geologic studies enable large areas to be rapidly and economically appraised as to their potential for groundwater development. Such an approach should be regarded as a first step in any investigation of subsurface water because no expensive equipment is required; furthermore, information on geologic composition and structure defines the need for field exploration by other methods.

The type of rock formation will suggest the magnitude of water yield to be expected. Stratigraphy and geologic history of an area may reveal aquifers beneath unsuitable upper strata, the continuity and interconnection of aquifers, or important aquifer boundaries. The nature and thickness of overlying beds, as well as the dip of water bearing formations, will enable estimates of drilling depths to be made. Similarly, confined aquifers may be noted and the possibility of flowing wells or low pumping lifts foretold. Landforms can often reveal near surface unconsolidated formations serving as aquifers. Faults which may form impermeable barriers to subsurface flow frequently can be mapped from surface traces.

Filling the data gaps (if any) of the geological mapping with scale 1:250,000 of the study area catchments and with scale 1:50,000 or more of the prospective groundwater potential sites to be the base map for the preparation of the hydrogeological map of the study area. The mapping mainly concentrates on the lithology, tectonics and structural geology. The objectives of the geological study includes but not limited to the following:-

- Conducting a regional geological study;
- Establishing the geological processes involved in the evolution of the Project Area
- Determining the litho-stratigraphic succession of the project area,
- Performing detail structural mapping and analysis of basic geological and structural information for the hydrogeological study.
- Major geomorphologic elements shall be mapped and their inter relationship with geological formation and structures shall be outlined.

The initial stage of the assignment will be undertaken at office works that includes collection and reviewing of geological maps, relevant data collection and analysis, aerial photographs and Landsat and SPOT imagery interpretation and production of updated base geological and geomorphological maps at a scale of 1:250,000 for assessing the data gaps if any. This is followed by field geological and structural mapping to check on ground the accuracy of the details compiled in the office and gather new information to enrich the preliminary geological and structural maps prepared. All pertinent geological data such as lithologic units, delineation of geological contacts, geological structures (linear features, fractures and faults) and geomorphological elements shall be mapped. Appropriate GIS softwares such as ERDAS, ENVI, ArcGIS, etc. is applied for imagery interpretation and map preparation.

2.2.1.1 Geological investigation field techniques (Source: Tigrai water Bureau Groundwater Study guide)

a) General Guidelines

- At the beginning of the field work, road geology (if road is available) across the strike of the main structures and units should be conducted to have an overview about the general trend of the geology of the area; since it is useful for actual traverse planning in the study area.
- Before starting geological traverse independently, geologists must take joint traverse(s) to have common understanding about the geology and hydrogeology of the area (if the team consists of two experts or more).
- At the beginning of the fieldwork, start geological traverses near to your campsite and in areas where the geology seems simple.
- Conduct daily or weekly traverse planning using aerial photographs and topographic maps.

- Relative location, station number, aerial photograph number and traverses data should be included in the note book before recording any geological data during daily traverse.
- Write the station numbers on the back of the aerial photographs using pencil after you pierce the aerial photographs using needle.
- During daily traverses, mark rock types, structures, mineralization/alteration zone and floats of mineralized rock(s) using different symbols or colours on the front of page of the aerial photographs that covered by overlay. Symbols and colours should be written using erasable pencil.
- At every station describe and record the physical and geometrical features, mineralogical composition and relationship of the type of rocks exposed.
- Estimate aeral extent and outcrop nature (continuous, blocky, jointed /fractured, massive, fragmented, degree of weathering etc) of every exposure.
- If many alternating rock types exist, describe their horizontal and vertical variation and determine their mode of occurrence (percent of proportion in the intercalation/ inter layering).
- Note any occurrence of mineralization and/or alteration zone(s) in any rock types.
- Sketch and/or photograph any interesting rock type, mineralization/alteration zone and structural features.
- Sketches and/or photographs should contain scale bar, direction of view, north direction, locality name and explanation of the sketched or photographed geological feature.
- Take representative and fresh samples from different rock types. Labeled every sample accurately, and keep them from contamination due to abrasion.
- Identify, describe and record the type of structures (primary and/or secondary) observed on the outcrop.
- Transfer all observation points, lithological and structural data etc from aerial photographs into the topographic base map once or twice a week (or daily after completion of daily traverse if possible) at the camp site.
- Conduct group discussion once or twice a week for experience sharing (or daily if possible).
- Write daily or weekly summary note about the geological and hydrogeological data collected within that week or day.
- At the end of the field season, produce tentative geological map(s) and preliminary report in the field before you return back to office.
- Make preliminary selection of samples for analysis while you are in the field.
- During sampling symbols are represented by taking the first two letters from the name of the sub sheet or area under consideration. Both letters must be upper case; and followed by number in ascending order. For example, if the name of the sub sheet or area under consideration is Zana, the symbol that is given to the samples taken in this subsheet or area is ZA-01, ZA-02 …….. ZA-n+1. No expert should use new number every year until he/she stays in the team working for regional geological mapping.
- List all collected rock samples including their sample number, location and short lithological and structural description in a tabular form in the field.
- The geological mapping for shallow groundwater mapping related to house hold irrigation should focus on superficial deposits grain size areal distribution, weathered and fractured zones in volcanic rocks, regolith thickness and structural discontinuities in basement rocks.

Note: In addition to the field guides outlined in the following sections the user is advised to refer Hussien,B. 2007, for standards of regional geological mapping, Geological Survey of Ethiopia.

b) Field data collection in metamorphic terrain

General Guidelines

- Traverse lines should run across the strike of the main lithological units and structures.
- If there are creeks, streams or rivers, which cut the strike of the main lithological units and structures; it is better to follow them, since fresh out crops are exposed on their floors and/or banks and it can be water bearing zone.
- The maximum traverse lines interval should be designed depending on the complexity of the geology and structure and the scale of the map intended to produce.
- Observation points should be made at every 500 m interval, but it can be also closer depending on the change of lithological units/subunits and structures.

Lithological data

- First recognize and record the physiographic nature of the rock exposure/out crop (e.g. ridge forming, flat-lying, cliff forming, ruggedness etc).
- Before describing the rock type(s) at any station, see if there is heterogeneity in fresh or weathered colour, grain size, structural fabric and mineralogical composition by moving from one spot to another spot on the rock exposure/out crop. If variation is found out, describe all variations across and/or along the strike of the rock exposure. See whether the variation is systematic or random; and try to identify and record the factor(s) that control the variation.
- If possible try to identify the protolith (parent rock/pre-metamorphic rock) of the metamorphic rock by determining the occurrence of preserved primary features, and marker layers.
- If intrusive rock(s) intrudes(s) the parent rock(s) see their contact relationship.
- The lenses or layers found as minor occurrence associated with the main lithological units usually get less attention; therefore you must describe and record carefully.
- If the metamorphic rock is represented by layered/banded rock types describe and note the following features:
- The contact relationship between each layer/band (gradational or sharp) related to composition and physical features along and across the strike.
- Their relative response to permeability.
- Try to see if each discrete layer or band is constantly homogenous along and across its strike.
- The mode of occurrence and frequency (percent of proportion) of the individual layers/bands.
- Thickness, colour, grain size, mineralogical composition of individual layers/bands
- During describing the rock exposure regarding its composition, visually, determine the proportion of major, minor and accessory mineral constituents. Note alteration of any mineral.
- Describe any types of small intrusions (veins/vein lets, stringers and dykes/sills). Record their thickness, orientation, attitude, their physical features (fresh and weathered colours, grain size and mineralogical composition) and contact relationship with the host rock. Determine their relative age from their cross cutting relationship if they are of different generation.

Structural data

- Foliation
- Determine the type of foliation (slaty cleavage, phyllitic cleavage, schistosity and
- gneissosity) by looking at the spacing of splitting surface; and preferred orientation of the minerals that define the foliation.
- Measure the attitude of the foliation (dip direction/dip amount).

- Try to see if there are different sets of foliations; measure and give them different symbols.
- See the relationship between primary bedding (So and S1), and/or different sets foliations (S1 and S2) and (Sx and Sx+1) etc.
- Lineation

Lineation includes:

- Mineral lineation: Note the mineral that defines the mineral lineation.
- Stretching lineation: Note stretched mineral(s) or aggregate of minerals that define
- mineral stretching (elongation) lineation.
- Intersection lineation: Note the two planar surfaces that define intersection lineation.
- Consider the axis of fold as lineation, and measure it similar to other lineation.
- Measure the trend and plunge of the lineations (direction of plunge/amount of plunge).
- Plot the lineation on the stereographic net, and see their relationship with the foliation plane, which contained them.
- Folds
- Determine the direction of closure of the folds (antiform, synform, recumbent etc).
- Classify the fold based on interlimb angle as (open-, gentle-, close folds etc); and plunge
- of hinge and dip of axial plane/surface as (upright-, sub-horizontal upright-, recumbent folds etc).
- When the hinge zone of the fold is exposed, measure the attitude of the fold axis (direction of plunge/amount of plunge) and axial plane/surface (direction of dip/amount dip). For folds where the hinge zone is not clear measure the orientation of the axial trace.
- Note any development of axial planar cleavage/joints/fractures associated with the fold (if any).
- Determine the vergence of asymmetric mesoscale folds.
- Try to relate the fold with deformational events.
- Shear zone
- Identify the shear zones at all scales (meso-to regional scale) in the field.
- Determine the type of shear zone (strike-slip, trust related and flexural type).
- Try to see the relationship between the structural fabrics in the shear zone and preexisting fabrics.
- Faults
- Determine the type of fault (normal, dip-slip, oblique-slip, reverse, strike-slip or trust).
- Determine if the fault is represented by discrete simple fault plane or fault zone.
- Measure the magnitude of displacement by referring offset of marker layer(s) or rock type(s).
- Note if there is fault controlled mineralization, alteration and/or veining.
- Measure striation and slickenside on fault plane (if exist).
- Measure the attitude of the fault plane (dip direction/dip amount).
- If fault associated rocks are present give their textural field name (cataclastic, breccia, fault gouge, mylonite, ultramylonite etc) by taking into consideration proportion of matrix to the fragments, and describe them. See the field description of metamorphic rocks, (Norman Fry, 1984, page 93).
- Joints/fractures
- Note the distribution of joints (random/regular joint sets).
- Measure joint spacing between consecutive joints/fractures.
- For each set of joints record their frequency, lateral dimension and their attitude (dip direction/dip amount)
- Measure the opening along the joint plane.

- Try to see if the joints/fractures that are filled with veins/vein lets and fine sediments.
- Try to see the alteration of the joint plane
- Determine the relationship between joints and other structures (foliation, faults, folds etc).

C) Field data collection in sedimentary terrain

General Guidelines

- Try to trace out all individual layers from the aerial photograph before going to traverse in
- the field (if possible).
- Traverse lines should be made at pertinent spacing
- Observation points should be made at every 500 m interval, but it can be also closer depending on the change of lithological units/subunits, structures and purpose of the study.
- Traverses should be made following creeks, streams or rivers that cross the geological formation normal to its bedding surface/plane.
- During geological logging a graphic log sections have to be selected in areas where there are good exposures.
- Start section logging from the bottom to the top part or vise versa of the sedimentary sequence.
- Collect representative rock samples from the possible aquifer and aquiclude layer.

Lithological data

- Classify the sedimentary rocks based on mineralogical composition, texture and structure, i.e.use proportion of sand, silt and clay for terrigineous and proportion of carbonate, mud and allochems (grains) for carbonate rocks (The field description of sedimentary rocks, Maurice E Tucker, 1982). For sandstone classification use proportion of quartz, feldspar and rock fragments (Pettijohn et al., 1973).
- During section logging see the vertical and lateral variation of individual layer.
- Try to log many sections, correlate and interpret them after you have enough data.
- Describe and record the thickness, lateral extent, grain size, shape, fresh and weathered colours, degree of sorting and compaction, degree of weathering and mineralogical composition of individual layer.
- See the contact relationship (gradational, straight, irregular or sharp) between layers.
- Identify and describe the presence and type of unconformity between different sedimentary sequences, and other rocks found underlying or overlying it.
- In carbonate rocks observe clearly the size, shape, and distribution of solution holes.
- Note any interesting mineralization and/or alteration associated with the sedimentary rocks.
- If the sedimentary rock is represented by clastic/terrigenous sedimentary rocks, record grain size and shape, degree of sorting, percent of clastics and matrix, type of cementing material, source and composition of clasts in sandstone (lithic arenite and greywacke), conglomerate and tillite rocks.

Structural data

- Observe and describe the following primary structures on the external and/or internal parts of the bed.
- External form of beds:-
    - Uniform thickness laterally and vertically.
    - Lateral continuity or pinching of beds
    - Shape of the beds.

- Bedding plane marking and irregularities:-
  - Load structures (load casts).
  - Current structures (scour marks and tool marks).
  - Organic markings (ichino fossils).
  - Parting lineation.
  - Ripple marks.
  - Erosional marks (rill marks; current crescents).
  - Pits and small impressions (bubble and rain prints).
  - Mud cracks, mud-crack casts, ice-crystal casts, salt-crystal casts.
- Deformational structures:-
  - Founder and load structures (ball-and-pillow structures, load casts).
  - Convolute bedding.
  - Slump structures (folds, faults, and breccias)
  - Injection structures (sandstone dykes, etc) (barriers)
  - Organic structures (burrows, etc).
- Internal organization and structure:-
  - Massive (structureless).
  - Laminated (horizontally-laminated; cross-laminated)
  - Graded bedding (normal or reverse).
  - Imbricated and other oriented internal structures.
  - Growth structures (stromatolites, etc).
- Note any secondary structure occurrence (joints/fractures and/or faults) and measure their attitude; and post depositional structures (concretions (nodules) and stylolites).
- Measure the attitude of the bedding plane and attitude of fractures.

d) Field data collection in volcanic terrain

General Guidelines

- The maximum traverse line spacing depending on the change of lithological units/subunits and structures.
- Observation points should be made at every 500 m interval, but it can also closer depending on the change of lithological units/subunits and structures.
- Traverses should be made following creeks, streams or rivers during section logging. Try to conduct logging at sections that contain more geological formations (for volcanic rocks).
- Collect representative rock samples.

Lithological data

Extrusive (lava flows) and associated hypabyssal rocks

- Description has to be started from the bottom to the top part of the formation or vise-versa.
- Make a lateral and vertical log of lithologies in different sections.
- Note the color, thickness, mineralogical composition, grain size, texture and degree of weathering of individual layer vertically and laterally.
- While you are in the field give a tentative classification of basalt in terms of texture (as porphyritic/phyric-, aphanitic-, amygdaloidal-, vesicular-, phaneritic basalt etc).
- When the volcanic rock is vesiculated note the shape and size of the vesicles.
- When the volcanic rock is amygdaloidal, note the mineral(s) represent the amygdules, and see also if the vesicles are partially or wholly filled.

- See if there are veins, dykes/sills and pegmatites associated with volcanic rocks, and relate them with the regional or local tectonics.
- If volcanic plugs (trachyte, phonolite, etc) are found associated with different volcanic rocks, try to see their age contact relationship with respect to each volcanic rock unit.
- Note baking effect between the volcanic rocks and the underlying units.
- Try to establish the stratigraphic sequence of the volcanic rocks.

Pyroclastic rocks

- Determine the genetic type of the pyroclastic deposit whether it is fall, flow, surge or lahar.
- When the pyroclastic deposit is represented by fall, classify to tuff, agglomerate, lappilli tuff,volcanic breccia etc. after determining the proportion of the pyroclasts with respect to their size and/or their shape.
- Observe the presence of graded bedding and determine whether it is reverse or normal graded bedding.
- Look for the existence of sequences of size-graded layers, and decide the type and events of eruptions (if possible); and describe the internal part of each layer.
- Try to see the lateral distribution of the accidental and juvenile fragments (clasts) with respect to their size; and estimate the center zone (within 2 km from the central vent), proximal zone (about 5-5 km from the central vent) and distal zone (about 5-15 km beyond the central vent) of the eruption (if possible).
- Observe if there are associated marine or lacustine sediments so that to get an insight about the environment of deposition.
- In surge deposit, see and describe cross-bedding/lamination, dune and anti-dune structures pinch and swell.
- See the variation of degree of welding (well, moderate, poorly, none etc) in the pyroclastic flow deposit (ignimbrites).
- Look for accretionary, lappillies and measure their size, shape and note their distribution within the deposit.
- Determine the type of the clasts whether they are juvenile (glass shards, pumice and crystals) or accidental.
- Observe the degree of sorting of the pyroclastic materials, and determine the proportion of accidental and juvenile fragments.
- Try to observe the lateral thickness of the deposit, and if it shows considerable variations correlate with the pre-depositional topographic nature.
- Compare and contrast the composition of the accidental fragments with that of the underlying rocks.
- Look for any alteration at the contact of the host rock and the accidental fragments.
- Observe the distribution of vesicles including its porosity throughout the section, including their shape and size and also the presence of secondary precipitates and their composition.
- Observer if there exists primary compositional zoning vertically or laterally.
- Look for secondary zonation such as welding, compaction, crystallization of solids from the entrapped gases and crystallization of the glassy material.
- Observe the orientation of mineral grains/clasts in a deposit and compare with the alignment of the welded clasts (fiamme).
- Look for devitrification of glassy material and at what part of the deposit (sequence); and if exists look for its color which usually has red purple, brown and pink in contrast to the black color of the none devitrified layer.
- Observe any replacement of glass by spherulites and lithophysals.

Structural data

- Look for primary structures, bedding (irregular, undulatory, horizontal); lava flows (ropy, smooth, flow folding pillow, etc.) and jointing (columnar).

- Collapse and eruption structures; caldera and crater (diameter, height, shape).
- Secondary structures (joints and/or fractures).

e) Field data collection Intrusive rocks

General Guidelines
Lithological data

- Determine the mode of occurrence of the plutonic rocks (e.g. batholiths, stock, laccoliths, lopolith, or dyke/sill etc.).
- Note the general form of the outcrop (ridge or hill form, mountain chain etc).
- Note the contact relationship between each intrusive rock, and the rocks in which they intrude (whether it is simple or complex).
- Classify and give name provisionally to intrusive rocks.
- Note the texture, color and composition, degree of weathering of the outcrop.
- Estimate the proportion of major, minor and accessory minerals.
- If the outcrop contains veins, pegmatites, dykes/sills, describe them and determine the nature of their contact relationship (gradational or sharp and also if there is chilled margin).
- Try to see if the intrusive rocks are concordant or discordant to the bedding or foliation with respect to their maximum dimension.
- Identify igneous layering defined by mafic and felsic rich layers; and record the physical and compositional nature of individual layer. Examine the boundary between the layers.
- If there are xenoliths/roof pendants, enclaves and inclusions associated with plutonic rocks.

Note:

- Differentiate the shape and contact relationship with the host rock.
- Determine the fabric of the intrusive rock if there exist an alignment of xenoliths, crystals or miarolytic cavities.
- Note any mineralization and/or alteration associated with the intrusive rocks.

Structural data

- Joints: - Measure dip direction/dip amount and average spacing of joints.
- Observe if there are faults and shear zones and take all the necessary measurements that describe them.
- Observe if the existing fractures are filled with dykes/sills and/or veins.
- Try to see if there are fragments of rocks along the joints.
- Try to look for banding and/or layering including their way of manifestations.
- Especially in silicic plutones try to look for miarolytic structures and observe if there are secondary precipitates filling these cavities.

2.2.2 Hydrological studies

The main purpose of hydrologic data collection is to evaluate the equation of hydrologic equilibrium regarding inflows to and outflows from the area of study and define sound hydrologic cycle to evaluate the interrelationship of all hydro-meteorologic parameters. The major activities outlined hereunder are required to estimate the available water for recharge and includes but not limited to the following:

- Collection of climatological and hydrological data, analysis of data quality and adequacy required for the hydrological study.
- Checking data adequacy, reliability and consistency by using tools like:
  - Statistical tools: percentages, mean, variance, standard deviation etc

- Graphic tools for consistency checking like:
  - ✓ Internal consistency checking
  - ✓ External consistency checking

- Analysis and interpretation of hydro-metrological data (areal precipitation, relative humidity, sunshine, wind speed) , and carry out hydrological frequency analyses
- Computation or evaluation of potential evapotranspiration and actual evapotranspiration
- Formulation and calibration of water balance model for each stream catchments of study area
- Analyze the interaction of surface water with groundwater.
- Estimating groundwater recharge

2.2.2.1 Groundwater recharge estimation

A) General

Various techniques are available to quantify recharge; however, choosing which of a wide variety of techniques is likely to provide reliable recharge estimates is often difficult. Various factors need to be considered when choosing a method of quantifying recharge. A thorough understanding of the attributes of the different techniques is critical. Important considerations in choosing a technique include space/time scales, range, and reliability of recharge estimates based on different techniques; other factors may limit the application of particular techniques. The goal of the recharge study is important because it may dictate the required space/time scales of the recharge estimates. Typical study goals include water-resource evaluation, which requires information on recharge over large spatial scales and on decadal time scales. The range of recharge rates that can be estimated using different approaches should be matched to expected recharge rates at a site.

The reliability of recharge estimates using different techniques is variable. Techniques based on surface-water and unsaturated-zone data provide estimates of potential recharge, whereas those based on groundwater data generally provide estimates of actual recharge. Uncertainties in each approach to estimating recharge underscore the need for application of multiple techniques to increase reliability of recharge estimates.

B) Background Information for Recharge Estimation

The first stage of a recharge study in an area that has not previously been studied should involve collecting existing data on potential controls on recharge, such as climate, hydrology, geomorphology, and geology. These data are used to develop a conceptual model of recharge in the system. The conceptual model describes location, timing, and likely mechanisms of recharge and provides initial estimates of recharge rates.

Climate plays a major role in controlling recharge, as shown by differences in recharge sources and rates between arid and humid settings. Preliminary recharge rates for a site can be estimated using available meteorological data and soil hydraulic-parameter data in unsaturated-zone models. Available hydrologic data should also be evaluated, including streamflow data (for evaluating gaining and losing sections of streams) and water-table depth (for determining unsaturated-zone thickness).

Variations in geomorphology reflect differences in topography, vegetation, and soil type, which can affect recharge. The impact of topography on local and regional groundwater flow paths was demonstrated by Tóth (1963). Recharge is generally considered to occur in topographic highs and discharge in topographic lows in humid regions, whereas in arid alluvial-valley regions recharge is usually focused in topographic lows, such as channels of ephemeral streams. Delineation of hydrogeomorphic settings on the basis of topographic attributes – including slope classes, breaks in slope, curvature, and elevation – is greatly facilitated by the use of geographic information systems (GIS) and digital elevation models.

Vegetation cover is important in assessing recharge potential at a site. Recharge is generally much greater in non-vegetated than in vegetated regions (Gee et al. 1994) and greater in areas of annual crops and grasses than in areas of trees and shrubs (Prych 1998).

Therefore, information on land use/land cover is important for evaluating recharge. Irrigated areas should also be identified because irrigation return flow often contributes significant amounts of recharge. Soil texture and permeability are important because coarse-grained soils generally result in higher recharge rates than do fine-grained soils.

Information on topography, land use / land cover, and soil types is combined to define geomorphic systems that control recharge. Such systems are closely related to underlying geologic systems. Examples of such provinces include alluvial-fan, fluvial, eolian, regions that may have characteristic recharge attributes.

2.2.2.2 Techniques for groundwater recharge estimation

Techniques for estimating recharge are arbitrarily subdivided into various types, on the basis of the three hydrologic sources, or zones, from which the data are obtained, namely surface water, unsaturated zone, and saturated zone. The different zones provide recharge estimates over varying space and time scales. Within each zone, techniques are generally classified into physical, tracer, or numerical modeling approaches. This overview focuses on aspects of each approach that are important in choosing appropriate techniques, such as the space/time scales, range, and reliability of recharge estimates. Because many techniques in the different zones are based on the water-budget equation, this topic is described hereunder.

Water Budget
The water budget for a basin can be stated as:

$$\mathbf{P} + \mathbf{Q_{on}} = \mathbf{ET} + \mathbf{Q_{off}} + \Delta\mathbf{S} \qquad (1)$$

where P is precipitation (and may also include irrigation); Q_{on} and Q_{off} are water flow onto and off the site, respectively; ET is evapotranspiration; and ΔS is change in water storage. All components are given as rates (e.g.,mm/day or mm/year). Individual components consist of subcomponents. Water flow onto or off the site is written as the sum of surface flow, interflow, and groundwater flow. ET is distinguished on the basis of the source of evaporated water (surface, unsaturated zone, or saturated zone). Water storage takes place in surface-water reservoirs, the unsaturated zone, and the saturated zone.

Rewriting the water-budget equation to incorporate many of these subcomponents results in:

$$\mathbf{P} + \mathbf{Q^{gw}}_{\mathbf{on}} = \mathbf{ET^{sw}} + \mathbf{ET^{uz}} + \mathbf{ET^{gw}} + \mathbf{R_0} + \mathbf{Q^{gw}}_{\mathbf{off}} + \mathbf{Q^{bf}} + \Delta\mathbf{S^{sw}} + \Delta\mathbf{S^{uz}} + \Delta\mathbf{S^{gw}} \qquad (2)$$

where superscripts refer to the subcomponents described above, R_0(runoff) is surface-water flow off the site, and Q^{bf} is base flow (groundwater discharge to streams or springs). Groundwater recharge, R, includes any infiltrating water that reaches the saturated zone and can be written as (Schicht and Walton 1961):

$$\mathbf{R} = \mathbf{Q^{gw}}_{\mathbf{off}} - \mathbf{Q^{gw}}_{\mathbf{on}} + \mathbf{Q^{bf}} + \mathbf{ET^{gw}} + \Delta \mathbf{S^{gw}} \quad (3)$$

This equation simply states that all water arriving at the water table either flows out of the basin as groundwater flow, is discharged to the surface, is evapotranspired, or is retained in storage. Substituting this equation into Eq. (2) produces the following version of the water budget:

$$\mathbf{R} = \mathbf{P} + \mathbf{Q^{sw}}_{\mathbf{on}} - \mathbf{R_o} - \mathbf{ET^{sw}} - \mathbf{ET^{uz}} - \Delta \mathbf{S^{sw}} - \Delta \mathbf{S^{uz}} \quad (4)$$

Water-budget methods are those that are based, in one form or another, on a water-budget equation. They include most hydrologic models, such as surface-water and groundwater flow models. For any site, some of the terms in Eq. (4) are likely to be negligible in magnitude and therefore may be ignored. An advantage of water-budget methods is flexibility.

The major limitation of the residual approach is that the accuracy of the recharge estimate depends on the accuracy with which the other components in the water budget equation are measured. This limitation is critical when the magnitude of the recharge rate is small relative to that of the other variables, in particular ET. In this case, small inaccuracies in values of those variables commonly result in large uncertainties in the recharge rate. Some authors (e.g., Gee and Hillel 1988; Lerner et al. 1990; and Hendrickx and Walker 1997) have therefore questioned the usefulness of water-budget methods in arid and semiarid regions. However, if the water budget is calculated on a daily time step, P sometimes greatly exceeds ET on a single day, even in arid settings. Averaging over longer time periods tends to dampen out extreme precipitation events (those most responsible for recharge events).

Techniques based on surface-water studies

The status of recharge related to surface-water bodies depends on the degree of connection between surface-water and groundwater systems. Humid regions are generally characterized by gaining surface-water bodies because groundwater discharges to streams and lakes. In contrast, arid regions are generally characterized by losing surface-water bodies, because surface-water and groundwater systems are often separated by thick unsaturated sections. Therefore, surface-water bodies often form localized/focussed recharge sources in arid settings. Recharge can be estimated using surfacewater data in gaining and losing surface-water bodies.

A. Channel-water budget

Surface-water gains or losses can be estimated using channel-water budgets based on stream-gauging data.

Lerner et al. (1990), Lerner (1997), and Rushton (1997) provide detailed reviews of this approach. The channel water budget is described as (Lerner 1997):

$$\mathbf{R} = \mathbf{Q_{up}} - \mathbf{Q_{down}} + \sum \mathbf{Q_{in}} - \sum Q_{out} - E_a - \Delta S/\Delta t \quad (5)$$

where R is recharge rate, Q is flow rate, Q_{up} and Q_{down} are flows at the upstream and downstream ends of the reaches, Q_{in} and Q_{out} refer to tributary inflows and outflows along the reach, E_a is the evaporation from surface water or stream bed, and ∆S is change in channel and unsaturated-zone storage over change in time (∆t). The term transmission loss refers to the loss in stream flow between upstream and downstream gauging stations (Lerner et al. 1990). This loss reflects potential recharge that can result in an overestimate of actual recharge because of bank storage and subsequent evapotranspiration, development of perched aquifers, and inability of the aquifer to accept recharge because of a shallow water table or low transmissivity (Lerner et al. 1990). Recharge values generally reach a constant rate when the water-table depth is greater than twice the stream width, because flow is generally controlled by gravity at these depths (Bouwer and Maddock 1997; figure2-1).

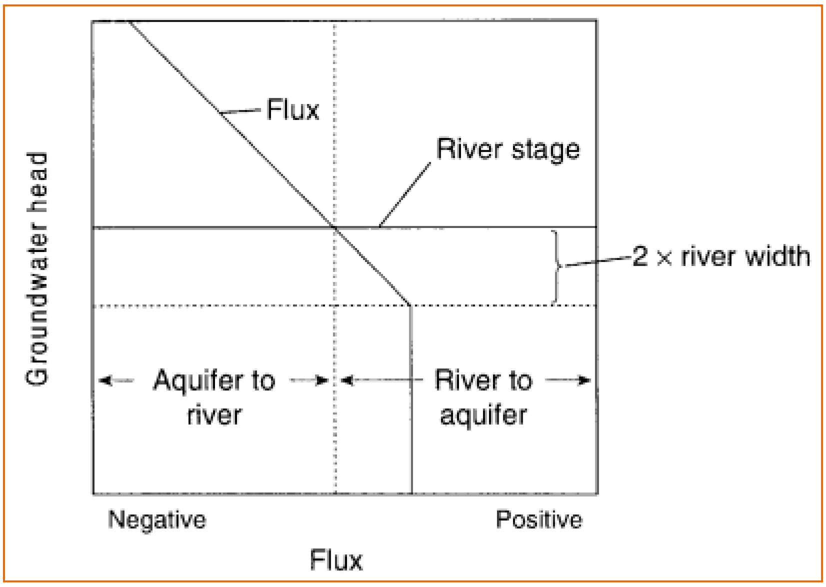


Figure 2-1: Water fluxes related to the degree of connection between rivers and aquifers

Note:The aquifer discharges to the river when the groundwater head is greater than the river stage, whereas the river recharges the aquifer when the river stage is greater than the groundwater head. Recharge values generally reach a constant rate when the water-table depth is greater than twice the river width (Bouwer and Maddock 1997)

B. Base flow discharge

I. Annual hydrograph

In watersheds with gaining streams, groundwater recharge can be estimated from stream hydrograph separation (Meyboom 1961; Rorabough 1964; Mau and Winter 1997; Rutledge 1997; Halford and Mayer 2000). Use of base flow discharge to estimate recharge is based on a water-budget approach (Eq. 3), in which recharge is equated to discharge. Base flow discharge, however, is not necessarily directly equated to recharge because pumpage, evapotranspiration, and underflow to deep aquifers may also be significant. These other discharge components should be estimated independently. Bank storage may complicate hydrograph analysis because water discharging from bank storage is generally derived from short-term fluctuations in surface-water flow and not from areal aquifer recharge and could result in overestimation of recharge. Various approaches are used for hydrograph separation, including digital filtering (Nathan and McMahon 1990; Arnold et al. 1995) and recession-curve displacement methods (Rorabough 1964).

The accuracy of the reported recharge rates depends on the validity of the various assumptions. Recharge estimates based on hydrograph separation range from 152 to 1,270 mm/year in 89 basins (Rutledge and Mesko 1996) and from 127 to 635 mm/year in 15 basins (Rutledge and Daniel 1994) in the eastern US. Rutledge (1998) recommended an upper limit on basin size of 1,300 km2 for application of this method because of difficulties in separating surface-water and groundwater flow and bank storage effects in larger systems and because of the areally uniform recharge assumption. The minimum time scale is a few months. Recharge over longer times can be estimated by summation of estimates over shorter times.

Recent progress has been made on the use of chemical and isotopic techniques to infer the sources of stream flow from end members such as rainfall, soil water, groundwater, and bank storage (Hooper et al. 1990; Christophersen and Hooper 1992). This approach is data intensive, but it provides information that is useful in conducting hydrograph separation. Suecker (1995) used sodium concentrations in a two-component mixing model to determine the subsurface contribution to three alpine streams in Colorado, USA.

The hydrograph of a stream during a period with no excess precipitation will decay, following an exponential curve. The discharge is composed entirely of groundwater contributions. As the stream drains water from the groundwater reservoir, the water table falls, leaving less and less groundwater to feed the stream. If there were no replenishment of the groundwater reservoir, base flow to the stream would become zero. Figure 2-1 shows base flow recession hydrograph for a stream in a climate with dry summer season.

The base flow recession for a basin is a function of the overall topography, drainage pattern, soils and geology of the watershed. Figure 2-2 shows the annual summer recession of a river for six consecutive years. The recession is similar from year to year. The base flow of the stream decreases during a dry period because as groundwater drains into the stream, the water table falls. A lower water table means that the rate at which groundwater seeps into the stream declines.

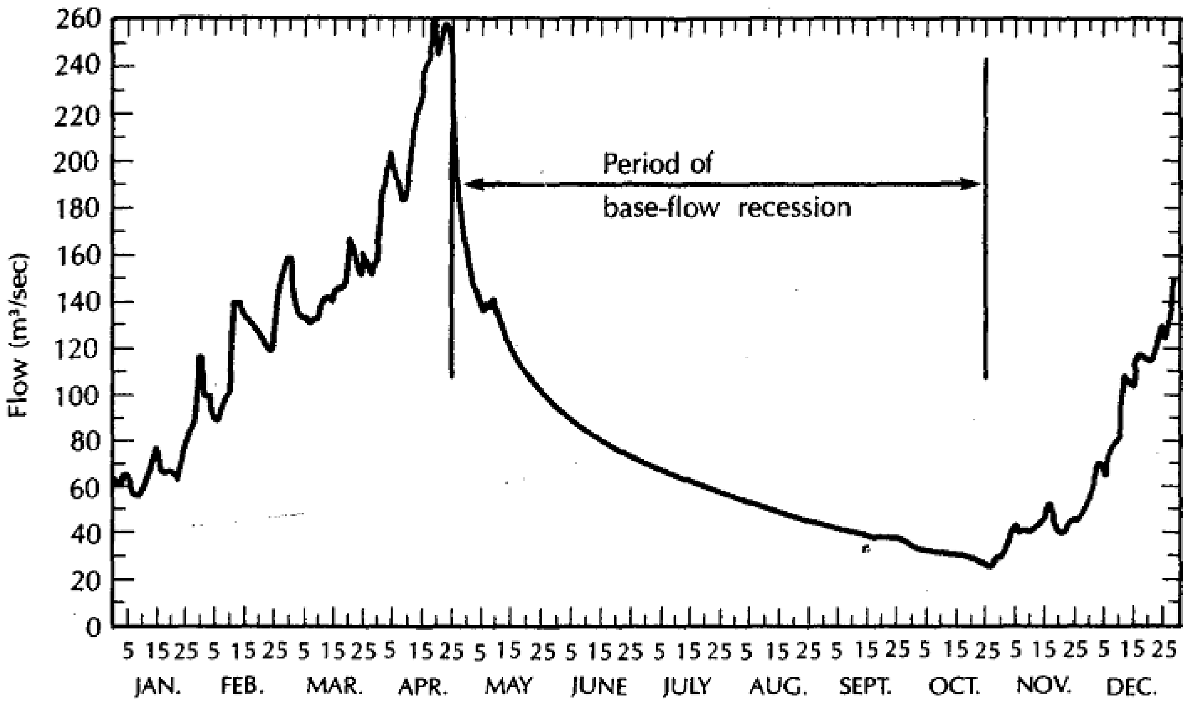


Figure 2-2: Typical annual hydrograph for a river with a long, dry summer season (adapted from C.W. Fetter, 4th ed, 2001, applied hydrogeology)

The base flow recession equation is

$$Q = Q_0 e - at \qquad (6)$$

Where

Q is the flow at some time t after the recession started (M^3/s)

Q_o is the flow at the start of the recession (M^3/s)

a is a recession constant for the basin (d^{-1})

t is the time since the start of the recession (d)

II. Seasonal Recession Method (Meyboom Method)

The Meyboom method is a simple method of estimating groundwater recharge in a basin. The underlying assumptions of this method are that the catchment area has no dams or other method of stream flow regulation. It utilizes stream hydrographs from two or more consecutive years. The base flow recession equation (Equation 6) indicates that Q varies logarithmically with time, t. A plot of a stream hydrograph with time on arithmetic scale and discharge on a logarithmic scale will therefore yield a straight line for the base flow recession. Figure2-3 shows a stream hydrograph. The base flow recessions are shown as dashed lines; they were considered to start when the summer stream level dropped below the adjacent water table and to end when the first spring flood occurred. The total potential groundwater discharge is the volume of water that would be discharged during a complete groundwater recession (Meyboom 1961 as cited in C.W. Fetter). Its value can be found from:

$$V_{tp} = \frac{Q_o t_1}{2.3026} \quad (7)$$

Where

V_{tp} is volume of the total potential groundwater discharge (m^3)

Q_o is the base flow at the start of the recession (m^3/s)

t_1 is the time that it takes the base flow to go from Q_o to 0.1 Q_o (s)

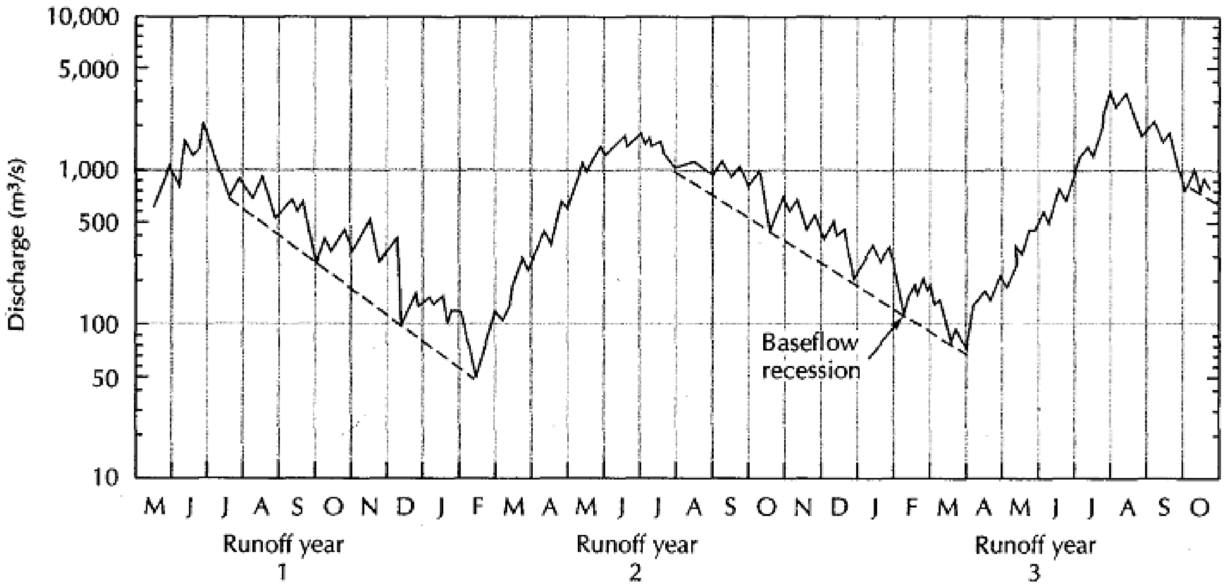


Figure 2-3: Semi logarithmic stream hydrograph showing base flow recessions

If one determines the remaining potential groundwater discharge at the end of a recession and then the total potential groundwater discharge at the beginning of the next recession, the difference between the two is the groundwater recharge that has taken place between recessions. The amount of potential base flow, V_t (m^3), remaining for time, t (s), after the start of a base flow recession is given by

$$V_t = V_{tp}\ 10^{(t/t1)} \quad \textbf{(8)}$$

This analysis assumes that there are no consumptive uses of groundwatw in the basin so that all groundwater discharge is by means of base flow to streams.

III. Recession Curve Displacement Method(Rorabaugh)

The seasonal base flow recession method has the disadvantage of requiring a long term record runoff of at least two seasons. It also is most useful for a drainage basin where there is a seasonal recharge event and then a long base flow recession with little intervening groundwater recharge.

The recession curve displacement method (Rorabaugh) method can be used in situations when a series of groundwater recharge events occur during one runoff season. The recession curve is shifted upward by the recharge event. The amount of grounwater recharge can be determined by the amount of the upward shift (Rorabaugh 1964; Rorabaugh and Simons 1966). This method is applicable to drainage basins where the groundwater recharge is more or less evenly distributed through the basin and where all the groundwater discharges from the basin via seepage into the stream or springs that feed the stream, and groundwater recharge, can be assumed to be instantaneous. Figure2-4 shows the upward shift of a recession curve after a precipitation event. The hydrograph peak is caused by overland flow, direct precipitation, and possibly interflow as well as increased base flow from groundwater recharge. As we are intersted only in the groundwater component, we use equation 7 or 8 to determine the time period when an overland flow component exist. After D days have elaapsed, the streamflow can be considered as entirely base flow, although the volume of discharge in the streams has increased, as has the total potential base flow, V_{tp} .

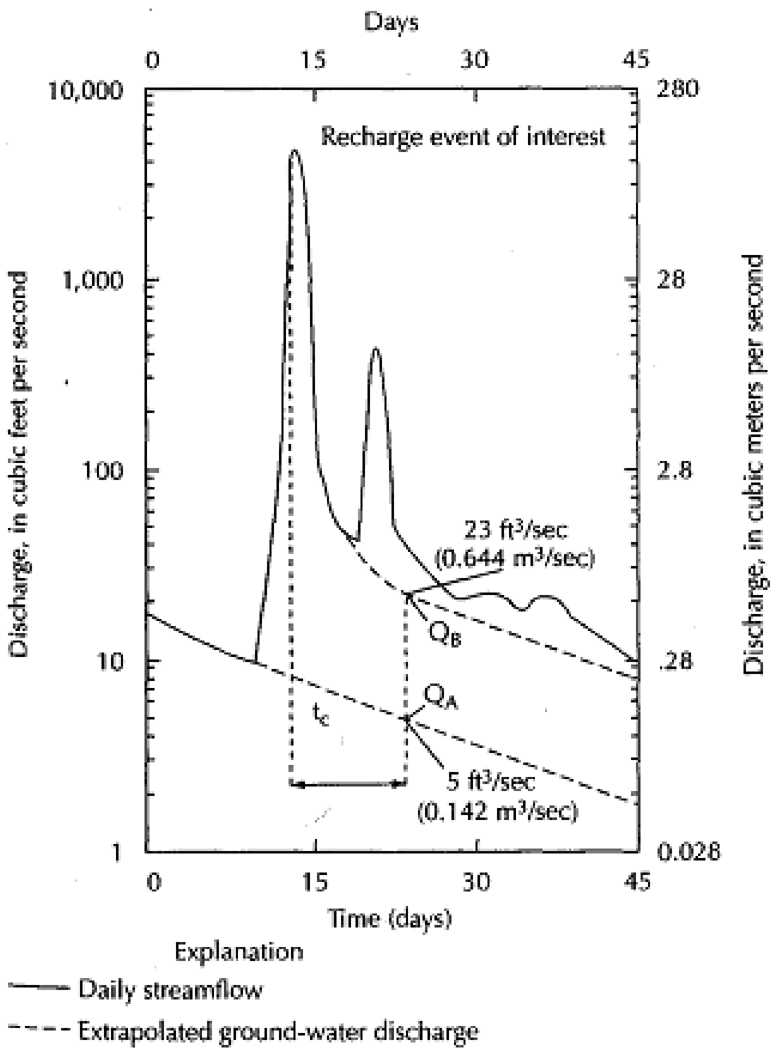


Figure 2-4: Determining groundwater recharge from base flow from the incremental method of Rarobaugh(Mau and Winter as cited in C.W.Fetter).

Rorabaugh (1964) defined a critical time, t_c , which can be shown to be equal to $0.2144t_1$ (Rutledge and Daniel 1994). At the critical time past the hydrograph peak, the total potential groundwater discharge is equal to approximately one –half of the water that recharged the groundwater system. Figure2-4 shows base flow recession A, then a hydrograph peak caused by a precipitation event, followed by base flow recession B. Q_A is the base flow of recession A at the critical time, t_c, after the hydrograph peak; and Q_B is the base flow of recession B ,also at the critical time. The increase in the total potential base flow, ΔV_{tp} at t_c from recession A to recession B, is:

$$\Delta V_{tp} = \frac{Q_B t_1}{2.3026} - \frac{Q_A t_1}{2.3026} \quad (9)$$

Since the total volume of recharge at the critical time is twice the increase in the total potential base flow, then G, the volume of water that recharged the aquifer as a result of the precipitation event that caused the flood peak, is equal to 2 x ΔV_{tp} or

$$G = (2(Q_B - Q_A)t_1)/2.3026 \quad \textbf{(10)}$$

The steps in finding the volume of water recharging the groundwater system are as follows:

1. Find t_1 , the number of days it takes for the base flow recession to decline by one log cycle of time (days/log cycle), by inspection of the recession curves
2. Compute the critical time, t_c, which is $0.2144t_1$
3. Locate the time that is t_c days past the peak
4. Extrapolate recession A to find Q_A at t_c
5. Extrapolate recession B to find Q_B at t_c
6. Find total recharge by equation 10.

C. Numerical modeling

Watershed (rainfall/runoff) modeling is used to estimate recharge rates over large areas. Singh (1995) reviewed many watershed models, which generally provide recharge estimates as a residual term in the water-budget equation (Eq. 4; Arnold et al. 1989; Leavesley and Stannard 1995; Hatton 1998). The minimum recharge rate that can be estimated is controlled by the accuracy with which the various parameters in the water budget can be measured (~±10%) and the time scale considered. The various watershed models differ in spatial resolution of the recharge estimates. Some models are termed lumped and provide a single recharge estimate for the entire catchment (Kite 1995). Others are spatially disaggregated into hydrologic-response units (HRUs) or hydrogeomorphological units (HGUs) (Salama et al. 1993; Leavesley and Stannard 1995).

Watershed models are applied at a variety of scales. Bauer and Mastin (1997) applied the Deep Percolation Model to three small watersheds (average size 0.4 km^2) in the Puget Sound in Washington, USA. Average annual recharge rates are 37, 138, and 172 mm for the three basins. Arnold et al. (2000) applied the SWAT model to the upper Mississippi River Basin, USA (492,000 km^2). The basin was divided into 131 hydrologic-response units with an average area of 3,750 km^2. Estimated annual recharge ranged from~10 to 400 mm. Small-scale applications allow more precise methods to be used to measure or estimate individual parameters of the water-budget equation (Healy et al. 1989). Time scales in models are daily, monthly, or yearly. Daily time steps are desirable for estimation of recharge because recharge is generally a larger component of the water budget at smaller time scales. Other recent applications of watershed models to estimate recharge include Arnold and Allen (1996; recharge rates 85 to 191 mm/year, Illinois, USA), Sami and Hughes (1996; recharge rate ~6 mm/year in a fractured system, South Africa), and Flint et al. (2002, this volume; recharge rate 2.9 mm/year at Yucca Mountain, Nevada, USA).

Techniques Based on Unsaturated-Zone Studies

Unsaturated-zone techniques for estimating recharge are applied mostly in semiarid and arid regions, where the unsaturated zone is generally thick. These techniques are described in detail in Hendrickx and Walker (1997),Scanlon et al. (1997), Gee and Hillel (1988), and Zhang (1998). The recharge estimates generally apply to smaller spatial scales than those calculated from surface-water or groundwater approaches. Unsaturated-zone techniques provide estimates of potential recharge based on drainage rates below the root zone; however, in some cases, drainage is diverted laterally and does not reach the water table. In addition, drainage rates in thick unsaturated zones do not always reflect current recharge rates at the water table.

A. Historical tracers

Historical tracers result from human activities or events in the past, such as contaminant spills (Nativ et al. 1995) or atmospheric nuclear testing (^{3}H and ^{36}Cl). These historical tracers or event markers are used to estimate recharge rates during the past 50 years (Phillips et al. 1988; Scanlon 1992; Cook et al. 1994). Industrial and agricultural sources produce contaminants such as bromide, nitrate, atrazine, and arsenic, and these can provide qualitative evidence of recent recharge; however, uncertainties with respect to source location, concentration, and timing of contamination, as well as possible non conservative behaviour of contaminants, make it difficult to quantify recharge. The presence of an event marker in water suggests that a component of that water recharged in a particular time period. In many areas where these tracers have been used, the bomb pulse peak is still in the root zone (^{36}Cl, 1.8 mm/year, Norris et al. 1987; ^{36}Cl, 2.5 to 3 mm/year,^{3}H, 6.4 to 9.5 mm/year, Phillips et al. 1988; ^{36}Cl, 1.4 mm/year, ^{3}H, 7 mm/year, Scanlon 1992), indicating that water fluxes at these sites are extremely low, which is an important consideration for waste disposal. Because much of this water in the root zone is later evapotranspired, water fluxes estimated from tracers within the root zone overestimate water fluxes below the root zone by as much as several orders of magnitude (Tyler and Walker 1994; Cook and Walker 1995). Deep penetration of thermonuclear tracers has been found in sandy soils in arid settings (^{3}H, 23 mm/year, Dincer et al. 1974; ^{3}H, 22 to 26 mm/year, Aranyossy and Gaye 1992). The maximum water flux that can be estimated may be limited by depth to groundwater. For example, if the average water content is 0.1 m^3/m^3 and the time since peak fallout is 40 years, a recharge rate of 50 mm/year would result in a peak at a depth of 20 m. Therefore, this technique is generally unsuitable where recharge rates are much greater than 50 mm/year. Theoretically, the technique could be used for higher recharge rates if the water table were deeper; however, the difficulty of soil sampling at these depths and locating the tracer peak may be prohibitive. Historical tracers provide point estimates of water flux over the last 50 years.

B. Environmental tracers – chloride

I. Theoretical Background

The major chemical behavior of chloride ion includes: they do not significantly enter in to oxidation or reduction reactions; they form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, they are not significantly adsorbed on mineral surfaces, play few vital biochemical roles, and the circulation of chloride ions in the hydrologic cycle is largely through physical processes.

Chloride ions moved with the water through most soils tested with less retardation or loss than any of the other tracers' tested-including tritium that had actually been incorporated in to the water molecules. This conservative behavior should not, however, be expected where movement is through compact clay or shale (Kaufman and Orlob, 1956 in Aychiluhm 2006).

Chloride ions may be concluded characteristically to be retained in solution through most of the processes that tend to separate out other ions (Mairs, 1967).

Environmental tracers such as chloride (Cl) are produced naturally in the Earth's atmosphere and are used to estimate recharge rates (Allison and Hughes 1978; Scanlon 1991, 2000; Phillips 1994). The mass of Cl into the system (precipitation and dry fallout, P) times the Cl concentration in P (C_P) is balanced by the mass out of the system (drainage, D) times the Cl concentration in drainage water in the unsaturated zone (C_{uz}) if surface runoff is assumed to be zero:

$$\mathbf{PCp} = \mathbf{DC_{UZ}} \qquad D = PCp/C_{UZ} \tag{11}$$

Chloride concentrations generally increase through the root zone as a result of evapotranspiration and then remain constant below this depth. Drainage is inversely related to Cl concentration in the unsaturated-zone pore water (Eq. 11). This inverse relationship results in the Cl mass-balance (CMB) approach being much more accurate at low drainage rates, because Cl concentrations change markedly over small changes in drainage. The CMB approach has been most widely used for estimating low recharge rates, largely because of the lack of other suitable methods. Water fluxes as low as 0.05 to 0.1 mm/year have been estimated in arid regions in Australia and in the US (Allison and Hughes 1983; Cook et al. 1994; Prudic 1994; Prych 1998). Low recharge rates are reported to be consistent with radioactive decay of ^{36}Cl at a site in the US (Scanlon 2000). Somewhat higher recharge rates have been calculated from Cl concentrations measured in sinkholes in Australia (>60 mm/year; Allison et al. 1985), sand dunes cleared of vegetation in Australia (4 to 28 mm/year; Cook et al. 1994), and sands with sparse vegetation in Cyprus (33 to 94 mm/year; Edmunds et al. 1988). The maximum water flux that can be estimated is based on uncertainties in measuring low Cl concentrations and potential problems with Cl contributions from other sources and is generally considered to be about 300 mm/year. Scanlon and Goldsmith (1997) report uncertainties of an order of magnitude beneath ephemeral lakes (playas) in the US because of uncertainties in Cl input from runoff to playas. The CMB approach provides point estimates of recharge rates. Temporal scales range from decades to thousands of years (Scanlon 2000).

II. Approaches and Assumptions

The method is based on the assumption of mass between the input of atmospheric chloride and the chloride flux in the sub-surface.

Ignoring the direct inputs of pollution, the fluxes for a catchment can be interpreted in terms of a mass balance equation: (Drever and Clow, 1995)

Solutes in outflow = solutes from atmosphere + solutes from weathering of minerals ± solutes from change in biomass ± change in exchange pool

Where, solutes in out flow = the volume and chemical composition of water leaving the catchment

Solutes from the atmosphere = the atmospheric input comes in the form of precipitation and dry deposition

Solutes from changes in the biomass = as plants grow, they extract inorganic nutrients from the soil solution and incorporate them in to plant tissue. (Plant growth may affect the budgets of most of the budget solutes; the solutes least affected are Na and Cl).

Solutes from changes in the exchange pool = exchangeable cations and anions are contained in soils that are in equilibrium with the soil solution. As the composition of the soil solution changes, ions will be exchanged between the solid phase and solution. If the soil solution composition does not change with time, adsorbed ion will not change either, and ion exchange will make no net contribution to the solute budget.

Application of the Chloride mass balance follows the following assumptions:

1. The only source of chloride in groundwater is from precipitation falling directly on the aquifer material;
2. Concentration of chloride in groundwater is by evapotranspiration with in the unsaturated zone, not from recycling, dissolution of minerals containing chloride, or inflow from adjacent aquifers;
3. Chloride is not retarded by adsorption nor accelerated by anion exclusion
4. Chloride is conservative and its mass flux has not changed over time
5. Chloride application rate is constant and known
6. There is no appreciable chloride run off or run on from the sampling sites and
7. Steady state conditions prevail.

Although the existence of these conditions may be difficult to confirm at each site, the method is applied to meet the following objectives.

1. To compare the results with the mean recharge depth obtained from other methods including water-balance, base flow recession method, and long-term mean minimum flow there by suggesting the applicability of the method
2. To test the workability of the method in such a climate and a hydrogeological environ with reference to results obtained from the conventional approaches mentioned above.
3. To forward suggestions in which application of the method is effective and improved results are achieved in the area under investigation and in others which have similar climatic and hydrogeologic characteristics.

The general equation for mean annual recharge estimation from chloride data and attributes is:

$$R = PPT * (Cl^{-}p)/(Cl^{-}gw) \quad (12)$$

Where R=mean groundwater recharge in mm/year

PPT= mean annual precipitation depth in mm

$[Cl^{-}_{GW}]$ = average concentration of chloride in ground water in mg/l

$[Cl^{-}_{p}]$=Concentration of chloride in precipitation in mg/l

Techniques Based on Saturated-Zone Studies

Most unsaturated-zone techniques provide point estimates of recharge; saturated-zone techniques commonly integrate over much larger areas. Whereas surface-water and unsaturated-zone approaches provide estimates of drainage or potential recharge, saturated-zone approaches provide evidence of actual recharge because water reaches the water table.

A. Water-table fluctuation method

The water-table fluctuation (WTF) method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as

$$R = Sydh/dt \tag{13}$$

where S_y is specific yield, h is water-table height, and t is time. The WTF method has been used in various studies (Meinzer and Stearns 1929; Rasmussen and Andreasen 1959; Gerhart 1986; Hall and Risser 1993) and is described in detail by Healy and Cook (2002). The method is best applied over short time periods in regions having shallow water tables that display sharp rises and declines in water levels. Analysis of water-level fluctuations can, however, also be useful for determining the magnitude of long-term changes in recharge caused by climate or land-use change. Difficulties in applying the method are related to determining a representative value for specific yield and ensuring that fluctuations in water levels are due to recharge and are not the result of changes in atmospheric pressure, the presence of entrapped air, or other phenomena, such as pumping. The method has been applied over a wide variety of climatic conditions. Recharge rates estimated by this technique range from 5 mm/year in the Tabalah Basin of Saudi Arabia (Abdulrazzak et al. 1989) to 247 mm/year in a small basin in a humid region of the eastern US (Rasmussen and Andreasen 1959). Water-level fluctuations occur in response to spatially averaged recharge.The area represented by the recharge rates ranges from tens of square meters to several hundred or thousand square meters. Time periods represented by the recharge estimates range from event scale to the length of the hydrographic record.

B. Darcy's law

Reliable water level contour and transmissivity maps can be used to determine reliable recharge estimation by applying Darcy Approach. Darcy approach is derived from Darcy law of groundwater flow in a saturated aquifer system. The method requires hydraulic parameter like, weighted average transmissivity, flow gradient values and width of a flow at right angle to the direction of groundwater flow. It can be given by the formula:

$$\mathrm{Q = T * I * L * 365} \tag{14}$$

Where,
- Q - Average annual groundwater recharge in million meter cube (Mm^3)
- I - Hydraulic gradient
- T - Transmissivity in m^2/day
- L - Width of flow at right angle to the direction of flows in meters

Calculating the weighted average transmissivity, hydraulic gradient, width of a flow at right angle to the direction of flow from the hydrogeological map of the project area, groundwater recharges have been estimated for the alluvial aquifers in Uppe Fafen Sub Basin and Raya Valley as follows:

In Upper Fafen Sub Basin of Somali Region, the general groundwater flow direction is from NW-SE direction. The calculated weighted average hydraulic parameters are: T = 1800 m2/day, I = 0.006944, L= 16000 m. The estimated recharge of Fafan sub-basin using the above formula (Equation 14).

Q_F = 73 M m^3/year.

Calculating the weighted average parameters of transmissivity and flow gradient values from figure2-5 and figure2-6 and applying the above formula (Equation 14), recharge is estimated for the two groundwater sub-basins (Alamata and Mehoni Sub Basins) of Raya Valley plain alluvial aquifer.

Alamata sub-basin: In this sub-basin the groundwater flow direction is from west to east and discharged along Selen wuha outlet to Afar depression.

The weighted average parameter values are: T = 1269 m2/day, I = 0.009, L= 35,818 meters. Calculating the recharge for Alamata sub-basin by Darcy equation

Qa = 426,823m^3/day or 155.8 MCM/year (MCM – Million cubic meter)

Mahoni Sub-basin: From Mahoni sub-basin the groundwater flow to southeast and concentrate to the internal graben which flow to SSW direction to Alamata sub-basin, finally flows west to east and discharged along Selen wuha outlet to Afar depression.

The weighted average parameter values are: T = 914m2/day, I = 0.02 L= 22, 400 meters. Calculating the recharge for Alamata sub-basin by Darcy equation

Qm = 360,973m3/day or 131.8 MCM/year (MCM – Million cubic meter)

The total mean annual dynamic groundwater recharge of Raya valley plain alluvial aquifer is estimated to be about 787,796m3/day or 287.5 MCM/year.

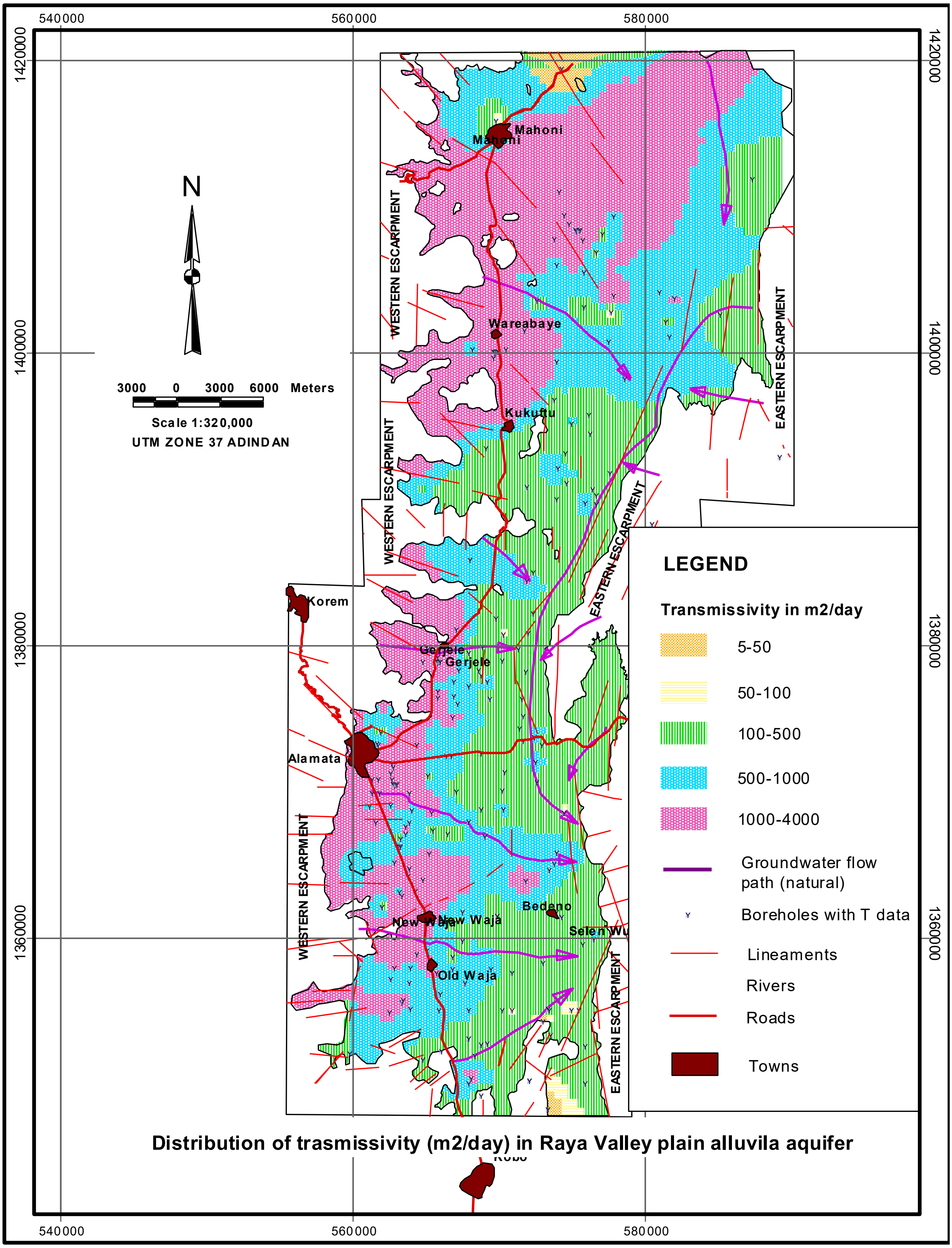


Figure 2-5: Transmissivity (m2/day) map of raya valley plain alluvial aquifer

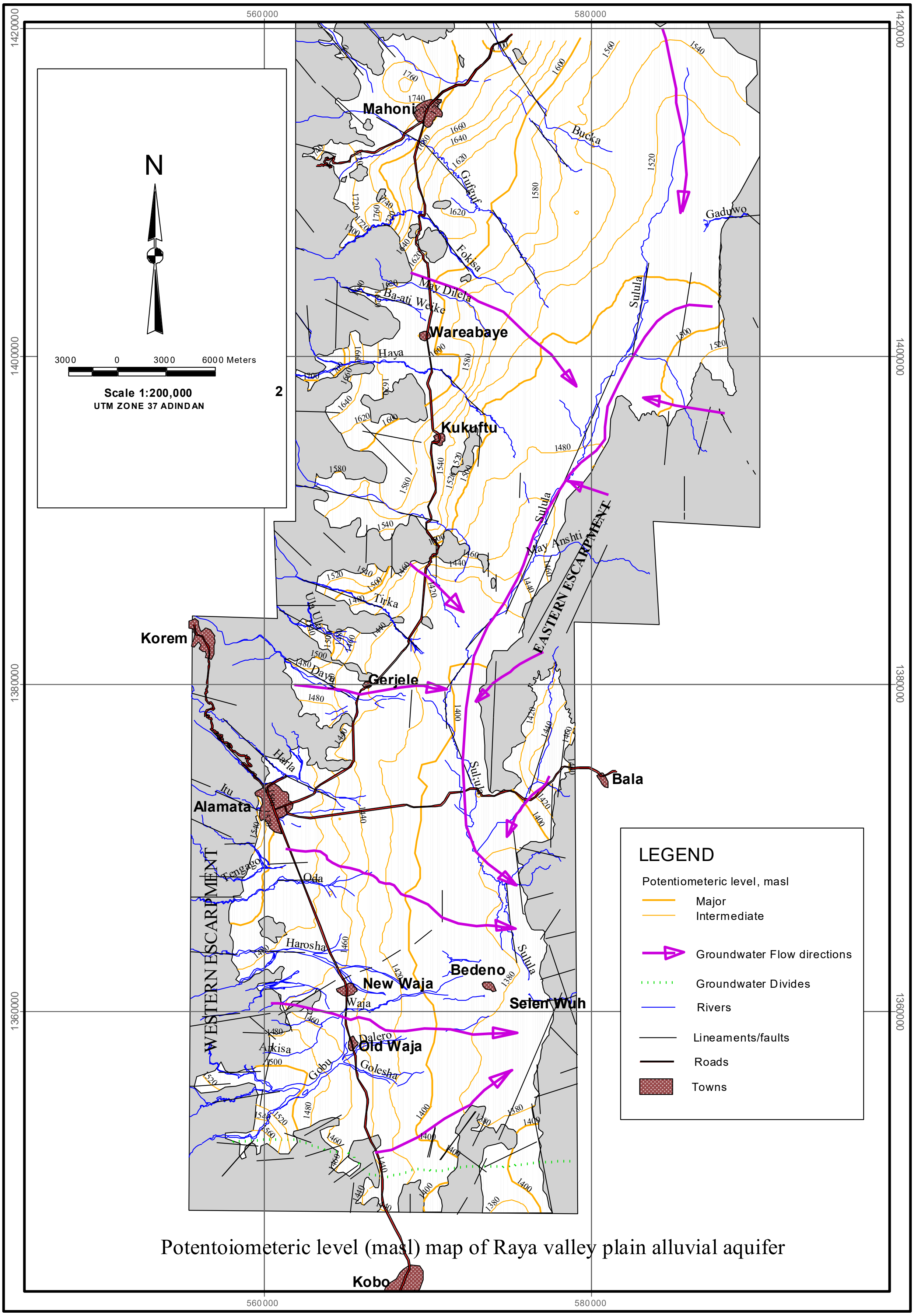


Figure 2-6: Potentiometeric surface map of Raya Valley plain alluvial aquifer

2.2.3 Hydrogeological survey

The objectives of the survey are mainly:

- For further familiarizing and visualizing the general feature of the study area.
- Verify findings revealed at the office works when reviewing previous studies and interpretation of aerial photo and imageries.
- Collection, interpretation and analysis of secondary water point data, borehole log data
- Depth to groundwater data measurement, groundwater level fluctuation data
- Identifying Boundary conditions, source of recharge, and recharge and discharge mechanisms
- Sampling of groundwater for water quality analysis to determine the physical, chemical and isotopic characteristics of the groundwater conditions
- Application of Darcy's law and flow net analysis to identify groundwater flow direction
- Conducting pumping test and interpretation of the pumping test data for aquifer characterization

During field survey the hydrogeologist makes traverse in the study area and identify the hydrogeological set up, geological structures (faults, lineaments, folds, dykes and etc.) which are important and related with the groundwater occurrences, distribution and storage and thereby verify the office level findings with the visual observation at the field. The water point inventories in the field will constitute the following component of works:

- Geo-referencing of all water points (Boreholes, dug wells, springs) using GPS
- Measuring of depth to groundwater of water points at places where there is possible to insert sensor such as deep meters.
- Describe geological, geomorphologic and Hydrgeological conditions of each water points and other parameters.
- Identify preliminarily the recharge and discharge zones in the study area

The water points inventory data shall be recorded in the format given in appendix1.

2.2.4 Water quality survey

As indicator of groundwater quality the following analysis are required i.e. physical, bacteriological and hydro-chemical analyses. Water samples are collected systematically from surface water bodies (rivers, ponds, reservoirs), spring, dug wells and existing wells in the study area. The water sampling points shall be chosen on the basis of the study results from the regional hydrogeological, geological, structure and tectonics study of the area. The water samples collected shall be analyzed for physical and chemical determinations. The main parameters to be determined are:

- Field measurement of electrical conductivity (EC), pH and water sampling from different water sources (bore holes, hand dug wells, springs, rivers and streams).
- Physio-chemical analysis of water samples are analyzed
- The water quality study involves the collection of relevant physio-chemical for different water bodies of interest in the study area and adjacent areas in order to:
- Characterize the chemical composition of the aquifers and adjacent area to establish their relationships,
- The interaction of surface water with ground water systems.
- To prepare groundwater quality maps (EC, TDS, SAR…)
- Characterize the groundwater of the study area, its suitability for irrigation based on Sodium Adsorption ratio (SAR) and the United States Salinity Laboratory (USSL).

Table 2-1: Water quality parameters to be analyzed and method of analysis

No.	Water quality parameters	Method of analysis
1	. Electrical Conductivity(EC)	Conductometry
2	. pH	Potentiometry
3	. Total Dissolved solids (TDS)	Gravimetry
4	. Hardness . Calcium (Ca) . Magnesium (Mg) . Chloride (Cl) . Alkalinity . Carbonate (CO3) . Bicarbonate (HCO3)	Titrimetry
5	. Fluoride (F) . Iron (Fe) . Manganese (Mn) . Phosphate (PO4) . Sulphate (SO4) . Nitrate (NO3) . Boron(B)	Spectro photometer
6	. Sodium (Na) . Potassium (K)	Flame Emission

In any evaluation of groundwater resources the quality of the groundwater is of equal importance to the quantity available. In other words, the physical, chemical & biological and isotopic characteristics of the surface and groundwater are of major importance in determining whether the water is suitable for domestic, industrial and agriculture.

Furthermore, details pertaining to groundwater quality may throw light on such factors as the interconnection between surface water and aquifers, groundwater movement and storage.
The groundwater sample can be tested at field, laboratory (physical, chemical & biological, and isotopic)

a) Field Test

PH, Temperature, EC and TDS

b) Laboratory test

Physical Test: Temperature, color, turbidity, odor and Taste
Biological Tests: Pathogenic bacteria (commonly coli form bacteria), virus and gases
Chemical Tests: It analyzes the major, minor and trace ionic (both cations and anions) content of the ground water sample.

Major constituents (1mg/lt – 1000mg/lt)	Minor constituents (01mg/lt – 10mg/lt)
Sodium	Iron
Calcium	Strontium
Magnesium	Potassium
Bicarbonate	Carbonate
Sulphate	Nitrate
Chloride	Fluoride
Silica	Boron

2.2.5 Geophysical investigation

It is a scientific measurement of the physical properties of the earth's crust for investigation of geologic structures and groundwater conditions. The methods are frequently inexact or difficult to interpret and they are most useful when supplemented by subsurface investigations. They detect difference or anomalies of physical properties within the earth's crust: Density, magnetism, electricity and electrical resistivity are properties most commonly measured. Experience and research have enabled pronounced difference in these properties to be interpreted in terms of geologic structures, rock types and porosity, water content and water quality, temperature. The main surface geophysical methods are:

- Electrical resistivity's (VES & Profiling)
- Magnetics
- Gravity
- Seismic refractions

The objective of the geophysical investigation is to determine:

- Thickness of the different geological formation
- Depth to the groundwater
- Qualitative and/or quantitative evaluation of degree of salinity of the groundwater
- To identify geological structures
- To identify aquifer thickness.

VES (Vertical Electrical Sounding) is mainly employed in groundwater exploration. Magnetics and Imaging, however, are applied depending on the geological setting and aquifer thickness.

The VES survey commonly applied in groundwater investigations is described as follows:

Theoretical Background

Geophysical exploration methods are among the primary tools for the investigation of ground water resources and are applicable to a wide range of problems. Among the various techniques of geophysical prospecting, the electrical methods have branched out from a broader and more basic discipline geoelectricity, which utilizes the electrical properties of rocks and soils. Among the highly diversified techniques, electrical resistivity is the one most extensively used in prospecting for groundwater resources. In this method a direct current or a low frequency alternating current is introduced into the ground using a pair of electrodes and the resulting distribution of the potential in the ground is measured by using another pair of electrodes connected to a sensitive voltmeter.

The variation of resistivity with depth is studied by a progressive increase of current electrode separation so that the effects of rocks at depth will be more significant. This method is known as vertical electrical sounding (VES).

Resistively value is determined from the relation developed using potential drop, measured current and the geometrical configuration of the electrodes. If the ground is homogeneous the resistivity calculated would be independent of electrode spacing and location. But in reality, since the real ground is locally heterogeneous both laterally and at depth the resistivity varies with the relative position of electrodes.

The sub-surface material resistivity variation affects the electrical current flow lines and these in turn affect the distribution of surface electrical potential lines, compared to their pattern over a homogeneous medium. The apparent resistivity (ρ_a) is then computed.

The usefulness of the resistivity method in solving geological and hydrological problems depends to a considerable extent on the sub-surface resistivity contrast. In considering the resistivities of varies geologic units it is found that the overall resistivity is very sensitive to variation in porosity, water content, and water quality (ionic concentration) and can be considerably lower than the resistivity of the rock matrix (Kearey, et al., 1984).

The survey procedure is according to Schlumberger electrode configuration as shown in the schematic diagram in figure 2-7. The configuration is laid out using two current and two potential electrodes AB and MN, respectively.

The spreading is performed in such a way that the potential electrodes remain fixed for defined current electrode separation while the current electrodes are spread apart for each measurement. The acquired resistance values in Ohms and the electrode spacing in meters are used to calculate the apparent resisitivity of each measurement point. The resistivity value in ohm-m is calculated using the following empirical formula:

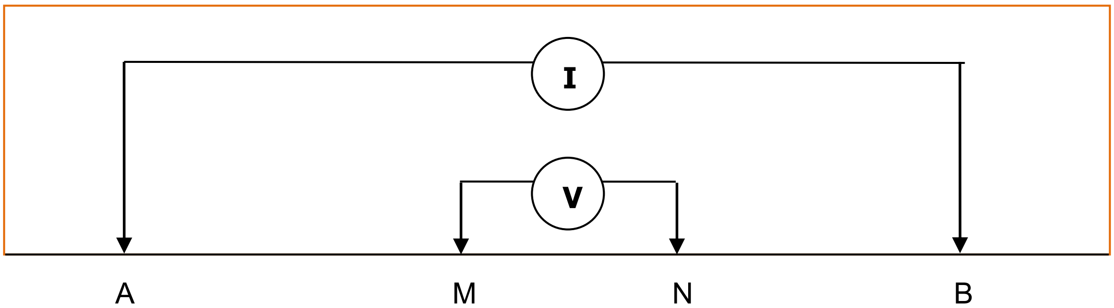


Figure 2-7: Schematic array in Schlumberger configuration

$$\rho_a = K * (\Delta V / I)$$

$$K = (2\prod)/((1/AM) - (1/AN) - (1/BM) + (1/BN))$$

Where:

ρa - Apparent resistivity

K – Geometric Constant

ΔV - Potential difference between M & N

I - Current drained through A & B

A, B - Current electrode spacing

M, N - Potential electrode spacing

Magnetic method

Many geological formations by virtue of their content of magnetic minerals will behave like large buried magnets and will then have associated with them a magnetic field. This very local magnetic field will be superimposed on the normal magnetic field of the earth.

Measurements of the magnetic field taken in the locality of such geological formations will show departures from the undisturbed earth's magnetic field in the vicinity of these formations. These changes, or anomalies as they are called, could be large or small and could be either an increase or a decrease of the earth's field and will depend on the depth of burial, degree and direction of magnetization, and the attitude of the formation in relation to the direction of the earth's field at that locality.

Magnetometers are the instruments used for measuring the magnetic field and by virtue of their sensitivity and range are able to measure not only the changes of field between two rock types with only small differences in magnetic content, but also the prominent anomaly of a dolerite dyke or the extremely large anomaly over a magnetic iron ore deposit.

Magnetic surveys are often used in groundwater exploration to locate and delineate
Geological structures (magnetic dykes, faults etc) which may control the occurrence and movement of groundwater. Details of the basic principles, instrumentation, field procedures for data collection, analysis and interpretation methods should be referred in (Geological Survey of Ethiopia, 2006, Geophysical Standard Guides).

Gravity method
Gravity measurements indicate variations in the earth's gravitational field caused by lateral differences in the density of the subsurface soil or rock or the presence of natural voids or man - made structures. By measuring spatial changes in the gravitational field, variations in subsurface conditions can be determined.

Detailed gravity surveys (commonly called micro-gravity surveys) are used for near-surface geologic investigations. Geologic and geotechnical applications include location of buried channels, bedrock structural features, voids, and caves, and low-density zones in the sub surface for groundwater studies.

Seismic refraction method
The seismic refraction method is used to map geologic conditions including depth to bedrock, or to water table, stratigraphy, lithology, structure, and fractures or all of these. The calculated seismic wave velocity is related to mechanical material properties. Therefore, characterization of the material (type of rock, degree of weathering, and rippability) is made on the basis of seismic velocity and other geologic information. Details of the basic principles, instrumentation, field procedures for data collection, analysis and interpretation methods should be referred in (Geological Survey of Ethiopia, 2006, Geophysical Standard Guides). However, the method is so expensive that it is not frequently applied in groundwater exploration.

2.2.6 Drilling of test wells

It is test drilling of small diameter wells to ascertain geologic and groundwater conditions which are useful in verifying other means of investigations and to obtain assurance of groundwater conditions prior to production well drilling. Test wells are drilled on representative areas based on the geological, hydro-geological and geophysical survey results. The main purposes of the test wells are to calibrate the surface geophysics interpretation and determine preliminary aquifer parameters of the potential formation. The test wells to be drilled are representative from aspect of spatial distribution in the project area.

The detailed description of the main subsurface hydrogeologic information that can be gathered from test well drilling and its associated investigation methods are:

Geologic Log, Drilling-Time Log, Water level Measurements, Sonic (acoustic) logging, Casing logging, Temperature logging, Caliper logging, Analysis of Borehole-Geophysical logging(Resistivity logging, Spontaneous Potential logging, Radiation logging, Natural-Gamma logging, Gamma-Gamma logging, Neutron logging, Fluid conductivity logging, Fluid velocity logging, Camera or Television logging)

Specially designed wide angle camera with less than 7cm in diameter, is equipped with lights and provide continuous visual inspection of a borehole. With video tape a record of the interior can be preserved. Among the variety of application are: Locating change in geologic strata, Pinpointing large spaces, inspecting the condition of the well casing and screen, Checking for debris in wells, locating zones of sand entrance and searching for lost drilling tools.

Regardless of the practice mainly to use only the borehole resistivity logging in most of the drilled test or production wells in our country, using multiple borehole geophysical logging techniques is very important depending on the required information as indicated in table3-2 below.

Table 2-2: Summary of geophysical logging applications to groundwater hydrologic and hydro geologic investigations, source (After Keys & Mac Crary)

Required Information	Possible Logging Techniques
Lithology and stratigraphic correlation of aquifers and associated rocks	Resistivity, sonic or caliper logs made in open holes, radiation logs made in open or cased holes
Total porosity or bulk density	Calibrated sonic logs in open holes, calibrated neutron or gamma logs in open or cased holes
Effective porosity or true resistivity	Calibrated long-normal resistivity logs
Clay or Shale content	Natural Gamma logs
Permeability	Under some conditions, long –normal resistivity logs
Secondary permeability, fracture and solution openings	Caliper, sonic or television logs
Specific yield of unconfined aquifers	Calibrated neutron logs
Grain size	Possible relations to formation factor derived from resistivity logs
Location of water level or saturated zones	Resistivity, temperature or fluid conductivity logs, neutron or gamma-gamma logs in open or cased holes
Moisture Content	Calibrated neutron logs
Infiltration	Time-interval neutron logs

Required Information	Possible Logging Techniques
Source and movement of water in a well	Fluid velocity or temperature logs
Chemical and physical characteristics of water including: salinity, temperature, density & viscosity	Calibrated fluid conductivity logs, temperature logs and resistivity logs
Construction of existing wells: diameter and position of casings, perforations, screens	Gamma-Gamma logs , caliper logs, casing logs and camera or television logs
Guide to screen setting	All logs providing data on the lithology, water bearing characteristics and correlation and thickness of aquifers
Casing corrosions	Under some conditions, caliper logs, casing logs or camera logs
Casing leaks and/or plugged screens	Fluid velocity logging

2.2.7 Evaluation of the groundwater potential and reporting

In the report the following analyses, discussions, conclusions and recommendations are carried out:

- Analysis of the hydrogeological setup, hydro-lithology, aquifer parameters, groundwater quality, recharge and discharge condition
- Estimation of the mean annual groundwater recharge by different methods such as Darcy approach method, water balance, base flow separation, etc whichever appropriate for the hydrogeological conditions and availability of data.
- Estimation of the groundwater reserve.
- Preliminary estimation of the exploitable groundwater potential of the area by mathematical analytical or numerical methods modeling depending on the availability of data.
- Based on the preliminary estimation of the exploitable groundwater potential of the basin and water quality, it will be evaluated that whether the groundwater potential is promising for further study.
- If the groundwater potential is promising then a number of prospective groundwater potential zones shall be selected and prioritized for further study.
- Preliminary cost estimates of groundwater exploitation, Birr/m3 for different energy scenario.
- Groundwater regime monitoring system that includes specification of regime monitoring equipment for groundwater level and quality monitoring to be installed on test wells and production boreholes.
- Exploratory wells design and comprehensive contract document that incorporate contract condition, bidding instruction, specification and bill of quantities as well contract agreement for drilling and testing work for feasibility phase work shall be prepared.
- Conclusions and recommendations.
- Methodology, work volume and Work program for the next phase activities (Phase II).

3 PHASE II (FEASIBILITY STUDY)

3.1 INVESTIGATION ON PROSPECTIVE SITES

3.1.1 Geological, geomorphological and structural study

The geological, geomorphological and structural study at this phase shall focus to fill data gaps and produce respective maps at larger scales as required.

3.1.2 Geophysical survey

Reconnaissance reveals whether the proposed target areas are accessible for geophysical investigations and possible follow-up exploratory drilling. Geophysical techniques are used to obtain further characteristics of formations identified in previous levels of investigation. There are a number of techniques available for geophysical investigations in groundwater exploration, examples Resistivity, magnetic, electro-magnetic, seismic refraction and gravity. Expertise available and the geological conditions determine the geophysical method ultimately employed in a project. However, it is recommended that more than one method is employed, as two methods may serve as complements to each other. Geophysical investigations are used to pin point target for exploration drilling. Targets for exploration drilling are selected from a detailed assessment of geophysical investigations, i.e. anomalies, and their correlation with features mapped from other sources, e.g. lineaments.

Detail geophysical investigation mainly Vertical Electrical Sounding and Profiling are to be carried out at selected prospective sites for investigation for groundwater resources development.

Volume and depth of penetration of geophysical investigation depend on the findings of phase I report. If other method of geophysical investigation is required, it is to be discussed thoroughly in phase I report and upon the approval of the Client amendments can be made.

3.1.3 Drilling and pumping test of pilot production wells

A well site or well field area is selected based on geological, hydrogeological and geophysical investigation. Exploration test holes are essential in order to assess geology and to evaluate the quality and quantity of water.

Once the site is found to be good aquifer production wells are drilled at appropriate distance between wells to minimize interference.

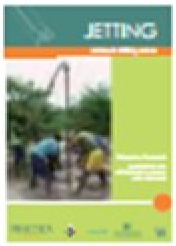
There are many methods of drilling but the fastest drilling is percussion drilling of (DTH) type. On the upper unconsolidated material or top weathered or clayey zone rotary drilling of bigger diameter bit (tricone) is applied. In case the formation has caving problem rotary mud drilling can be used.

Exploratory drilling and test pumping is the sole method to evaluate the true groundwater potential of an investigated site and will provide that the siting procurers were optimal, confirm the inferences of the previous investigations. Exploratory drilling, however, is costly means of exploring for groundwater that is why sites have to be selected with great care so that successful boreholes can be developed to serve as production boreholes.

The high cost of developing water sources prevents many rural people from gaining access to irrigating the available land. Increasing access to water sources for irrigation for the under-served communities while keeping up with growing populations will require serious consideration of lower cost alternatives to the existing expensive water source options. The manual drilling sector has proven itself as a successful, lower-cost approach with great potential under suitable conditions. In numerous countries manual drilling techniques are used as an alternative or to complement machine drilling. Drilling 'shallow' water wells by hand using local enterprises, can reduce the cost of a well by a factor 4 - 10 compared to a machine-drilled borehole. This cost reduction not only enables NGOs and Governments to construct more water points, but also 'opens the door' to villagers, farmers, schools and small communities to fi nance well construction independently through the private sector. Strategies and programs should be adopted to professionalize the manual drilling sector in order to scale-up rural water supply for household irrigation purposes.

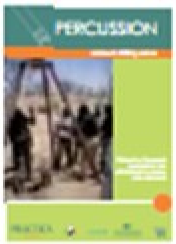
Variations of four manual drilling technologies are being used, each with their own advantages, disadvantages and suitability for different geological conditions.

It is suggested that the four drilling handbooks are used in combination with the manual: 'Understanding Groundwater & Wells in manual drilling'. So the user is advised to refer the following handbooks on manual drilling:



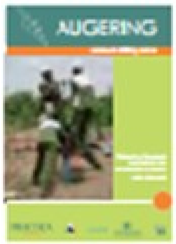
1. Manual drilling series: JETTING

This handbook describes in detail the various jetting techniques that can be used to drill wells in loose and soft soil formations. With this technique, wells are drilled in a number of hours rather than days.



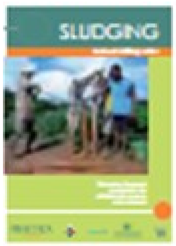
2. Manual drilling series: PERCUSSION

This handbook describes in detail the percussion technique. Although the technique is slower than other drilling techniques, it is the only drilling technique that is able to drill through consolidated rock layers.



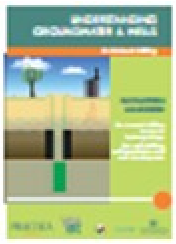
3. Manual drilling series: HAND AUGER

This handbook describes the hand auger technique. This cheap and effective technique is very suitable for sinking shallow wells in soft soils and is excellent for soil surveys. Many drilling teams have this technique in their drilling toolkit to complement other drilling techniques.



4. Manual drilling series: SLUDGING

This handbook describes the sludging technique, and in greater detail the ROTA-sludge technique. It is combination of sludging and percussion and is particularly useful due to its versatile application for a range of soil formations.



5. Manual: 'Understanding Groundwater and Wells in manual drilling'
The manual 'Understanding Groundwater & Wells in manual drilling' complements the 4 technical training handbooks and highlights those essential subjects which are relevant to manual drilling, geo-hydrology, hygiene, well installation and well development in practice, in simple and understandable language.

Source: Practical Foundation, Technical Training Handbooks on Affordable Manual Well Drilling

In order to further evaluate the groundwater potential in terms of sustainable yield and aquifer characteristics the borehole should subsequently be subject to test pumping.

Information collected during drilling e.g. lithology, stratigraphy, water strikes and water quality, should be incorporated in the project database. This information may prove useful for forth coming drilling within a project and future ground water development in the area.

Number of wells to be drilled and depths are as per the evaluation of the groundwater condition of the area at the reconnaissance phase, which proposes design of exploratory wells as test wells. The exploratory/test wells can be used as productive wells for future uses.

To achieve adequate data and result close supervision is to be conducted during construction and pumping test of wells.

After the well has been constructed and developed the contractor shall notify the supervisor to that effect and shall make the necessary arrangements for conducting the final pumping tests. Pumping tests shall follow immediately after the completion of the Development Works.

Besides these final tests the supervisor may order the Contractor to carry out such additional tests during and after construction, as he may deem necessary. All tests shall be run with similar equipment and in a manner described herein.

The Contractor shall furnish all labour, materials, equipment and supplies required and shall operate the pumping unit at such rates of discharge and for such periods of time as required for the execution of the tests.

Step Draw down Tests: The following requirements shall apply to step drawdown and step recovery tests:

Before the test commences, a deep-meter, a stopwatch, and graph paper pad and pencil shall be on hand. The deep-meter shall be checked by lowering into the casing and a trial measurement shall be performed.

Once the equipment has been checked, at least three readings of the water level shall be taken during the half hour immediately preceding the test at ten-minute intervals to obtain the trend of the water level. If two of these are identical, it is possible to proceed with the test. If variations occur, the readings must continue for some time until a definite pattern is obtained.

The test shall cover at least four or five steps. During successive steps, the discharge shall be increased and water levels subsequently measured. Discharges shall preferably, but not necessarily, be increased in steps of 0.2x Q-max. The Q-max will be known approximately from the pumping development stage. The test shall commence with the lowest envisaged discharge rate.

Water levels shall be recorded during this time at intervals as follows for each of the steps:

Every	1	Minute	From	1-10	Minutes of Pumping
"	2	"	"		10 to 20 " " "
"	5	"	"		20 to 50 " " "
"	10	"	"		50 to 100 " " "
"	20	"	"		100 to 180 " " "
"	30	"	"		180 to 360 " " "
"	60	"	After more than 6 hours		

During this time the discharge rate shall be kept constant and recorded periodically.
The duration of each step shall be in no case less than 90 minutes, and if necessary longer, until a stable dynamic water level has been achieved.

At successive steps, the procedure for recording water levels and rates of discharge shall be repeated. The discharge rates of each subsequent step shall be increased by at least 50% of the preceding step until the maximum discharge is attained. A similar procedure shall be followed when a reverse step test is carried out.

At the start of a reverse step test pumping from the borehole shall be at the maximum discharge and the dynamic water level shall be stable. Discharge and water levels shall be recorded. In the first step, the discharge shall be decreased. The following steps will be in the same pattern as the conventional step draw down test.

The consistency of the arrayed discharge/draw down readings, i.e. the anticipated rectilinear regression line, is to be checked in the field.

Should further development of the well be decided upon, another step-draw down test shall be carried out at the well after the additional development.

Draw down and recovery test: The following shall apply to draw down and recovery tests:

Draw down and recovery tests shall be carried out in wells after development and the step draw down tests have been completed. Tests shall commence after a stable water level trend has been ascertained. During the draw down test, the discharge to be determined by the (most probably Q-max) will be constant at all times. The time of its start will be noted by use of a stopwatch. Water levels will be recorded immediately preceding the start, and then at the following intervals of time in minutes.

The test shall be continued at least for 72 hours or may be terminated earlier in case the dynamic water level has stabilized for more than 8 hours.

At the end of a draw down test, a recovery test will be carried out. This test is a mirror image of a draw down test. The time at which recovery commences, is when pumping stops. This time is recorded, and water levels are recorded at the same time interval arrangement as previously noted. The drilling, construction and pumping test works data shall be recorded in the format given in appendix2.

For pumping test and discharge measuring procedures for tube wells, the user is advised to refer Hune Nega (ed). 2012. Manual Tube well drilling and installation for small-scale irrigation in Ethiopia, A practical guideline for development agents in Ethiopia, Ministry of Agriculture, Addis Ababa, Ethiopia.

3.1.4 Hydrogeological investigation

Feasibility study is carried out on the prioritized and selected prospective groundwater zones by applying the following methods. On the prospective groundwater potential zones Geological mapping at 1:50,000 scale or larger, hydrogeological survey, geophysical survey, drilling boreholes and pumping test are conducted.

Hydrogeological and geophysical surveys, drilling of exploratory bore holes, regime observation and modeling are to be carried out on the delineated prospective groundwater sites in particular in order:

- to study in detail the hydrogeological conditions
- to evaluate the quantity and quality of groundwater
- to get more accurate aquifer parameters, establish conceptual models and select appropriate method for estimation of the exploitable groundwater potential
- to determine rational technical and economical distribution of well fields and bore holes
- to estimate the total exploitable groundwater resources in the sites, and
- to assess the environmental impact of exploitation of groundwater in the study areas.

Detail hydrogeological survey at 1:50,000 scale or more is conducted using the information obtained through different investigation methods (geological, geomorphological and structural mapping, geophysical survey, drilling and pumping tests, regime observation etc.)

Based on the hydrogeological survey, different maps to be prepared include hydrogeological map and x-sections, geomorphologic and hydrogeological conditions (groundwater depth, aquifer parameters, water quality, etc.) maps.

3.2 DESIGN OF WELLS

3.2.1 General design considerations

Groundwater and geology cannot be seen separately. Dealing with groundwater development requires sound knowledge of the governing geological conditions. The type of rocks, their physical and chemical properties, the lateral and vertical extent and boundary conditions should be carefully studied in designing a well.

For instance, well design in sedimentary formations mainly focuses on how to handle the related problems with partial penetration of the aquifer, clogging of the borehole wall and the subsequent effects of acid treatment, etc. The well design in igneous and metamorphic rocks may require different approaches than is required in sedimentary formation. Water is obtained at the weathered portion and or at fractured, jointed and faulted zones. Thus the main water bearing property of these types of rock is the result of fracture porosity or permeability, which is highly influenced by depth.

Naturally, due to the overlying pressure effect joints and fractures become narrower and less numerous at depth. The design in such type of rocks need close attention about the determination of the optimum well depth in relation to the occurrence and distribution of fractured zones. Unless reliable geological information about the structures is available, the optimum depth is determined by economic factor. However, in this guideline, a shallow well up to 100mts depth has been considered in the design of wells for exploitation of shallow groundwater for conjunctive use with surface water as water sources of SSIP.

3.2.2 Hydrogeological conditions

The groundwater investigation study should include the important factors that influence the preliminary design aspects. The study should be able to indicate at least the following:

- The expected aquifer thickness, type and depth
- The slope of the ground surface
- The soil cover and expected subsurface geological formations
- Expected slope of groundwater table (groundwater flow direction)
- The recharge zone and the current and long term water balance
- The water quality and if it is possible to speculate the nature of the groundwater whether it is aggressive or mineralized etc.
- Possible source of pollution, distance and direction and how to protect the well or the well field from liquid and solid wastes and pointing out protection measures

The well design for homogeneous and non-homogeneous confined and unconfined aquifers generally proposed to be as follows:

3.2.2.1 Homogenous and non-homogenous unconfined aquifers

For homogenous unconfined aquifer covering one-half to one-third part of the aquifer with screen would enable to obtain very good result. On the other hand, it is advisable to cover one-third of the aquifer with screen for non-homogenous unconfined aquifers.
In unconfined aquifers the well screen is positioned in the lower portion of the aquifer because the upper part is usually dewatered during pumping.

3.2.2.2 Homogenous and non-homogenous confined aquifers

For homogenous confined aquifers 80 - 90 % of the water bearing formation has to be covered with the screen casing. Precaution has to be made that when the well is pumped, the drawdown should not go down below the top part of the aquifer. For non-homogenous confined aquifers also 80 - 90 % of the bottom section of the permeable formation can be covered with screen.

3.2.3 Purpose of well design

- To achieve the highest yield with minimum drawdown this is consistent with the aquifer potential.
- To obtain good quality water which is free from sand and contaminants and hence to avoid undesired physical or chemical characteristics that would contaminate the groundwater.
- Ensuring long service life of the well with the objective of attaining optimum yield and durability by taking into account the initial and the running costs.
- Minimizing operation and maintenance cost.
- To enable to utilize fully every natural sanitary protection offered by the geologic and groundwater conditions.
- To enhance the compatibility of the source with demand.

3.2.4 Stage of well design

3.2.4.1 Preliminary well design

One has to consider the following:

- The intended purpose of the well (for irrigation).
- The overall design period, design command area.
- Possible sources of pollution.
- Limitations of the investigation and
- Technical specifications (the geological formations, drilling diameter, depth, position of temporary casing, casing and screen type and quantity, gravel size and amount, dimensions, strength requirements, etc.) and bill of quantities and cost considerations need proper attention.

3.2.4.2 Final design

- Nature of the unsaturated zone
- The aquifer type and its hydraulic properties
- Depth and diameter of the well
- Diameter of the casing, its strength, quality, total length and the height above the ground level
- Screen diameter, strength, percentage open area, quality and position in the well
- The method and conditions of applying cement, sand, etc for pollution protection.
- Type and size of gravel pack,
- Pumping test and groundwater sampling results, etc.

Final design should include:

- The geological and electrical logging
- The installation position of casings, screens, grouting
- Installation of observation pipe
- Appropriate pumping rate
- Description about the water quality,
- The installation of pumps and motors etc.

3.2.5 Types of well design

3.2.5.1 Single well design (test well, production well or observation well)

It is apparent that proper well design can easily be achieved by paying modest attention to the following points:

- Detail investigation of the site
- Applying appropriate drilling technique as DTH or mud rotary depending on the nature of the geological formation in subsurface
- Utilizing quality materials as casing, screen, gravel, etc
- Proper collection and respective analysis of the obtained data and information.

3.2.5.2 Well field design

Well spacing

The less is the mutual interference the farther apart the wells are spaced. The spacing of wells has no as such predetermined distance. The governing factor is the actual field condition, i.e., the geological and hydrogeological conditions, the property (land) boundaries, etc. In any case the well spacing has to avoid or minimize possible interference.

When two wells are located close to each other, then their draw down curve will intersect and the discharge of one well will interfere with the discharge of the other. This is known as wells interference. Due to interference, the discharge of each well will be decreased. For this reason, wells should be located at a distance as much as possible away from each other depending on the groundwater condition of the area. The number of wells recommended for a given catchment can be determined by different reasons. Among them, the main ones are the following:

- The reserve of groundwater within the catchment
- Pumping rate
- Level of groundwater table
- Type of aquifer

On the other hand when the discharge of groundwater exceeds the recharge of the system, several adverse effects can occur. Most common is lowering of the water table, resulting in increasing the depth of drilling.

Well spacing rules are designed to reduce the interference between wells when pumped. Possible limits of radius of influence in unconfined aquifer/unconsolidated deposits is indicated to be 30 to 600mts depending on the soil formation and texture (Hune Nega (ed). 2012).

3.2.6 Well design options for test / production wells

In this guideline three well design options for test / production wells have been considered taking the expected yield of shallow aquifers. Here the expected discharge from one well is categorized into three. Discharge rate up to 10 l/s, 30l/s and 50l/s are considered for well design in each category.

In all the three well design options, water level observation pipe should be installed in the annular space between the well and the casing in a rectilinear way to allow the free passing of probes. The observation pipe should preferably be 3/4 " diameter galvanized steel pipe. The slotted section could be cut by a hack saw. Drilled or torch-cut slots are not permitted. The pipe should be closed at the bottom and the depth and slot arrangement will be provided by the Supervisor. Non-compliance with this requirement entitles the Client not to accept the well.

Preliminary well design for each category and the corresponding drilling and casing diameters are given below.

For test/ production wells with expected discharge of up to 10l/s, 17 ½ and 10 inches bit diameter shall be used to a total depth of about 100m. The final depth of a well may increase or decrease by 20% depending on the local conditions (Temporary design of the wells to be drilled is given in figure3-1).The upper soft, friable or loose sediment section shall be drilled with 17 ½ inch to a depth of about 12m or determined by the supervising hydrogeologist and 10 inch diameter bit shall be used to drill below the upper soft, friable and loose section to 100 m depth. The depths specified in this section could be changed by the Supervisor depending on the local geological and hydrogeological conditions. The upper soft, friable or loose formation drilled with 17 ½ inches diameter bit will be cased with 14 inches steel surface casing and grouted as instructed by the Supervisor. The well shall be cased with 6 inches diameter steel or PVC casing and screens. The Supervisor shall decide and give instructions on the diameter of bits to be used for drilling, on the sections of the wells to be cased and on the diameters of the casings and screens to be installed.

For the design of tube wells for household irrigation, the user is advised to refer Hune Nega (ed). 2012.

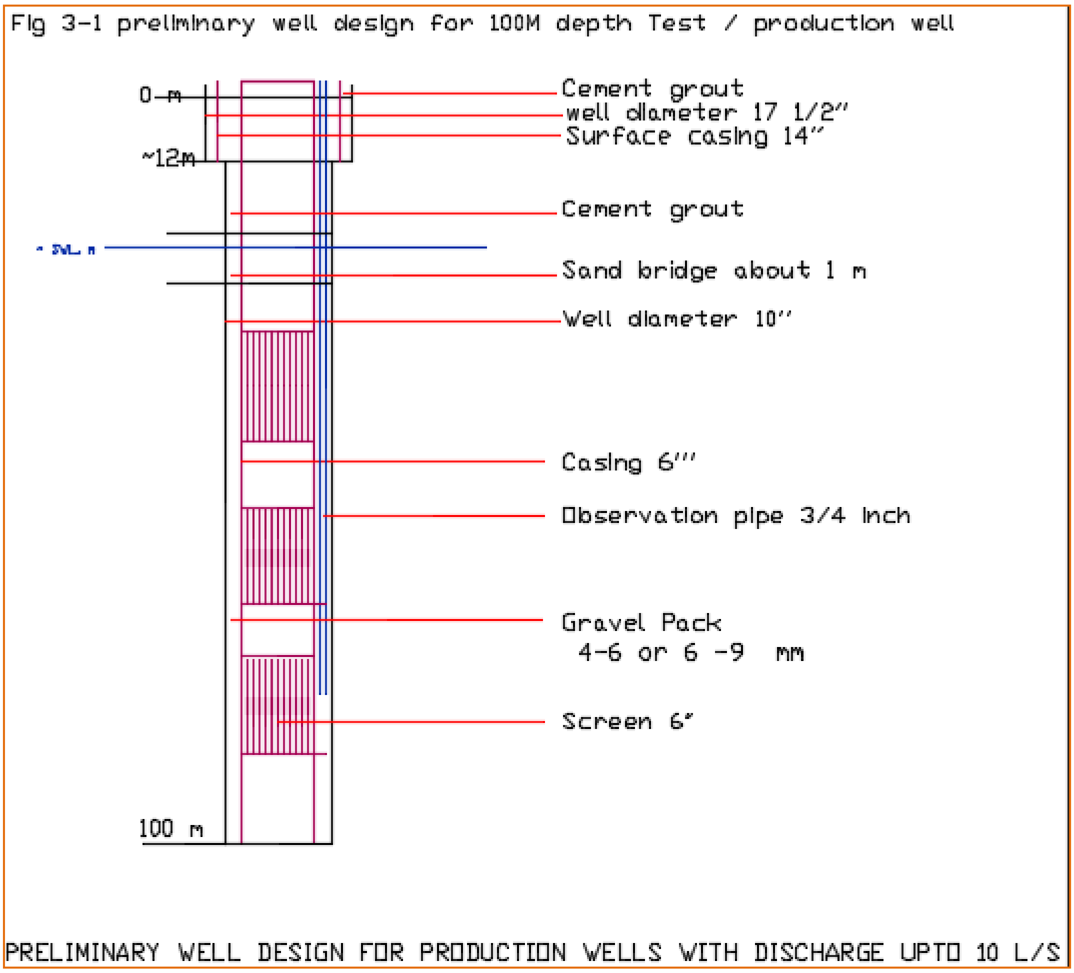


Figure 3-1: Preliminary well design for test/production wells with discharge up to 10 L/S

For test / production wells with expected discharge of up to 30 l/s, 17 ½ and 12 inches bit diameter shall be used to a total depth of about 100m. The final depth of a well may increase or decrease by 20% depending on the local conditions (Temporary design of the wells to be drilled is given in figure3-2).The upper soft, friable or loose sediment section shall be drilled with 17 ½ inch to a depth of about 12m or determined by the supervising hydrogeologist and 12 inch diameter bit shall be used to drill below the upper soft, friable and loose section to 100 m depth. The depths specified in this section could be changed by the Supervisor depending on the local geological and hydrogeological conditions. The upper soft, friable or loose formation drilled with 17 ½ inches diameter bit will be cased with 14 inches steel surface casing and grouted as instructed by the Supervisor. The well shall be cased with 8 inches diameter steel or PVC casing and screens. The Supervisor shall decide and give instructions on the diameter of bits to be used for drilling, on the sections of the wells to be cased and on the diameters of the casings and screens to be installed.

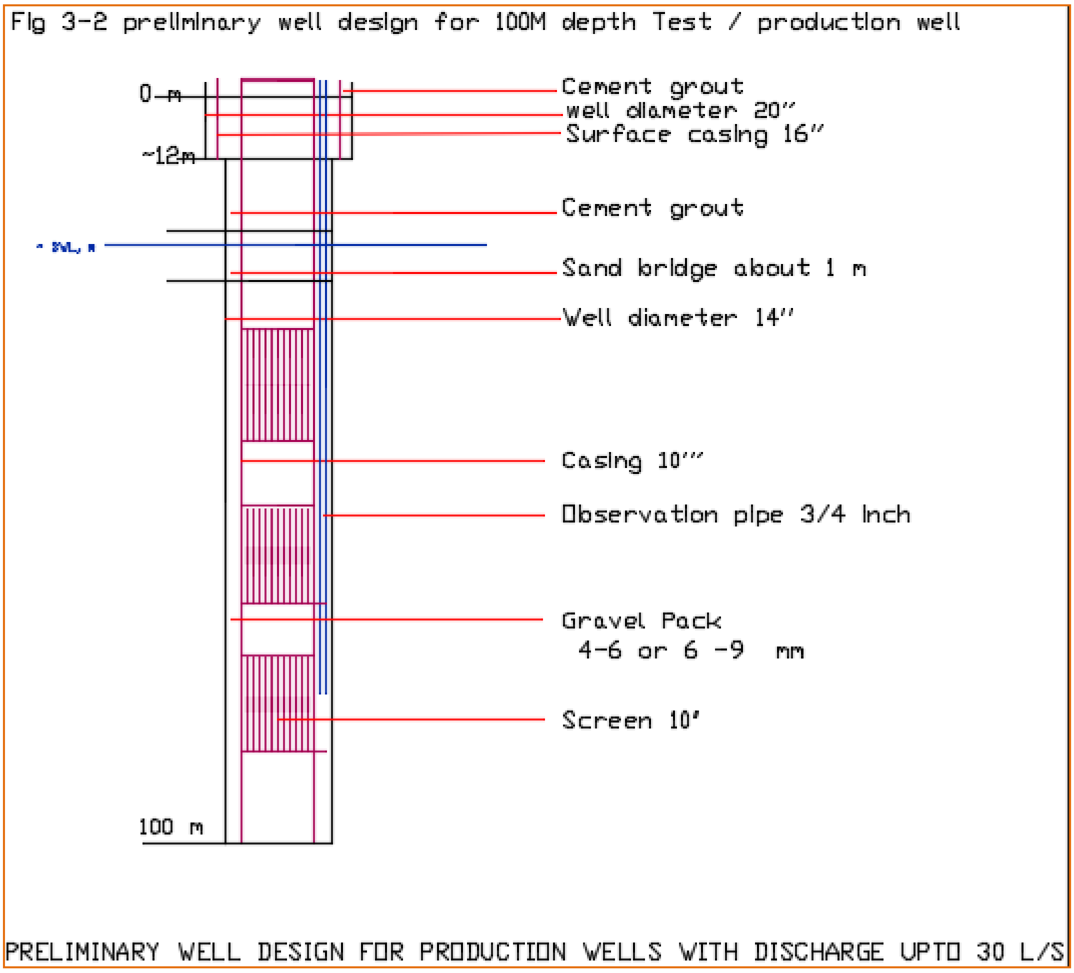


Figure 3-2: Preliminary well design for test/production wells with discharge up to 30 L/S

For test / production wells with expected discharge of up to 50 l/s, 20 and 14 inches bit diameter shall be used to a total depth of about 100m. The final depth of a well may increase or decrease by 20% depending on the local conditions (Temporary design of the wells to be drilled is as shown in figure3-3). The upper soft, friable or loose sediment section shall be drilled with 20 inch to a depth of about 12m or determined by the supervising hydrogeologist and 14 inch diameter bit shall be used to drill below the upper soft, friable and loose section to 100 m depth. The depths specified in this section could be changed by the supervisor depending on the local geological and hydrogeological conditions. The upper soft, friable or loose formation drilled with 20 inches diameter bit will be cased with 16 inches steel surface casing and grouted as instructed by the supervisor. The well shall be cased with 10 inches diameter steel or PVC casing and screens. The Supervisor shall decide and give instructions on the diameter of bits to be used for drilling, on the sections of the wells to be cased and on the diameters of the casings and screens to be installed.

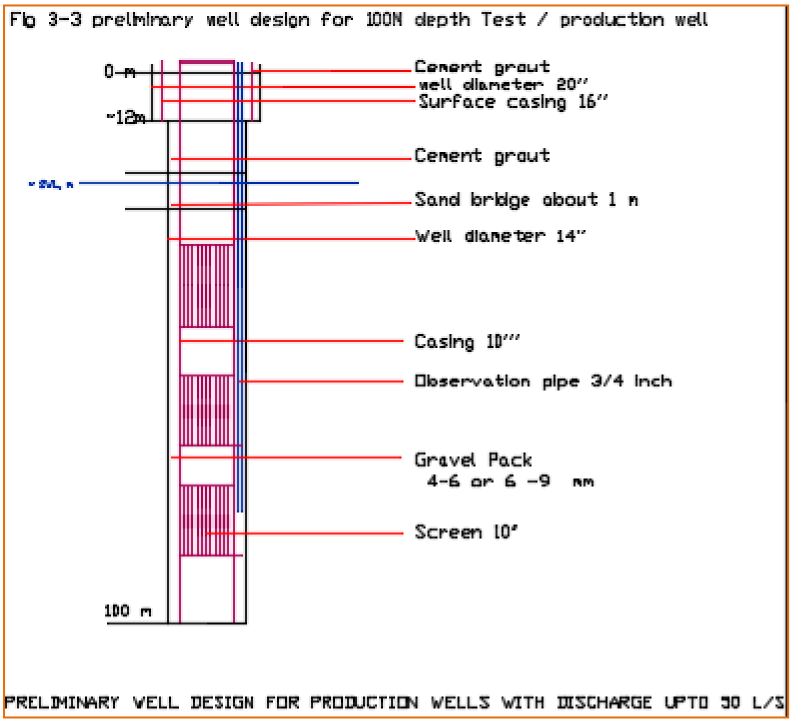


Figure 3-3: Preliminary well design for test/production wells with discharge up to 50 L/S

3.2.7 Drilling unit

The drilling unit shall consist of rigs adequate and equipped with all necessary tools, pumps, air compressors, service vehicles, welding units, etc. to drill to over 100 m depth plus 20% more depth with the specified bit diameters and lower or pull back the specified casings in the drilled wells. Each drilling unit shall be fully equipped to successfully construct, develop and test the wells as specified.

For details of the drilling units required in manual drilling techniques, the user is advised to refer Practica Foundation, Technical Training Handbooks on Affordable Manual Well Drilling.

3.2.7.1 Drilling depth

The initial depth is proposed based on the investigation study and would be indicated in the preliminary design. The maximum depth for the manual drilled wells and that of machine drilled wells in this guide for small-scale irrigation are taken respectively as 40m and 100m. However, the final depth is decided based on the actual field findings of the geological and hydrogeological conditions. The two most important points to be considered in defining well depth are:

- Partial penetration, and
- Unnecessary drilling depth

In any case it is advisable to penetrate fully the water bearing formation for the following reasons:

- To obtain adequate amounts of water by penetrating the whole aquifer thickness that may result in higher yield, for fewer drawdown and larger available drawdown.
- To be able to accommodate the possible high drawdown rate which may occur either as a result of over pumping or less recharge due to extended drought.

As opposed to the above noted advantages of full penetration of the aquifer, at times there are situations when partial penetration is favored. This situation may be considered:

- When the aquifer is very thick to minimize the construction cost,
- If the intended water demand is low as compared to the aquifer potential
- To avoid poor quality of water this may form part of the aquifer.

3.2.7.2 Drilling diameter

The diameter of a given borehole is dependent upon:

- The intended purpose of the well (here for irrigation),
- The expected subsurface formation,
- The diameter of the casing and the pump that are planned to be installed permanently. The casing size should be 1 nominal size larger than the diameter of the submersible pump.
- The well diameter must take into account the annular space to accommodate the grouting and the size of filter packing.

3.2.7.3 Well logging

The frequency of sampling and the subsequent sample handling and the respective logging techniques have to be indicated. The logging results have to be arranged in a manner that they can clearly indicate the water bearing formation and facilitate the casing and screen installation.

3.2.7.4 Casing installation

Designing a well that can give longer period of service depends upon the quality of workman ship and the applied materials. Casings may serve the following purposes:

- To protect the borehole wall from caving,
- To protect surface water from entering into the well and to seal out undesired groundwater,
- To protect the pump from damage.

In relation with this, the choice and installation of casing should take into account the following:

- Its collapse strength or the ability to shoulder vertical load,
- Its ability to resist lateral pressure from the borehole wall (formation pressure) and the gravel pack (gravel pressure) and other pressure variations,
- Its capacity to resist corrosion which may occur due to the nature of the water and the sub surface formation.
- The quality and standard of casing materials have to be assured or be accepted or should fulfill the standards set by internationally recognized institutions like API (American Petroleum Institute), ASTM (American Society for Testing Materials) etc.

The quality of the casing material expressed by:

- Its wall thickness,
- The pressure application.

There are different types of casings that are available in the market. Among the different types of casings mild steel, stainless steel and Poly Venile Chloride (PVC) casings are commonly used for water well drilling. Non metallic materials should be used where corrosion or encrustation by irons bacteria is a problem.

The following points have to be considered during the appropriate type of casing selection:

- The type of the subsurface formation (if the geological condition proved to be favorable, and the well is drilled in consolidated stable formation, boreholes can be left open),
- Depth and diameter of the well,
- Quality of the water and,
- Cost of the material.

When selecting the diameter of the casing the following points have to be taken into account:

- It should be able to accommodate the pump and the attached electric cables,
- The diameter has to be large enough to entertain the up-hole velocity of the water, which should be 1.5 meter per second or less.

If the up hole velocity is greater, excessive head loss will occur.

The user is advised to refer Hune Nega (ed). 2012, for casing types and installation of casings and screens in tube wells and hand dug wells for household level irrigation.

3.2.7.5 Screen design

Screens provide the same service as casings in supporting the formation. Besides they act as a filtering media in preventing sediments from entering into the well.

Important factors for the selections of the screen are:

- Diameter and depth of the well
- Material strength
- Water quality and,
- Cost.

A. Types of screens

There are different types of screens. Continues slots, v-shaped slots and continuous wire slot type etc. are the common ones. V-shaped slots that are narrowest at the outer face have the capacity to reduce clogging.

Slots, which are prepared by using, hacksaw, welding or oxyacetylene, may have the following possible problems and disadvantages:

- Slots cannot be closely spaced so the percentage open area is usually smaller
- Slot sizes vary significantly and may be non-aligned
- Cannot be cut small enough to prevent the entry of fine particles,
- Decrease the initial strength of the material,
- More susceptible for clogging, corrosion and incrustation

B. Factors in screen design

I. Length of the screen

The length of a screen in a given well determined by the aquifer thickness and the nature of stratification, its position and the available draw down during pumping. Since there is difference in the hydraulic conductivity and porosity of aquifers, it is advisable to distinguish these zones properly and to set the screen at the highly permeable and porous zones of the subsurface formation. This can be achieved by closely examining the drillers log, formation sampling and logging and by performing borehole geophysics.

Deciding the length of the screen requires the consideration of the specific capacity, available drawdown, cost and expected efficiency of the well. Figure3-4 shows screen positions in the well.

II. Diameter of screen

The diameter of screen is determined according to the required open area percentage. There have to be enough screen openings that allow the water to flow into the well smoothly. In order to reduce turbulence flow that results in excessive draw down and incrustation, the screen diameter should be sufficient enough that adequate open area is available. Thus, the entrance velocity (which is the ratio of expected yield and the total open area) of the water should not be greater than 0.03 m/sec. The reason for this limitation of the entrance velocity is to minimize friction losses and to avoid the formation (creation) of corrosion and incrustation. As the length of the screen determined by the thickness of the aquifer, by the same analogy the type of formation and the type of gravel pack determine the width of the slot of each individual screen.

III. Percentage of open area

The percentage open area of a screen is designed in a manner that it allows minimizing well loss as much as possible. It is a common practice to design an open area between 10 to 15 %. However it is possible to increase the open area by taking into account the diameter of the screen, its quality and the intended purpose of the well.

The required size of screen openings will depend on the grain size distribution of the aquifer, the degree of well development and on the presence of the filter pack. Limited open area hinders well development and then facilitates higher drawdown and finally may result in higher pumping costs.

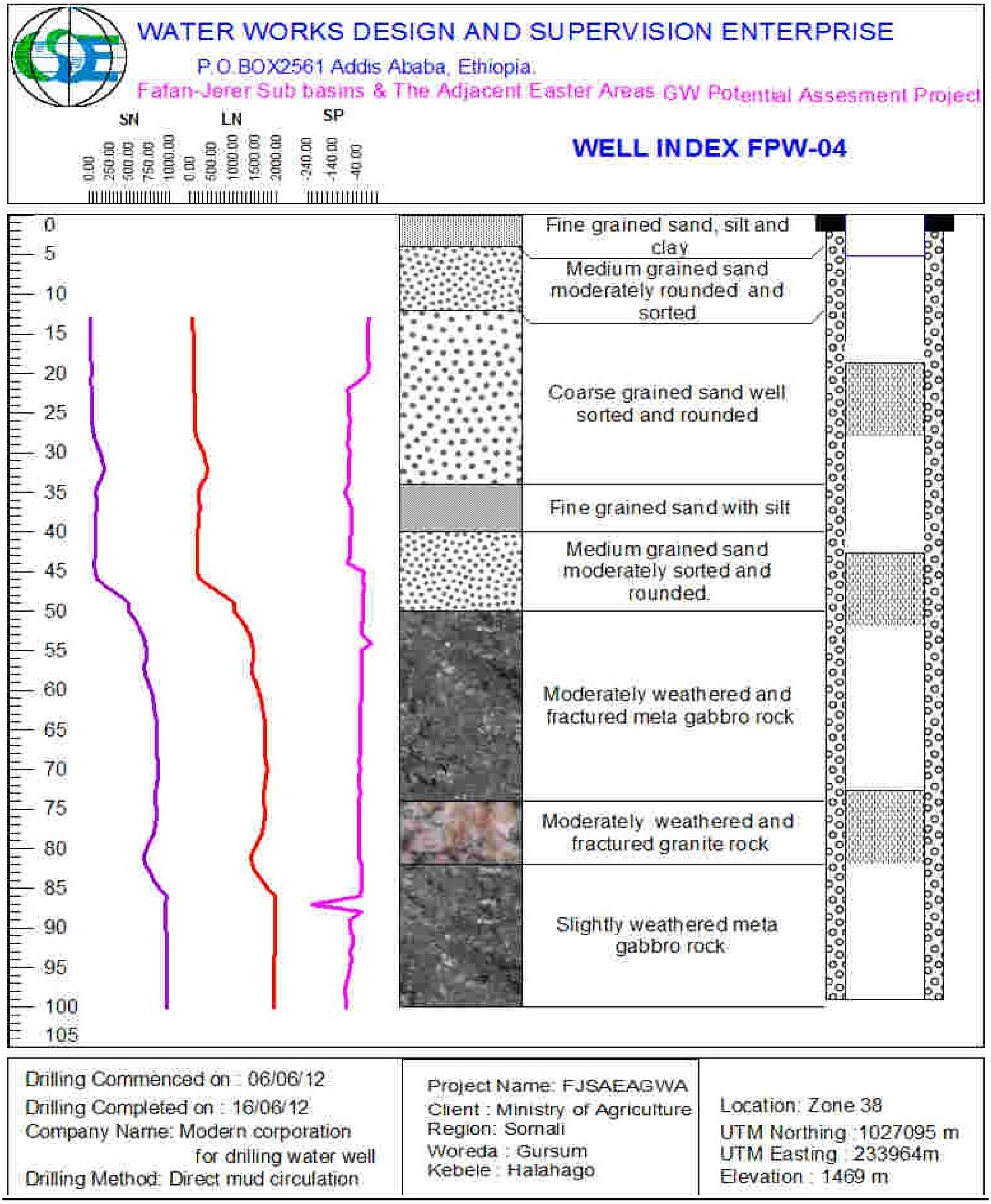


Figure 3-4: Screen positions in the well

3.2.7.6 Gravel pack

It is applied to maintain good quality of groundwater by replacing some of the formations immediately around the screen with a clean rounded and more permeable specially graded material. Moreover, to support the borehole wall it is a custom to put selected gravel between the annular space of the borehole wall and the screen.

However, it may not be necessary to apply artificial gravel packing in every well. Typical geological formations that favor artificial gravel packing are formations that contain unconsolidated finer materials, semi consolidated and friable formations, and loosely cemented and extensively laminated formations. Thus, the nature of the subsurface formation and the design of the screen are the governing factors during applying gravel packing. The gravel is usually packed about three meters above the top part of the screen. The annular space above the gravel pack is mostly filled with sand cement and selected back fill.

To avoid bridging which is a common problem during gravel packing, appropriate procedures should be followed while pouring the gravel. Applying different size of gravel may create a problem like clogging of the screen. Hence, the gravel pack should contain rounded and of uniform grain size and the particles should be more stable. Reasons for gravel packing can be summarized:

- To protect sand or other fine particles from passing into the screen
- To strengthen the borehole construction by supporting the wall of the borehole
- To increase the yield of the well by removing the formation material and replacing it with special type of graded coarse material.

3.2.7.7 Well development

A. General

The purpose of well development is to remove the mud cake and then to obtain smooth groundwater flow from the formation into the well. Another objective of well development is to change the physical characteristics of the aquifer by removing the drilling mud and thereby enable the groundwater to flow as freely as possible into the well. There are different types of well development methods where the appropriate type should be selected based on the specific field condition. The most common development techniques are: mechanical surging, back washing, jetting, etc

B. Well Development Methods

There are different well development methods that can be applied to clean and develop the well. The development methods are mainly governed by the geological condition of the aquifer and the type of drilling rig employed for the drilling. In any case the following points affect well development.

- Type of formation
- Type of drilling fluid
- The thickness of the gravel pack
- The type of screen, its percentage open area and the slot configuration

I. Mechanical methods

Surging

It is implemented with the help of surge plunger. By moving up and down the surge plunger or surge block, the water is agitated and enhanced to move in two directions, i.e., into the aquifer and back into the well through the screens and in the mean time remove sand, mud and sumps from the well. While applying this technique, lower the surge block into the well until it is 3 to 5 meter beneath the static water level but always above the screen. Percussion rigs are more appropriate to do this job. But it can also be done with rotary rigs. In both cases maximum care has to be taken in order not to damage the well.

Over pumping

Development by over pumping means pumping the well at a higher rate than it will be pumped when put into service. During this time of over pumping of the well at a higher pumping rate, the ground water moves from the aquifer into the well in order to replace the pumped water. In the meantime, the water would bring finer materials from the aquifer through the gravel pack and the screen, which can be removed from the well by repeating the over pumping.

The method is more appropriate to wells that produce small amount of water since it is easier to remove most of the water by over pumping. For wells that produce higher amount of water, high capacity pump is required to apply this technique. The disadvantage of this method is since water flows only in one direction, i.e., from the screen into the well, sand bridging may take place and partially stabilized formation created.

Jetting

High velocity jetting water is applied by using small diameter jetting nozzles, horizontally through the screens and removes sand, mud and similar materials. It should be performed from bottom to upward direction and lifting up the jetting device step by step and rotating it either 90° or 180° in each position depending upon whether 4 or 2 nozzles are used.

Back washing

It is a development technique applied by filling the well with water and forcing it to flow back out of the well through the screen by any appropriate method (pumping, compressor, etc).

The method helps to clean the finer materials by changing the flow direction of the groundwater flowing through the screen. This reversal of flow through the screen openings will agitate the sediments remove the finer fractions and then rearrange the formation particles. This reversing of flow is almost similar to a two way flow created in surging technique and helps in breaking down bridging of particles. The technique may not produce the intended result unless provision is made for using sufficient water and also is not effective unless combined with pumping, surging, bailing, etc.

Air-Lift method

It is a technique where the water is extracted (lifted) from the well by means of compressed air. The strong air pressure goes into the screen and the surrounding strata causing the rapid break down of the mud-cake that may be formed at the borehole wall.

II. Chemical methods

Acid Treatment

Either galvanized screen or pipes and fittings should not be used with acid treatment since the acid may quickly react and dissolve the zinc or the magnesium and generating gaseous hydrogen. It is highly effective method for developing wells drilled into carbonate rocks. It removes finer materials that have clogged the pores of rocks during drilling and development.

Commonly used chemicals are:

- Hydrochloric acid and sulfuric acid.
- Polyphosphates

It is a dispersing agent used for breaking down the mud. Adding some amount of this chemical before or during development helps in removing clays that occur naturally in the aquifer and those clays introduced into the borehole as part of the drilling fluid. It should be added to the water in a quantity of 6 kg Polyphosphate for every 1 m^3 of water.

Hypochlorite, Chlorine and AquaClear

These three chemicals are also used in chemical development of wells.

- Well development for manual drill wells can be done by pouring buckets of water into the hole and removing all the mud and cuttings from the bottom of the borehole with the bailer. This time, moving the bailer SLOWLY up and down. DO NOT drill any deeper and keep on adding clean water in the borehole during bailing. Doing this until the borehole is clean enables to develop the manually drilled well.

3.2.7.8 Aquifer development

In hard rocks where the available fractures are few and disconnected the amount of water is definitely small. However, there is a possibility to improve the yield of such type of aquifers by applying aquifer development techniques. Aquifer development when compared with well development it requires experience, close observation and the right tools to perform the task.

I. Blasting

By using explosives aquifers can be blasted to increase the yield. The result depends upon the appropriateness of the procedure followed for the specific rock type, the diameter and depth of the well. The following points do need consideration before deciding to apply this method:

- The geological condition (joints, fractures, faults) must be present,
- Depth of the well and depth of the water level should be clearly known
- Environmental and legal considerations.

II. Hydrofracturing

It is a method where high-pressured fluid is injected into the opened fracture in order to overcome the pressure of the overlying rock and thereby to increase the yields of production wells. With this method there is a possibility of increasing the yield of wells by improving poorly developed or tight fractures.

3.2.7.9 Grouting / sanitary sill

In order to protect the surface pollution, grouting the annular space between the borehole wall and the top part of the casing that is located above the screen is a common practice. For grouting the main components are cement and water. The ratio between these two components usually is for 100 kg, 45 to 55 liter of water can be used. Different mechanisms can be applied for pouring the cement grout into the desired place. To protect the cement from moving down to the screen position, before grouting pure sand that has the size of 0.3 - 0.6 mm has to be placed on the gravel pack.

The following points need proper care since they can represent problem during grouting:

- Premature setting of the cement
- Partial setting
- Cracks in the cement

Premature setting is a frequent problem in grouting. Hence, it is advisable to know the possible causes that enhance the problem.

- Mixing the cement with hot water
- Not keeping the appropriate ratio between the cement and the water
- Applying polluted water for mixing and,
- Facing mechanical problem while pouring the cement.

3.2.7.10 Well head construction

The well head has to be designed in a manner that it can be used as part of the pump house in most cases. During well head construction the casing has to be protruded above the ground surface say between 30 to 80 cm depending on the local hydrogeological condition in order to avoid surface water from entering into the aquifer.

Direct contact between the outer part of the casing and the concrete should be avoided. Leaving space between them is required in order to avoid the damage of casing by the concrete due to thermal expansion.

Sealing the well head
In order to protect external materials from falling into the well the top of the well has to be secured either by welding or by using nut and bolt until the permanent pump is installed.

3.3 HYDROGEOLOGICAL MAPPING AND HYDROGEOLOGICAL REPORT

3.3.1 Hydrogeological mapping

Hydrogeological maps are maps upon which the extent of aguifers are depicted, together with such geological, hydrogeological, meteorological and surface water features that may be necessary for an understanding of the groundwater regime. Such maps may be international, national, regional or local, and may vary from small (1: 1,000000, or smaller) to large (1:250000, or greater) in scale.

Hydrogeological maps are of importance to hydrogeologists and groundwater specialists. They are of use also to non specialists such as administrators and economists, engineers in the fields of town and country planning, technicians in agriculture and horticulture, as well as to farmers, school teachers and private individuals. However, the purpose of preparing this Hydrogeological Mapping guide line is to outline a uniform pattern on the generation, handling, analysis and presentation of results of groundwater studies (UNESCO, 1983).

It is aimed that the guideline would enable users to produce uniform hydrogeological maps. Experts who use the result of Hydrogeological findings as an input for their further contribution and policy makers and different part of the community will have the ease in understanding.

There is no universal classification of hydrogeological maps and principles of hydrogeological mapping. However, it is generally agreed that a hydrogeological map should show the following hydrogeological elements:

- Location of natural discharge zones (springs, swamps, etc) and artificial discharge zones (bore holes, dug wells, etc).
- Type of groundwater (confined or unconfined)
- Water levels of specified time
- Groundwater flow directions
- Groundwater recharge and discharge zones
- Water quality characteristics
- Aquifer parameters
- Interconnection with surface water, etc.

It should be noted:

a) Most of groundwater parameters (water level, discharge, salinity, temperature, etc.) vary with time. Therefore, on the map, contours should be presented by indicating the month-year the data was observed at field.
b) It is difficult to show all hydrogeological elements on a single map. However, it is recommended that a series of hydrogeological maps of the same scale should be prepared.
c) Hydrogeological maps are prepared based on previous available base maps, previous studies, Hydrogeological survey data, Hydrogeological investigations (borehole drilling, pumping tests, etc), geophysical investigation interpretations, laboratory analysis results, and hydrological studies and monitoring, etc.

3.3.1.1 Planning of maps preparation

All procedures of national and international guide lines shall be followed for the planning of Hydrogeological map preparation. However, it is advised that an investigator should give more emphasis on the following points:

- Identify the gap between the required and available data sets taking the coverage and quality into consideration.
- It is recommended to weigh the total coverage of the study area and select the appropriate map scale.
- Data that is generated in the field should be compiled and saved in an appropriate and uniform format which can easily be used by subsequent software packages.
- Available existing maps should be digitized geo-referenced and finally saved in GIS shape file format for further reference and application.
- All map elements should have a uniform geographic coordinate system in UTM Adindan-Datum of zones 36/ 37/ 38 for all places in Ethiopia.

3.3.1.2 Defining the purpose

The purpose of the hydrogeological map here is to identify the source of groundwater in an area for irrigated agriculture. It is aimed at delineating various parts of a project area to be distinguished according to their hydrological character in relation to the geology. Hydrogeological maps should indicate, on a topographic base, such items as the extent of the principal groundwater bodies, the scarcity of groundwater elsewhere, the known or possible occurrence of artesian basins, areas of saline groundwater and the usability of groundwater. They should also show, according to scale, information of a local character, such as the location of boreholes, wells and other works, contours of the potentiometric surface, the direction of groundwater flow, and variations in water quality.

In general, any information leading to a better understanding of occurrence, movement, quantity and quality of groundwater, should be shown on hydrogeological maps, depending upon the scale adopted. The data normally presented relate to such matters as precipitation, evaporation, surface hydrology, geometric data on water-bearing formations, hydrochemistry and availability of water. In addition, sufficient geology should be shown to lead to a proper understanding of the hydrogeological conditions. However, the geology should remain subdued and the hydrogeological features should be prominent.

3.3.1.3 Experts and software for mapping purpose (source WWDSE, 2012)

A. Experts

Hydrogeological mapping needs highly qualified experts equipped with latest knowledge in order to prepare a hydrogeological map in a better way. At the planning stage of the hydrogeological mapping work, the required staff should be identified and ready for executing the mapping work. The staff required for the hydrogeological investigation includes a group of experts that include geologists, hydrogeologists, hydrologists, geophysicists, Database specialist and cartographers (GIS experts).

Geologist

- The role of the geologist will be preparation of medium and large scale geological map of the intended mapping area in similar scale with the future hydrogeological map.
- This should be done only when geologic map in the desired scale could not be found from the Ethiopian Institute of Geological Survey in the desired file format which will be used as working material for the project.
- The geologist should produce geological map with similar scale to the TOR provided by clients or technical proposal.

Hydrologist

- The role of the hydrologist will be to study the surface hydrological condition of the intended study area, estimate the groundwater recharge and discharge zone and produce hydrological map of the same scale with the intended hydrogeological map.
- The procedures, techniques and method of the hydrological study with the scale of the output map (hydrological map) however will be provided in the TOR of the clients.
- The hydrology map should be in ARCMAP supported Arc GIS digital file format for further use and application.

Hydrogeologist

- The hydrogeologist will coordinate all the works of preparation of hydrogeological map by combining the out puts of the geologist and hydrologist.
- The hydrogeologist should characterize the groundwater potential of the different aquifers in the study area using existing and new generated groundwater data.
- The hydrogeologist will be responsible for the organization of groundwater data base.
- Conceptual and representative groundwater flow model should be produced by the hydrogeologist where the flow of groundwater through different geological formations is clearly described with appropriate symbols of the rock types and color of the hydraulic property of the aquifer classification.
- The hydrogeologist at the end of the preparation of hydrogeological map, should check the suitability of the symbols and legends used with the standards listed in this guide line.

GIS expert

The GIS expert will involve in producing the Geological, Hydrological and Hydrogeological map in collaboration with the above mentioned experts. The scale of the intended hydrogeological map, the contents of each hydrogeological map sheets where several information is going to be presented is decided by the Terms of Reference. The GIS expert will finally work with the hydrogeologist for the proper placement and presentation of hydrogeological symbols, colors of aquifer classes and texture of rock types as described in this guide line.

Database specialist

The database specialist will organize groundwater database for the proper handling, storage and analysis. The expert should have a practical experience in working with ArcMap database management system.

B. Software (source WWDSE, 2012)

There is no rule for the selection of software packages that will be used for hydrogeological map preparation. However from market availability, user friendly and compatibility for different file format, this guide line the use of the following software is advised for the preparation of hydrogeological map.

Global Mapper

Digital elevation model (DEM) for all places in Ethiopia is available freely with 90 and 30 meters resolution. The base for cross sections of an area should be generated from the DEM and should be saved as distance elevation file format which can be supported by CAD software for further application. For this reason Global Mapper software can be used.

Auto CAD

This software supports the opening and editing of distance elevation file format generated on Global mapper. The software enables export of the generated section drawings in DXF file format which is supported by Arc Map software for further application.

Arc Map

This software should be used for the final processing and presentation of hydrogeological maps and sections. All geological formations, hydraulic property of rock types and different water point types should have similar color and texture with their corresponding groups on the hydrogeological map. All colors and symbols used thereof should be as described and listed in this guide line.

SURFUR

Contour lines that represent different groundwater processes and related phenomena can be prepared with this software. Colors and thickness of lines used should be as described in this guide line.

Aquifer Test

Hydraulic parameter of different aquifers can be estimated using Aquifer Test software. Data input for this software can be done directly or it can be prepared in an excel spreadsheet and pasted on this software for processing.

Aqua Chem

Chemical constituents of water sample resulted from laboratory analysis can be analyzed using this software. Water types of the area, piper diagram and other graphical presentation tools can be done using this tool.

Modflow/Visual Modflow for groundwater modeling

Groundwater flow within the aquifer is simulated in MODFLOW/Visual MODFLOW using a block-centered finite-difference approach. Layers can be simulated as confined, unconfined, or a

combination of both. Flows from external stresses such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds can also be simulated.
To use MODFLOW, the area to be simulated must be divided into cells with a rectilinear grid resulting in layers, rows and columns. Files must then be prepared that contain hydraulic parameters (hydraulic conductivity, transmissivity, specific yield, etc.), boundary conditions (location of impermeable boundaries and constant heads), and stresses (pumping wells, recharge from precipitation, rivers, drains, etc.).

3.3.1.4 Legend for hydrogeological maps (adapted from UNESCO, 1983 and Struckmeier, W, F. & Margat, J., 1995)

It is clear that a single standard legend cannot serve all types of hydrogeological maps and map users. However, a legend proposing certain recommended standards for representations is considered useful, since it contains both a catalogue of signs, symbols, ornaments and colors as well as their meanings and significance. The legend presented here, therefore, should be considered as a tool box, rather than an exhaustive and complete list of colors and symbols binding hydrogeological map authors. It is not recommended to use all elements of this legend on a single map. Nevertheless, the legend herein is meant to show a reasonably complete catalogue of graphic elements, but flexible and intended to be used in hydrogelogical maps to depict groundwater flow system.The legends herein can help identify any of the layers depicted by the mapping process. This can be a rock/aquifer name, river, road, towns etc.

The background information of the hydrogeological map should lead to easy interpretation of the map and should be represented in the most up-to- date form. On thematic hydrogeological maps, a precise drainage network must be shown and should be supplemented by important surface hydrology features as names of rivers, lakes and reservoirs. This information should be printed in blue. Topographic information on roads, railroads, towns and settlements, and all geographical names are shown in dark grey or black. Altitude contours should be shown in grey tone.

The general principle followed is to represent aquifres, their hydrogeological characteristics and the contained groundwater in much more detail than strata containing little or no groundwater. Therefore the scheme oulined on figure3-5 offers many more colors in the upper part. The spectrum from blue to green may be expanded, where appropriate, e.g. to unambiguously outline karst aquifers, aquifers having a typically mixed regime such as several sandstone and volcanic sequences or productive alteration zones in basement areas.Aquifersin which flow is mainly intergranular (mostly unconsolidated material) are colored blue; fissred aquifers, including karst aquifers, are colored green. In each case a dark tone of the color indicates large and extensive groundwater resources and a high productivity of the aquifer, while a lighter tone indicates local and smaller resources and a lower productivity. Formations containing only limited or local groundwater resources are colored light brown, while strata with essentially no groundwater are colored dark brown. The colors, therefore, combine information on the occurrence of groundwater with information on groundwater flow. This information is essential for the recognition of the hydrogeologic units occurring in the mapped area.

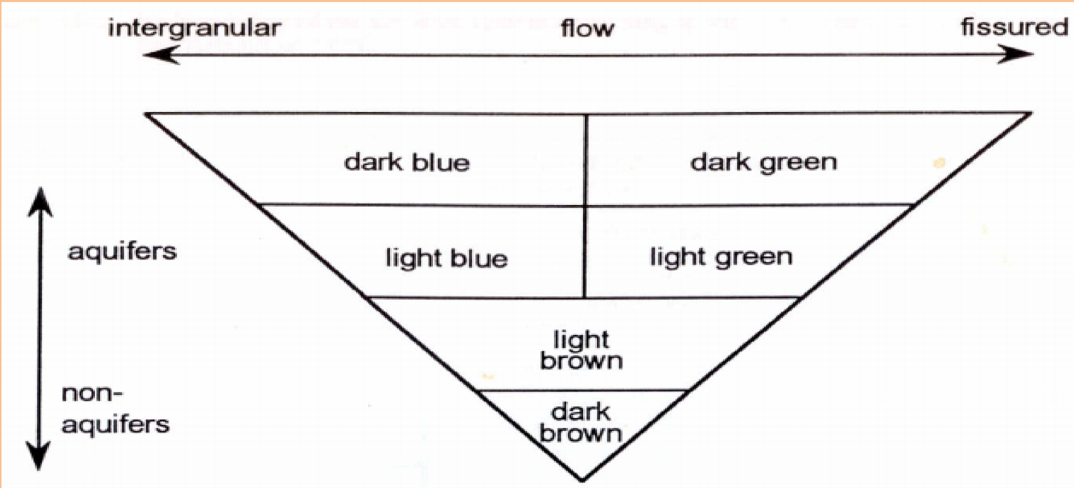


Figure 3-5: Scheme of areal colors to represent hydrogeological characteristics and occurrence of groundwater (adapted from Struckmeier, W, F. & Margat, J., 1995)

The colors, symbols and hatches that represent geological formations, rock textures, aquifer productivity, and water point types should be acceptable to the international standard as presented hereunder.

Aquifers & non aquifers

All strata that appear in outcrop upon the map, whether it is an aquifer or non-aquifer, it is shown in plain color. The classification can fall within one of the following groups:

- Inter-granular aquifers are colored blue –
- fissured and Karst aquifers are colored green, in each case a dark color indicating an extensive and highly productive aquifer while a lighter tone indicates the other aquifers with lower productivity
- Formations giving only limited or local yields are colored a light tone of brown, while strata with essentially no groundwater resources are colored dark brown

Productivity of boreholes is classified according to the transmissivity, Specific capacity and yield values. The value of the transmissivity, yield and specific capacity is taken according to the local condition. It can be higher or lower than the example given below.

Table 3-1: Productivity values (Source: Ministry of Mines and Energy, July 2006)

Productivity	Transmissivity (m2/d)	Yield (L/S)	Specific capacity
Very high productivity	>500	>25	>1
High Productivity	100-500	5-25	
Moderate Productivity	50-100	2-5	0.1-1
Low Productivity	10-50	0.5-2	0.001-0.1
Very Low Productivity	1-10	0.01-0.5	<0.001
Aquitard	< 1	< 0.01	

For the case of household irrigation in shallow and very shallow aquifers, obtaining transmissivity value is impractical. Instead classification of the aquifer units into productivity classes is made based on their yield characteristics (Table 3-4), based on the intended water use for minor and supplementary irrigation. A dug well with a yield of 1 l/s can irrigate one hectare of land or more, more than the average holding of a farmer in Ethiopia, thus this kind of aquifers could be considered as highly productive (ATA, 2017, Shallow Groundwater Mapping for Household Irrigation in Tana – Beles basin and Tramaber – Maychew area, unpublished report)

Table 3-2: Proposed classification of aquifers based on yield of wells to meet household irrigation water demand

Aquifer Productivity	Yield (l/s)
Very high productivity	>1
High productivity	0.5-1.0
Moderate Productivity	0.005
Low Productivity	0.002
Very Low Productivity	0.001
Aquitard	<0.001

Table 3-3: Colors and codes for aquifer productivity (adapted from UNESCO, 1983 and Struckmeier, W, F. & Margat, J., 1995)

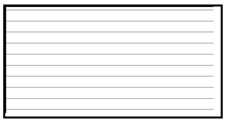
Aquifer	Very high productivity	High productivity	Moderate productivity	Low productivity	Aquitard
Unconsolidated inter granular					
Karst					
Fractured aquifer					
Low permeability minor localized aquifers					
extensive aquifer immediately underlying thin cover					
Color codes in Arc GIS (Red, Green, Blue or abbreviated RGB)					
Aquifer	Very high productivity	High Productivity	Moderate Productivity	Low Productivity	Aquitard
Unconsolidated inter granular	0,112,255	157,191,255	184,209,255	209,220,255	
Karst	0,120,0	0,200,0	112,255,112	96,255,176	
Fractured	86,144,30	115,192,0	170,255,0	205,255,130	
Low permeability minor localized aquifers		255,235,190	255,167,127	255,85,0	168,56,0
extensive aquifer immediately underlying a thin cover	Green- 86,144,30 Brown- 255,85,0				

- Where it is considered to be particularly important to show the continuation of an aquifer beneath a thin but persistent cover of drift, the appropriate aquifer color (blue or green) may be continued over the relevant area, but should be crossed by vertical bands of the appropriate color of brown.
- Certain aquifers combine intergranular and fissure characteristics. In such cases the relevant colors described should be used depending on which characteristic is dominant.

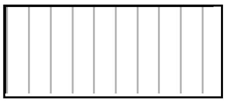
3.3.1.5 Lithology drawing symbols (Ornaments)

Ornament indicating the lithology is printed in grey. The orientation of the ornament indicates the type of bedding:

Horizontal = unfolded horizontal or gently inclined strata



Vertical = folded strata

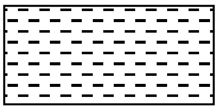


The following list contains ornaments which indicate general lithological types as well as some combinations to symbolize strata of varying lithology.

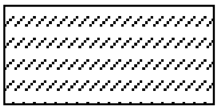
The ornament represents the lithology of the strata which is shown on the map. The exact lithological composition may be explained in detail in the map legend. Where combinations of ornaments are required, examples are shown as follows.

Combination of more than two ornaments is not recommended in the mapping practice.
The legend normally printed in the margin of the map sheet should state the order of maximum thickness of the drift cover.

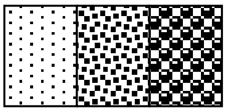
Lithology of sedimentary rock (UNESCO, 1983)



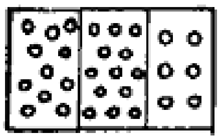
Clay, clayey loam, mud, silt, marl



Clayey loamy alteration products

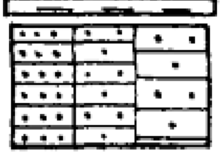


Sands (units can be distinguished by variation in thickness of points)

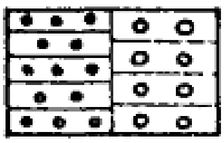


Gravels (distinction by variation of the arrangement of circles)

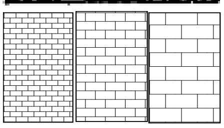
Claystone, Siltstone, shale



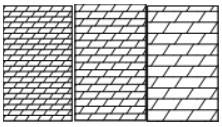
Sandstone (distinction by variation of the arrangement of circles)

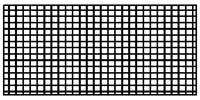


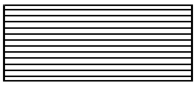
Conglomerate

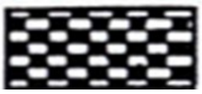


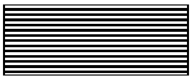
Limestone (distinction by variation of rectangle size)


Dolomite (distinction by variation of rectangle size)


Travertine


Marlstone


Siliceous Shale

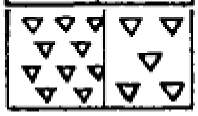

Complex alternation of different lithology

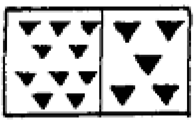

Rock salt

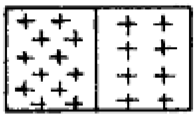

Gypsum

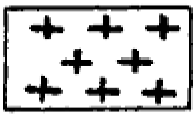
Lithology of Igneous rocks (UNESCO, 1983)


Pyroclastics

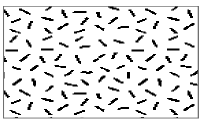

Acid to intermediate extrusives (distinguished by variation of triangle sizes)

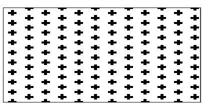

Basic extrusives (distinguished by variation of triangle size)

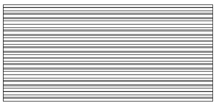

Acid to intermediate intrusives (distinguished by variation of arrangement


Basic intrusive

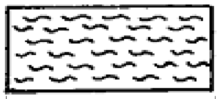
Lithology of Metamorphic rocks (UNESCO, 1983)


Ultrabasic rock

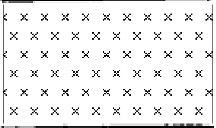

Acid and inter mediate intrusive (Variation by arrangement of crosses)



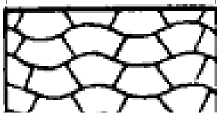
Slate, phyllite, mica schist, etc,



Gneiss

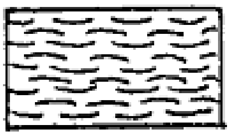


Granite or granite gneiss undifferentiated



Marble

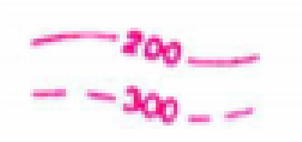
Quartzite



Undifferentiated metamorphic rocks

3.3.1.6 Presentation of detailed data on maps (UNESCO, 1983; Struckmeier, W, F. & Margat, J., 1995)

Height or depth of water level at a given time relative to mean see level Iso-piezometric lines or groundwater contour, broken where uncertain; different line ornament for different aquifers. In sections similar lines may be used (violet color, color code 135,33,255)

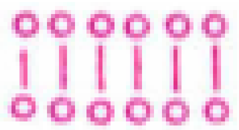


Contours of the potentiometric surface (solid or broken lines with height relative to reference level)

Direction of groundwater flow

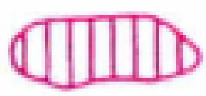
Groundwater Divide

a) stationary



b) Periodically changing

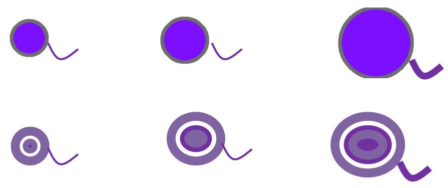
Limit of area with confined groundwater



Limit of area of artesian flow

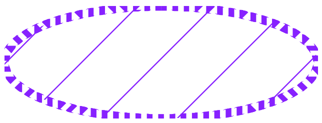
Groundwater barrier within the aquifer

Spring (yield varies with size) a) b) c)



Group of springs

Line of springs

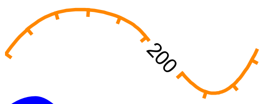


Groundwater seepage area

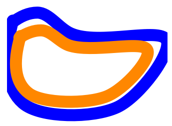
Groundwater quality and temperature (Orange color signs, color code 255,135,0)

(Adapted from Struckmeier, W, F. & Margat, J., 1995)

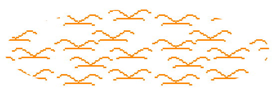
Boundary of saline groundwater



Isolines of equal groundwater salinity



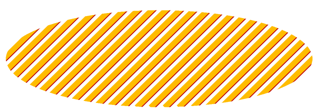
Lagoon or lake with saline or brackish water (blue shore line with orange band inside)



salt marsh

Limit of formations containing minerals susceptible for groundwater quality-deterioration (grey line with orange band)

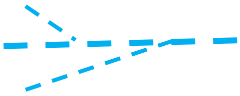
Cold mineral spring
Thermo mineral spring



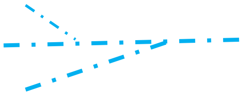
Thermal spring Area of increased geothermal heat

Surface water and karst hydrography (Blue)

Stream with perennial runoff

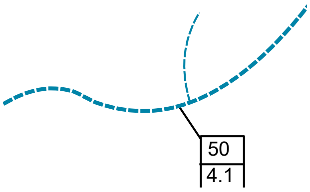


Stream with intermittent runoff



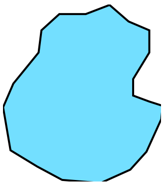
Dry valley, possibly with intermittent runoff (Ephemeral stream)

Stream ending in inland depression

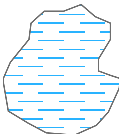


Flow Gauging Station

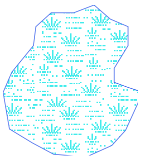
Water fall



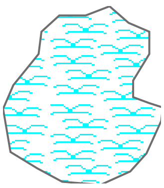
Freshwater Lake



Dry lake with only periodic Water



Marsh

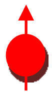


Bog

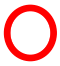
Man Made Features and alterations (Red color)

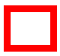

Well, Borehole

Abandoned well


Artesian well

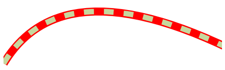

Thermal well


Mineral well


Pumping well


Pumping spring


Groundwater Recharge site


Limit of intensive groundwater usage


Borehole without recorder

Boreholes with recorder

River intake station

Towns, city, village, their name traced in red color

- International boundary (red, 3 points)
- Regional states boundary (red, 21/4 points)

Road (red, 1 point)

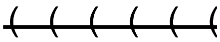
- Asphalt
- All weather
- Dry weather

Geological information (Black)

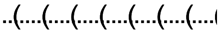
Geological or hydrogeological boundary

Fault Certain

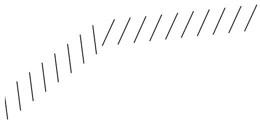
Fault inferred



Over trust fault certain

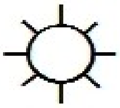


Over trust fault inferred



Fractured belt of hydrogeological importance

Limit of formations containing minerals susceptible for groundwater quality deterioration (grey line with orange band)



Volcanic cone

Volcanic crater

Line of cross-section

Stratigraphy symbols

Simple stratigraphic symbols are printed in black. They help to identify the unit which is represented on the map, whenever it is not characterized clearly by the combination of areal color and screen. With the knowledge of the stratigraphy, the map reader can recognize the geological structures in an easier way.

It is recommended to use the stratigraphic symbols according to the general legend of the Map. Stratigraphic symbols are to be used on hydrogeological maps. The representation of hydrogeological features is in any case predominant.

Moreover, it is obligatory to use stratigraphic symbols related with the age of the formation.
List of stratigraphic symbols (UNESCO, 1983)

q- Quaternary undifferentiated
qh- Holocene
qp- Pleistocene
m- Tertiary undifferentiated
m4- Pliocene
m3- Miocene
m2- Oligocène
m1- Eocene and Paleocene

c- Cretaceous undifferentiated
c2- Upper Cretaceous
c1- Lower Cretaceous
j- Jurassic undifferentiated
j3- Upper Jurassic
j2- Middle Jurassic
j1- Lower Jurassic
t- Triassic undifferentiated
t3- Upper Triassic
t2- Middle Triassic
t1- Lower Triassic
p- Permian undifferentiated
p2 - Upper Permian
p1 - Lower Permian
h - Carboniferous undifferentiated
h2 - Upper Carboniferous
hi - Lower Carboniferous
d - Devonian undifferentiated
d3 - Upper Devonian
d2 - Middle Devonian > pi-Paleozoic
d1 - Lower Devonian
s - Silurian
o - Ordovician
cb - Cambrian J
eo - Eocambrian
pr - Pre-Cambrian

3.3.1.7 Procedures for hydrogeological map preparation

A. Desk study

Before going to the field, previous data should be collected reviewed and evaluated. This helps to draw an action plan for the hydrogeological mapping project.

The project work begins with identifying the problem and defining the purpose, scope and scale of the study.

The base map that consists of topographic map and geological map should be prepared, and water points in the collected data should be plotted. This map will be used and modified during the course of the study. It is also very helpful to formulate a preliminary conceptual model and hypothesis, Plan the fieldwork and Collect all field scientific and other equipment.

B. Field work

The Field work should be made after evaluation and interpretation of the hydrogeological data collected during the desk study phase.

In the field work for the hydrogeological mapping the following information should be assessed.

- Geology of the area
- Hydrology
- Geomorphology

- Collect Water point data including boreholes, dug wells and springs
- Collect water chemistry data and water samples for detail analysis

C. Base map preparation

I) General

This guide line presents the procedures that should be followed for the preparation of a base map which at the end will be an input or background for the generation of Hydrogeological map. All advised procedures and techniques of conversion of an existing map to working material are in accordance with the national and international guide lines for hydrogeological map preparation. This guide line will outline simple techniques which help to prepare a base map from existing different maps, satellite imageries, and Digital Elevation Models etc.

Generally a base map should constitute the following maps in their up-to-date version.

- Geological
- Topographical
- Meteorological
- Hydrological maps

Satellite imagery and Aerial photo can also be used to produce base map for the intended Hydrogeological mapping area when the above mentioned maps are not available.

The Base map used for the preparation of hydrogeological map should contain the following parameters but not limited to these.

- all available existing base maps of the study area should be collected.
- Existing base map acquired in paper print should be converted to electronic file through scanning or digitizing.
- Scanned base map should be geo-referenced in UTM Adindan Datum geographic projection format.
- Field visit might be necessary for checking the validity of existing base map.
- the base map should be of similar scale with the intended hydrogeological map. GIS application aids a lot for the ease of preparation of a base map on the desired scale.
- a conceptual frame work should be developed on the natural processes of the groundwater and its interaction with different geological formations.
- Geological map used as base map should present and demonstrate all tectonic structures which govern the flow of groundwater. Spatial distribution and orientation of these structures should be presented clearly with their appropriate symbols.

a) Topographic base map

The topographic base map used for preparation of hydrogeological map should be of the latest version. More consideration should be given on the following points:

- The topographic map for the intended mapping area can be purchased on desired scale, from Ethiopian Map Authority with a written request
- The topographic map should be acquired both in soft and hard copy
- The topographic map should have location of all meteorological and weather stations in the country.

b) Geologic base map

- Geological map at medium and large scale for different places in Ethiopia can be purchased from the Ethiopian geological survey up on a written request for the given project.

- A suitable scale of geological map should be selected for the compilation of hydrogeological map and should have similar scale.
- The geological map needs to be translated to hydrolithology base map and a geologic code should be given to it by an experienced hydrogeologist.
- The rock types and their codes should be captured in spread sheet.
- Distinction should be made between consolidated and unconsolidated, permeable and impermeable rock bodies should be made on a rather crude and qualitative basis.
- all geological structures should present in the geological map with similarity in their symbols and legend described in section Legend of hydrogeological maps

The rock bodies considered permeable are then classified as continuous or discontinuous, Porous or inter-granular or fissured according to the dominant flow characteristics. Sample Geological Map is depicted in the figure below. Sample geological base map is shown in figure 3-6 below.

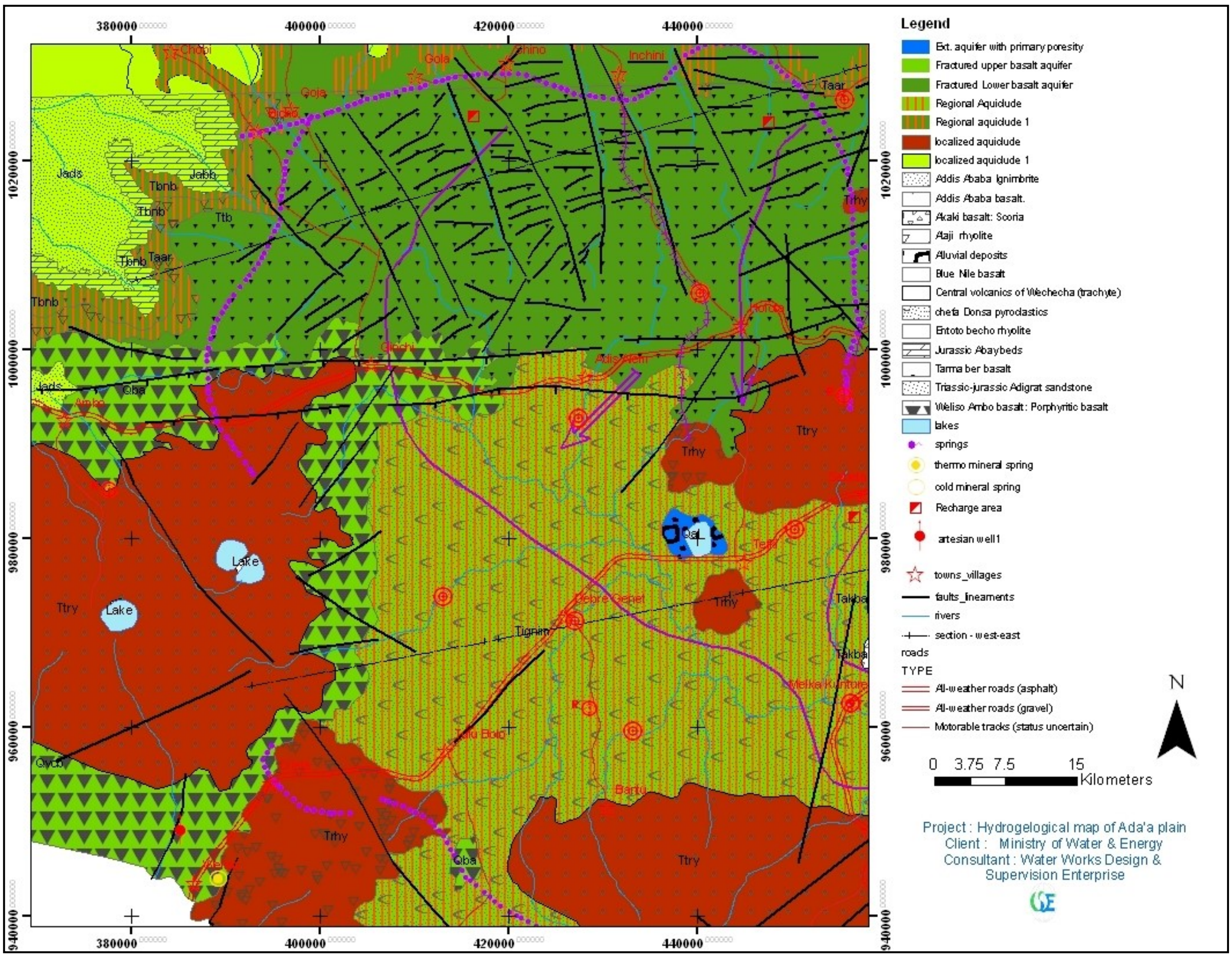


Figure 3-6: Sample geological map

II) Base Map Preparation from existing map

a) Scanning

Paper maps not found in digital format required for data capture need to be scanned at a resolution of at least 300 dpi (dot per inch), as black and white or alternatively grayscale.tif, .bmp, or .jpg images. The setting of the correct threshold on the scanner is important in order to avoid the merging of narrowly spaced lines into blobs. Colored maps may be scanned as a 24-bit color image and saved as a .tif file.

b) Digitizing

ArcGIS and ArcScan are normally used for data capture. ArcScan is an extention that is included with the full version of ArcGIS, and is used for the rapid vectorisation of especially line material from images or raster. The scanned image should be classified into two classes and the raster color can be selected as black or green to facilitate viewing. After vectorisation and editing, the geodatabase topology must be created. Topology concerns the special relationships between features. It is applied according to rules, and ensures integrity of data and facilitates editing.

c) Geo-referencing

In order to accurately represent features of a map to scale, the map should be projected using the projected corner coordinates of the map or any other clearly visible points of which the coordinates are known.

Geo-referencing can then be done by either manually entering the coordinates, or by digitizing the existing projected points with known coordinates. It is recommended to use Universal Transverse Mercator (UTM) for projection which falls in a given zones (Zones 36, 37, 38) or both as suitable.

For un-projected maps or for small-scale maps with a scale of less than or equal to 1:1,000,000, Latitude/Longitude (geographical coordinates system) is recommended, but it is good to put the UTM as required.

Adindan or WGS 1984 datum should be used during coordinate reading in the field as well as during GIS works.

d) Preparation of water point data for input

Most water point data may not have coordinate in works done in the past. However, sometimes it may be possible to find data in degrees or UTM. In order to make the data ready for the mapping project, the coordinate has to be transformed in to similar coordinate system, preferably UTM.

Then, the data has to be written in excel text format or has to be transformed in to access to input this data in to GIS.

e) Data Base for Hydrogeological Map preparation

The use of Data base management system for the storage and presentation of available multi parameter data sets creates the ease of access for hydrogeological map compilation. Data base management is believed to store a very large number of data sets in a systematic and economic way. The time consumed for the access, retrieval and editing is very much shorter than performing the same task on ordinary spread sheet. The following procedures should be followed regarding the use of Database for hydrogeological mapping.

- All hydrogeological study projects should establish an independent Database for the proper handling and storage of groundwater data sets.
- All available borehole hand dug well and spring data are suggested to be stored in Microsoft office access database.
- The database should be organized on Microsoft access of version not earlier than 2000 and should be manageable under windows.
- Tailor made independent data base application should be used with a minimum of 85 fields per water point.
- The data base should have at least three components for data entry, closing and database editing.

f) The data Entry

- The borehole data entry should have a record of borehole location, well construction, borehole lithology, pumping test and recording facility.
- All available water points will be given code in the database by the hydrogeologist who organizes the database.
- Coordinate of water points should be presented in UTM Adindan Datum zone 36or37or38 and also in Geographic coordinate.
- Existing data with Geographic coordinate system (X^0lat, Y^0 long) should be converted to UTM with above mentioned datum.
- all measurement units should be of the international standard unit (SI unit), depth to water level (m), discharge (l/s), Electrical conductivity (µS) etc
- The latest date of any data sampled repeatedly should be recorded to make time series database.
- The water quality data entry should contain concentration of major Anions and Cations in mg/l.

g) The Data edit

Most of the time, it is impossible to collect primary data in most of the study areas. Therefore, it is obligatory to edit or confirm the accuracy of the data before using it.

- The intended groundwater database should have the edit environment which allows the input and editing of all data sets.
- The latest date on existing data edited should be recorded.
- The data table in the database should enable export the data in EXCEL spread sheet and DBF format which allows the further application of the data with other software.

D. Layout of hydrogeological maps

There is no rule to determine the layout of hydrogeological maps. However all hydrogeological maps should appear proportional to the paper area and the content. The intended hydrogeological map should be presented in an attractive presentation in an optimal and proportional coverage of the paper area. Generally Landscape paper lay out is more commonly used to present hydrogeological map.

Geological symbols or patterns preferably be in black (grey) and white. Contact between different units should be black and broken where approximate and where uncertain. It is also possible to put the geologic boundary with its lithological code if the hydrogeological color is dominated by the geology.

The basic map properties such as Title, Author with logo, Legend, Grid (both UTM Adindan and Longitude/Latitude), Orientation direction (north arrow), Scale (bar and Text), Date & place of publication should be the basic constituents of the map.

The following hydrogeological properties should be incorporated on the map.

- Aquifer classification (quantitative and qualitative)
- Aquitards/ aquicludes and their boundaries
- Geology, structure and stratigraphy (using patterns as a background)
- Drainage basin, lakes, ponds, reservoirs, weir sites
- Ground water basin and flow direction
- Ground water table/Piezometric contours
- All water points and sample sites(boreholes, springs, dug wells, abandoned sites etc)
- Thermal and mineral waters

- Meteorological and hydrological stations
- Occurrence of artesian basins and boundaries
- Areas of saline groundwater
- Groundwater Divides
- Settlement areas, road, administrative boundaries of regional states and
- International boundary.
- Hydrogeological cross section and line of the cross section
- Topographic contours(as needed)

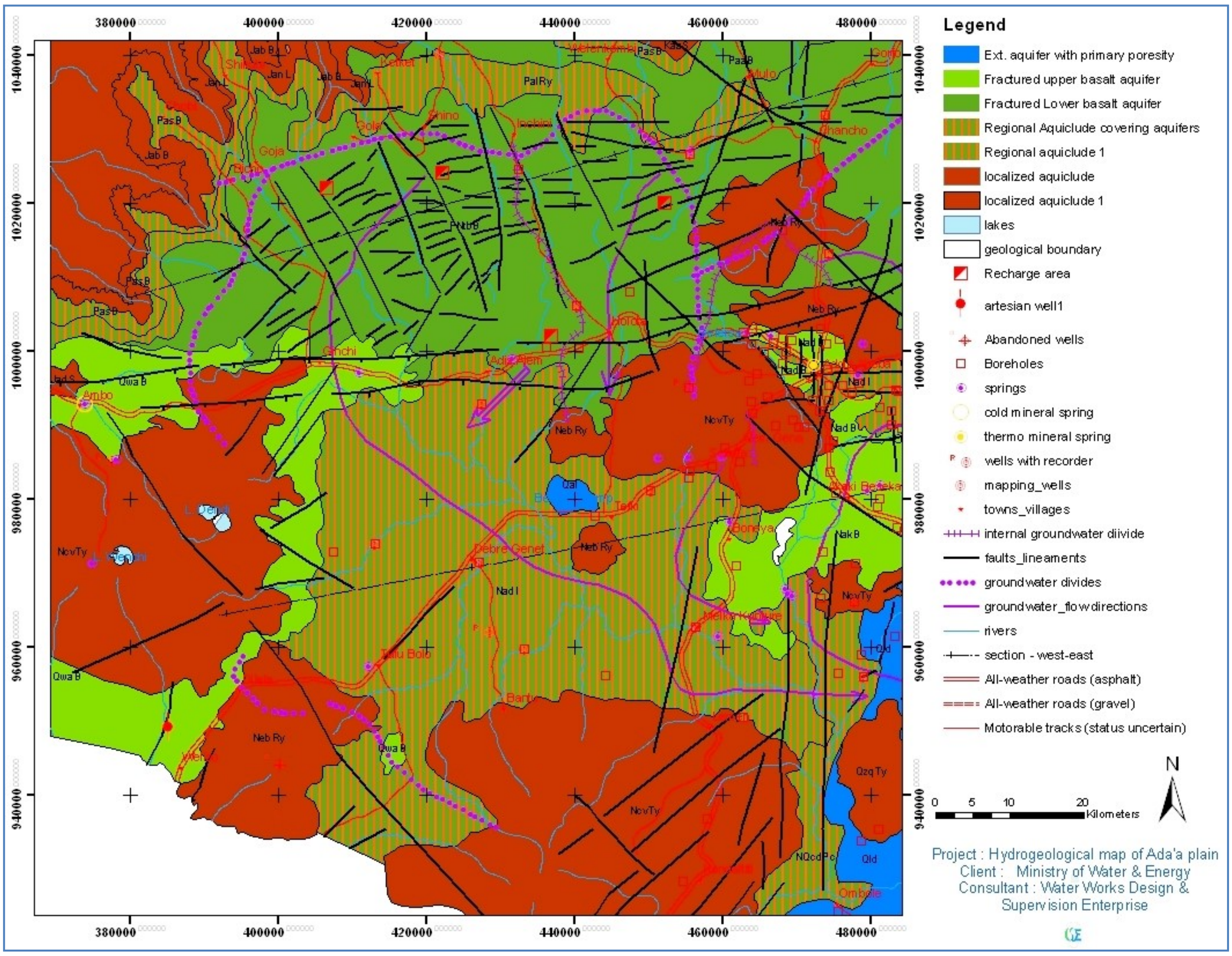


Figure 3-7: Sample hydrogeological map (adapted from WWDSE, Ade'a Becho groundwater potential investigation project)

E. Layout of geological maps

The geological map of the area is also very important for interpretation and also use it in the report to be presented as a background.

This map should contain the following elements:

Title, Author with logo, Legend, Grid (both UTM Adindan and Longitude/Latitude), Orientation direction (north arrow), Scale (bar and Text), Date & place of publication should be the basic constituents of the map.

Moreover, the geological map has to constitute the following:

- Lithology of the area
- Fault and lineation
- Settlement areas, road, administrative boundaries of regional states and
- International boundary.
- Quarry areas
- Geological cross section and line of the cross section
- Topographic contours(as needed)

3.3.2 Hydrogeological report components

Generally the Hydrogeological report includes but not limited to:

- Analysis of collected materials during investigation
- Preparation of different maps(Hydrogeological, aquifer parameters, well yields, etc) maps at 1:50000 scale
- Delineation of well fields at prospective and prioritized areas
- Evaluation of the exploitable groundwater resources and its quality at each well field in the prospective sites. Or the evaluation of the exploitable groundwater resources a groundwater software Visual Modflow or other appropriate software to be applied.
- Environmental impact assessment of well fields and its surrounding due to exploitation of groundwater
- Conclusion and Recommendations

Suggested hydrogeological report components is as outlined hereunder (Source WWDSE, 2012).

1- Title Page
2- Acronyms
3- Table of content

The content of a report is influenced by a variety of factors including the purpose of the work and of the report, client requirements, standards set forth in regulations or law, internal standards of the organization preparing the report and confidentiality requirements.

4- List of Tables, Figures and Appendixes
5- Introduction

The introduction presents a clear and complete statement of the purpose of the report and the work, including limitations regarding the scope, level of study and methods used. The introduction may include the location of the project and introduce a location map showing where the site is in relation to landmarks, topographic features, etc. The time frame of the work and statements regarding authorization and confidentiality requirements also may be included. It also discusses previous investigations, how the report is organized, and acknowledgement and indicates the end user of the report. The introduction may include a summary of the investigators findings, conclusions and, possibly, recommendations.

6- Purpose and Scope

Scope of the hydrogeologic investigation defines the main specified objectives of the project. Results of the investigation should also be specific as per the term of reference of the project objective.

- State the purpose and scope of the report and the hydrogeological investigation.
- Identify the level of the study, feasibility, and summarizing the report in executive summary

7- Review of previous study reports on the Area

- Review of Geological maps and reports
- Review of Geophysical Reports and Analysis results
- Review of Hydrogeological and Hydrological reports

7.1 Summary of findings from Report review
7.2 Data gaps from Report review
8- Methodologies used

- Discuss the method of data collection (both primary and Secondary)
- Data collection dates and procedures should be documented

The report should clearly describe data source, method of data collection and assess the quality and reliability of the data

- Project data source–maps and cross sections, Well logs, remote sensing imagery, water level data, water quality data, geophysical and others.

➢ Field mapping and data collection

- The need for and design of field investigation should be presented
- Discuss applicable field methods used (surface and subsurface methods), their advantage and limitations
- Clear distinction should be made between observed and inferred features and relationships

9- General descriptions of Hydrogeological systems

- Physiographic setting
- Geomorphologic setting
- Geologic setting (local and regional)
- Hydro geologic setting(Local and Regional)
- Description in the degree of spatial variability in groundwater occurrence, hydrostratigraphy and physical and hydraulic properties
- Groundwater flow system description
- Groundwater-Surface water interaction
- Conceptual groundwater model

10- Field Hydro geological Survey and Investigation Analysis
10.1 Water point Inventory and Analysis
10.1.1 Introduction and Field work

- The types of water points (springs, hand dug wells, boreholes, etc...) volume of data inventoried and distribution should be discussed

10.1.2 Characteristics of water points inventoried

- Ranges of discharge, water level, depth of boreholes in different geological formations should be discussed
- Statistical analysis and graphical presentation of water points in different geology and geomorphology is given

10.2 Groundwater Quality Analysis and Evaluation
10.2.1 Discussion on Field Sampling Methods and Statistical Analysis of Data and Interpretation

- Describe and summarized field methods for sample collection, field water quality parameter measurements, sample preservation and sample custody

- Discussion of the Analysis and interpretation of the data, method of interpretation and the bases for conclusion

10.2.2 Major element geochemistry of the groundwater and ranges of concentrations

10.2.3 Physical and Chemical characteristics of the Groundwater

- Spatial variations of GW quality and potential causes of this variation

10.2.4 Water Quality Standards

- Standards for water quality depending on the situation, impact or use of the water (health based standards for drinking water, ecological based standards, Agriculture/industry
- Report Appendix for full laboratory results and data table summarizing results

10.2.5 Discussion on Results

- Discussion of the results, discuss key hydrogeological findings based on results

10.3 Hydro geophysical Survey and Interpretations

- Discussion on the types of survey conducted, volume of works and distribution of survey points
- Discussion on the analysis and interpretation

10.4 Test wells Drilling and Pump testing

- Discuss on the test wells drilling and pump testing results if test boreholes were proposed i.e Well types, depth ranges, Discharge obtained from pump testing, hydraulic parameters calculated , distribution of test boreholes in the study area etc…

11- Aquifer Characterization of different geological formations

- Discussion on the major aquifer types (local and regional aquifers) their productivity, confining nature, extent, hydraulic parameters and water quality condition etc…
- Discussion on Major Aquitards and Aquicludes (local and regional)

12- Analysis on Groundwater flow, Recharge and Discharge

- Depth to Water table maps
- Groundwater contour Maps and flow system
- Hydro geological maps
- Discussion on recharge and discharge condition

13- Groundwater Potential Evaluation

- Discussion on the Quantitative evaluation of the groundwater potential from water balance computation or Darcian approaches or others

14 Discussion of findings and Results

15 Conclusions

- Describe the scientific reasoning behind the conclusion
- Discuss any conclusion ,un certainties and alternative interpretations
- Provide a statement of the limitation of the study

16- Recommendations

Recommendations should be based on sound, well supported conclusions

17- Reports Limitations

18- Reference and Data Source

19- Appendixes

4 OPERATION AND MAINTENANCE

4.1 WELL OPERATION

4.1.1 General

During operation of the well for irrigation, conducting groundwater observation is very essential to understand the changes if any of the groundwater quantity and quality with time. Groundwater observation/monitoring is therefore the basis for taking appropriate groundwater management measures timely before the aquifer gets deteriorated in quantity and/or quality.

4.1.2 Observation methods

4.1.3 Observation wells and piezometers

In this guide only techniques that monitor dynamic variables of groundwater in the field and the laboratory, such as elevation of water levels and water quality will be presented. The data on groundwater heads and the chemical composition are obtained at observation wells or piezometers installed in the irrigation field or test/production wells sunk in the well field.

Observation wells and piezometers should be installed carefully, taking account of rock type (consolidated, unconsolidated), and tested (WMO, 1994). An observation well is a non-pumping well used to observe the height of the water table. It is generally of larger diameter than a piezometer and may be screened throughout the thickness of the aquifer.

The observation well is a length of fully slotted tubing that is lowered into the bore hole and backfilled with sand or soil around the side of the tube. Water can freely enter the tube along its entire length. Comparisons between individual piezometers and an open well have shown that the open well may act as a vertical conduit for water to flow, thereby distorting the groundwater conditions in the vicinity of the measuring location.

A piezometer is a non-pumping we*ll,* generally small in diameter that is used to measure the groundwater head. It is an open-ended pipe, placed in a borehole that has been drilled to the desired depth in the ground. The bottom tip of the piezometer is fitted with a perforated or slotted screen (length about 1 m), to allow the inflow of water. The annular space around the screen should be filled with a gravel pack. The remaining annular space around the pipe can be filled with any material, except where the presence of aquitards requires a seal of bentonite clay or cement grouting to prevent leakage along the pipe. The water levels measured in piezometers represent the average hydraulic head at the screen of the piezometer. Rapid and accurate measurements can best be made in small diameter wells. If their diameter is large, the volume of water contained in the pipe may cause a time lag in water level changes.

Multi-piezometer installations are required for measuring the vertical hydraulic head distribution in anisotropic aquifer systems. Well-known methods are:

- Clusters of small-diameter piezometers that are placed in a single borehole at different depths and insulated by impervious material. The bottom part of each piezometer is screened. Leakage along the pipes from one piezometer to another has to be avoided.
- Clusters of piezometers in different boreholes in one place. The piezometers are installed at different depths. This is technically less demanding, but usually more expensive.

Before an observation well or piezometer is used, it should be developed. This entails injecting and abstracting water into and from the well, which induces groundwater flow alternately from and to the well. This procedure removes clogging from the screens and fine materials from the bottom of the well and the pack around the well. Subsequently a performance test is needed.

An adequately installed well or piezometer should quickly follow head changes in the aquifer. A simple test is carried out by observing the fall of the water level in the well after the recharge of a known volume of water injected in the well. If the decline is too slow, the well should be further developed. Occasionally the tests of the wells or piezometers should be repeated, e.g. every two or three years.

4.1.4 Methods for monitoring groundwater quantity

Methods to monitor groundwater heads are described below. Furthermore some information is provided about the monitoring of groundwater well discharge. Both manual-operated and automated-recording instruments are available to measure groundwater heads in observations wells or piezometers (Table 4.1).

Table 4-1: Summary of instruments commonly used to measure groundwater heads (From: Driscoll, 1986; Nielsen, 1991; WMO, 1994; Otto, 1998 as cited in UNESCO, 2004)

Method	Readout device	Advantages	Disadvantages	Costs, skills
A. Manual				
Wetted-tape or flexible steel	Tape markings sometimes with steel ruler	Accurate if depth is not too large	Several measurements needed to find approximate depth	Low price and easy to produce and use
Dipper	Tape markings sometimes with steel ruler	Accurate with 0.01m, fast	Not-applicable in noisy environments	Low price and easy to produce and use
Inertial devices	Tape markings	Accurate with 0.01m, fast and simple to use in pollutedgroundwater	Calibration	Moderately priced, easy to operate
Two-electrode devices	Tape markings	Fast and simple, accuracy decreases with depth	Calibration, regular maintenance, batteris	Moderately to high priced depending on cable length, easy to operate
B. Automatic recording				
Mechanical float recorder system	Drum chart or data logger	Widely applied	Float lag, mechanical failure, large well diameter	High priced, regular maintenance and checking
Pressure transducer	Data logger	Less components than float systems	Temperature effect, connection with the open air, calibration	High priced, regular checking
Ultrasonic sensors	Data logger	Less components than float systems	Temperature and humidity effects; for under-water types effects of pressure, solute oncentrations and air bubbles	High priced, regular checking

(i) Manual groundwater head monitoring

The most common manual method is to suspend a weighted plastic-coated tape or flexible steel cable from the well head to a point below the water level. The water level is determined by the difference between the length of the wound-out cable and the length of that part that has been submerged. The length can either be read out directly from the markers, or by using a steel rule and the nearest marker, if fewer markers are adjusted on the tape or cable. Sometimes chalk or pastes that change colour are used to simplify the determination of the part submerged. Depths of 50 to 100 m are measured with ease. At greater depth a thin steel cable or lightweight plastic coated tape is recommended. A skilled observer can achieve an accuracy of a few millimetres, although usually the error increases with depth.

The dipper is a cylindrical probe with a hollow space at the end, which is connected to a plastic-coated tape or flexible steel cable. If the dipper reaches the water table an audible signal is produced. Usually the depth is determined after raising and lowering the probe a number of times over a distance of a few centimetres. The depth of the water table equals the length of the tape or cable, usually measured at the well head.

An inertial device is a portable instrument that is designed so that a weight attached to a cable moves downwards at a constant velocity. If the weight reaches the water table, a braking mechanism prevents further downward movement. A counter gives the depth of the water table relative to the position of the portable instrument, usually the well head. With this equipment depths greater than 100 m can be measured. Accuracy is high if the cable has negligible stretch.

An advantage is the high resistance, for example, to oil-polluted water and corrosive waters. The two-electrode equipment consists of a portable reel with plastic-coated tape or cable connected to a probe at the end of the cable. The probe with a length of about 10 to 20 cm has two small adjacent electrodes. The circuit between the two exposed electrodes is closed when the probe reaches the water table, and a visible and/or audible signal is produced by a lamp or buzzer built-into the reel. The depth of the water table is read from the cable and is related to the position of the well head. With this equipment large depths to over 300 m are measured. The maximum depth is dependent on the length of the electrical cable, the design of the electrical circuitry and the acceptable weight of the equipment. The accuracy is comparable to the inertial device, although at great depth (in the order of 500 m) errors of 0.15 m are reported. However, if differences in water level have to be measured at this great depth (e.g. pumping test) and the cable is left suspended, an accuracy of millimetres is achieved.

Other techniques use other physical properties, such as the resistance or capacitance. The electrochemical effect of two different metals is also used. Then no batteries are needed. Measurable current flow can be produced in most groundwaters by immersing two electrodes (e.g. magnesium and brass). There is even a single electrode version: a magnesium electrode in the probe and a steel earth pin at the surface.

The above-mentioned instruments can also be used for free-flowing groundwater, as long as the groundwater head and the piezometer are no more than approximately 1.5 to 1.8 m above the soil surface. As an alternative the piezometer can be connected to a transparent tube just above the soil surface. The head is read from the marked tube, or a steel rule is used. If the head of the artesian aquifer is more than 1.8 m above the soil surface a pressure device needs to be applied (see below).

(ii) Automatic recording of groundwater heads

Automatic recording of groundwater heads is sometimes necessary, i.e. to investigate fast changes (e.g. pumping test, tidal effects, scientific research) or to monitor at remote places. The mechanical float recorder is widely applied. This device is based on a float that is linked to a counterweight by a cable that runs over a pulley. The device is above the well, and the float and the counterweight are in the observation well if the diameter permits. In wells or piezometers with small diameters a vertical pipe has to be installed in the ground for the counterweight next to the well with the float. Float and float-line friction against the well casing can be a problem in wells with deep water levels and should be avoided. A large-diameter float is recommended because of its greater sensitivity to water level changes. The cable should be long enough to account for the groundwater fluctuation between the dates that the site is visited. The turn of the pulley is converted into a vertical movement of a pen on a drum chart (analogue recorder), which is driven by a spring or an electrical clock. Usually the speed at which the drum rotates can be adjusted, e.g. drum charts from one day to one month are available. Instead of recording on a drum chart, the turn of the pulley also can be converted into digital information (electronic recorder) that can be stored on a data logger. Then the water level is not recorded continuously as with the drum chart, but it is stored only at prescribed intervals, for example every minute, 15 minutes or hour. A proper data storage is necessary; the data logger in the field should have a backup memory. Then the data can retrieved again, if something goes wrong with the data exchange between the data logger, the portable PC in the field and the central computer in the office.

Careful maintenance and checking of the float recorder is a prerequisite to avoid malfunctioning. Every time the recorder is visited the recorded level should be checked against manual observations. In reliability, versatility, maintenance efforts and need for skilled staff, the float type method is considered to be a good compromise compared to other automatic recording methods.
Other methods based upon the pressure transducer and ultrasonic sensors are being used increasingly (Table 4.1).

In a pressure transducer the water pressure is converted to an electrical signal. The transducers are designed so that the water pressure is linearly related to the electrical signal. A calibration of the pressure transducer is recommended. The small pressure transducer is lowered into the observation well or piezometer below the deepest possible water level and stays there.

The transducer is connected to the open air via a cable (atmospheric pressure is the reference) and to a logger which periodically stores the water level reading. Temperature affects both the electronic and the mechanical part of the transducer; at high or low temperatures the transducer

Table 4-2: Accuracy of various methods to measure groundwater heads (After Boiten et al., 1995 as cited in UNESCO 2004)

Method	Accuracy (m)
Floaters	
• analogue recorder	
- diameter 0.10 m	0.003 – 0.005
- diameter 0.20 m	0.001 – 0.003
• electronic recorder	
- diameter > 0.08 m	0.001 – 0.003
Pressure transducers	
• cheap types	0.010 – 0.050[1]
• expensive types	0.002 - 0.010[1]
Ultrasonic sensors	0.005 - 0.020

[1] Depends on measuring range, etc.

may not operate adequately. Nowadays there are probes that combine a pressure transducer and a data logger. The 15–20 cm long probes are lowered into the observation well and stay there for one month, recording pressure data every 15 minutes. This device is a good alternative for locations exposed to damage.

An ultrasonic sensor transmits ultrasonic pulses. These pulses are reflected at the water surface and received again by the sensor. The time between transmission and receipt is linearly related to the distance between the sensor and the water surface, and consequently to the water level. Ultrasonic sensors can be placed either above or below the water surface. Below the water surface the propagation velocity is lower than in the air. Ultrasonic sensors are sensitive to temperature and humidity. Furthermore the performance of underwater types is affected by variations in water pressure, solute concentration and occurrence of air bubbles. The ultrasonic sensor is connected to a data logger.

An indication of the accuracy of the various methods is given in Table 4.2. Errors from the conversion of readings related to the well head (local reference) to datum (e.g. m a.m.s.l.) are not included.

(iii) Abstraction monitoring

Mechanical flow meters record the total water abstraction and the data is read from the meter at periodic intervals. Electronic totaling flow meters are used if the data can be stored on a logger. For proper groundwater management, each abstraction well within a well field should be instrumented to monitor abstraction amounts and well performance.

4.1.5 Methods for monitoring groundwater quality

Methods for monitoring the chemical composition of groundwater are essential for the identification of groundwater flow systems (background monitoring). Furthermore the monitoring is necessary to investigate the development of the chemical composition during the exploitation of the groundwater resources (specific monitoring). This section will describe the sampling of aquifers, reasons why the chemical composition of the sample may differ from the composition of the aquifer itself, sampling devices and analysis techniques. For a more comprehensive description, users are referred to WMO (1994) and Otto (1998).

(i) Sampling of aquifers

The objective of groundwater quality monitoring programmes is to obtain samples of water that represent the groundwater within an aquifer, or within particular depth intervals in an aquifer.
For some purposes hydrochemical monitoring should be discrete in its location within the aquifer system, which implies that additional hydrochemical monitoring boreholes have to be constructed. Where possible installed observation wells or piezometers for head measurements should be used, provided that the design is suitable for efficient sampling.

When sampling aquifers for monitoring groundwater quality a distinction should be made between non-point and point sampling. Non-point samples obtained by pumping from open boreholes or fully screened observation wells provide information on the overall changes in groundwater quality; the samples might be a mixture of different groundwater types. Such a sampling programme monitors broad changes in the chemical composition of groundwater in an aquifer at relatively low cost. Non-point sampling, however, is inadequate for monitoring groundwater quality changes at a local and three-dimensional scale. Therefore a different sampling design to the non-point method is required to monitor site-specific groundwater changes such as salt water intrusion or plumes from waste disposal sites. Important consider- ations in the design include the need for close vertical interval point sampling and sampling locations that take the groundwater flow patterns into account. Using piezometers for water quality sampling, the screen length of the borehole casing or piezometer has to be considered.

There is little difference if hydraulic head is measured in a small or large volume of the aquifer, because the vertical hydraulic gradient in the permeable unit is usually small. However, the result can be dramatically different for water quality sampling.

The most reliable method for multilevel sampling can be achieved by piezometers in different boreholes at various depths at one site. The second best method is to bundle piezometers at different depths in one borehole and install samplers at discrete sampling points.

(ii) Factors changing the chemical composition of groundwater samples

To obtain a representative sample of groundwater the well casing volume of a well has to be purged by bailing or pumping at least three bore volumes. The adequacy of the purging can be checked in the field by examining readily measured physical-chemical components (e.g. temperature, pH, EC) of the purged groundwater that should approach a constant value. A small diameter well would also mitigate purging problems for chemical sampling. Three problems may seriously affect the chemical composition of a groundwater sample, namely:

- effects of well construction and contamination with drilling fluid. For example, the use of cement rings in dug wells (higher pH) or bentonite as seal in a piezometer can affectthe water chemistry. Also, drilling fluid that has infiltrated into the surrounding aquifer material is often difficult to remove.
- sample deterioration. The chemistry of samples can change due to variations in temperature and gas pressure. Cool and dark storage of samples is necessary. Insitu analysis, or prompt transportation to the laboratory can preserve data quality;
- careless field and laboratory practices. Sample contamination caused by improper bottle washing and filtering is a main concern. It is recommended to wash the bottle with the groundwater to be analysed, prior to the collection of the sample. Organic compounds can be absorbed by plastic containers, also the loss of volatile components can be a problem. The quality of laboratory analyses should be checked by submitting blanks and duplicates.

(iii) Sampling devices

The initial consideration in selecting a sampling device is whether the well will accommodate the device. The smaller the diameter of the well, the more limited, complex and expensive the available samplers become. Depending on the analytical requirements of a sampling programme, the device should not affect the chemical and physical composition of the sample:

- the material of the device should not sorb or leach contaminants;
- pH, Eh of the sample should not alter;
- no volatile should be released from the device;
- the device should not introduce air or non-inert gas into the sample.

Also, the depth of sampling has to be considered. The deeper the sampling interval, the more head a pump must overcome to deliver a sample to the surface. Ease of the sampling procedure, transportation, cleaning and maintenance of the device should be considered. Otto (1998) lists the characteristics (e.g. well and device diameter, sampling depth, sample volume, chemical

alteration, relative costs) of some standard sampling devices, such as the cheap bailers and the expensive submersible pumps.
Free-flowing or artesian wells are easy to sample by making a small hole in the observation well about 15 to 20 cm above the soil surface, which is normally closed to allow the observer to measure the correct groundwater head. The water is allowed to flow for some time to purge it, before taking samples.

(iv) Analysis techniques
Analysis techniques can be subdivided into the conventional analytical chemical techniques predominantly used in the laboratory and sensors that measure one or more physical-chemical components either in the laboratory or in the field. Excellent handbooks are available that describe the former group (e.g. Clesceri et al., 1989; Velthorst, 1993). In this section only the sensor-based approach that has produced encouraging results in recent years, is described.

For many years, sensors have been used to measure the physical-chemical properties (pH, Eh, T, EC, turbidity) of groundwater in a well. There are many commercial sensors available. Currently a few monitoring devices are on the market that can measure chemical components (major anion and cations, dissolved oxygen) either in the laboratory or directly in the field. These portable in-situ monitors are expensive, but when many samples have to be analysed the costs per sample may be below those of the conventional analytical techniques. They require repeated and careful calibration but are easy to operate. CSIRO[2] has developed an in-situ water quality monitor that can measure a range of physical and chemical water parameters. Another promising device, HYDRION-103, analyses samples with a set of integrated ion-selective or ion related electrodes (ISEs). It consists of a sensor unit and a measurement unit. The sensor unit is made of stainless steel and contains the electrodes. This unit fits into an ordinary 500 ml glass beaker. A water sample of 250 ml is sufficient for the analysis. The sensor unit can also be put directly into the water, e.g. in a free-flowing well or in a surface water stream. The measurement unit takes care of the operation and the data storage. The operational features include the simultaneous measurement of EC, pH, K^+, Ca^{2+}, Mg^{2+}, $NH4^+$, Cl^-, $NO3^-$, and $HCO3^-$; the specially-developed software automatically corrects for (mutual) effects affecting the measurement of an individual component. No additives are needed, but filtering is necessary for turbid water. About 10–15 samples can be measured per hour.

4.2 WELL REHABILITATION

There is a need for well rehabilitation works because there could be different reasons that can be accounted as of well deterioration.

4.2.1 Causes of well deterioration

The following are among the major causes of well deterioration:

- Plugging of the formation and the screen with fine particles
- Chemical incrustation
- Structural collapse of the well casing
- Sand pumping

I. Well failure caused by physical plugging

When the well screen is plugged with sediments the invasion of small particles reduces the yield, increases the drawdown and may damage the screen.

This problem occurs due to the following reasons:

- Improper well design
- Insufficient or improper well development
- Corrosion of casing/screen
- Over pumping

II. Well failure caused by chemical incrustations

Chemical and biological incrustations are the main causes of well failure. Well failure that is caused by iron bacteria and as a result of corrosion is the common ones.

These problems may be prevented or can be treated by:

- Proper development of the well during its completion
- Chemical treatment to remove clay or silt
- Physical agitation of the borehole water

4.2.1.1 Well rehabilitation

Well rehabilitation can be defined as restoring a well to its most efficient condition by applying various rehabilitation techniques. Planning ahead of time about the timely maintenance of borehole is the best approach to overcome possible problems. With this approach the life of the well not only is prolonged but also the rehabilitation program becomes cost effective and would enable to save operation cost.

4.2.1.2 Well rehabilitation methods

A. Mechanical Methods

- Surging
- Over-pumping
- Bailing
- Back washing
- Jetting
- Air-lifting
- Brushing
- Compressed air

B. Chemical Treatment

- Acid treatment
- Polyphosphates
- Hypochlorite
- Chlorine

REFERENCE AND DATA SOURCE

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APPENDICES

APPENDIX I: Water Points Inventory Format

MINISTRY OF AGRICULTURE & NATURAL RESOURCES (MoANR)

LOCATION OF WATERPOINT

Zone____________________Woreda____________________Kebele____________

Water point ID:_______________Name of locality____________________________

Northing UTM: _______________m,Easting UTM east: _______________m

Elevation (masl): ______________ m

Description of the water point location

Type of well (Test well, Production well, observation (monitoring well))

WELL CONSTRUCTION

Drilled By (Name of drilling Company):____

Drilling Date (end): ____________________Drilling Method: ______________
(R=Rotary, C= Cable /percussion,D= Hammer down the Hole)
WELL LOG:
Geological formation of boreholel:

No.	Lithology	From (m)	Down to (m)
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			

Comments on the log of the well if any:

____

____

____

PUMPING TEST RESULT

Pumping test conducted:___________ Discharge: ___________(l/s)

(mm/dd/yy)

Draw down: ____________ m Specific yield (capacity.): ____________ l/s/m.

Type of aquifer: _____________________(Unconfined, confined, leaky)

Type of pumping test_________________

(Provisional (P), Step(S), Constant(C), Recovery(R))

Transmissivity ____________ m^2/day Thickness of aquifer:______________m

Permeability:_______________m/day Storage coefficient _______________

WATER QUALITY

Electrical conductivity (at 25 ^{0}C): ___________ µS/cm

Total dissolved solids (or filterable residue at 105 C): ___________ ppm or mg/l

Water temperature: ___________ ^{0}C; pH of the water (at 20 ^{0}C): ___________

Cations:		Anions:	
Total Hardness (in CaCO3)_____			
NH4+	______________	Cl-	__________
Na+	______________	NO2-	__________
K+	______________	NO3-	__________
Ca++	________________	F-	__________
Mg++	________________	HCO3-	__________
Fe total	________________	CO3--	__________
Mn++	________________	SO4--	__________
		PO4---	__________ (ortho)

Date of analysis: ___________________________ (mm/dd/yy)

WATER USE

Well is for domestic (D) or for industrial (ID) or Irrigation (IR) purposes: ________________ (enter D, ID or IR)

How many hours per day the well is pumped: __________________ hours (average)

The well supplies water to how many persons:_______________________ persons

Is the well sometimes dry? (y/n):_______________________________________

Total abstraction from the Bore hole: _________________ m^3/day (mean)

How to measure water level in the well:

Depth to groundwater: ______ m. Date of measurement ______________

(mm/dd/yy)

1. Is there visible observation pipe? (Y/N) ___________________
2. Is the observation pipe housed inside the surface casing? (Y/N/Not known)_______________________
3. Is the observation pipe well protected or does it have cover? (Y/N)_________

4. Is it possible to measure the water level by deep meter through lowering sensor?(Y/N)_________________Ifyes,SWL_______________________
5. If your answer for question number 5 is No, then what other possible option do you suggest for measuring the water level? Please specify____

Information on the well discharge:

1. What is the pumping rate from the well (M^3/day or l/s)?_____________________
2. How many hours a day is the pump operating?____________________________
3. How many days is the pump operating in a month?_________________________

In which months of the year the pump is operating?

____

4. Is there water meter fitted to the well (Y/N)_______________________________
5. How often is the water meter reading recorded? (Monthly/other) Please specify if the water meter reading recording interval is not on monthly basis___________________________
6. What is the water meter reading at the time of site visit?____________________
7. Is there electric power consumption bill for the well under question? (Y/N)________
8. How often is the electric power consumption reading recorded? (Monthly/ other) __________________
9. If your answer for question number 8 is other, please specify_________________

G. DATA BASE RECORDING

The data source:____

Data recorded by, Name:____

Date of recording :____(mm/dd/yy)

APPENDIX II: Field data sheet for Test / Production well drilling and Pumping Test Data Recording (Source, WWDSE)

Name of Project: ____

WELL ID: ____

Data Recorded by:____

WATER WELL DRILLING AND PUMPING TEST DATA RECORDINGFORMAT

1. DRILLING GENERAL INFORMATION

Client: __________________________Drilling Contractor__________________
Date of contract: ____
Drilling started: ___________________ Drilling Completed:__________________
Type of work: __________________*(Test well, observation well, production well)*
Well use :________________(*Water supply, Industrial, Irrigation, specify if other)*

2. LOCATION
Well ID__________ Region: _________________ Zone: ______________

Woreda:___________ Kebele:________________

UTM Zone _____________East: ______________North:_____________________

Description of the well site:

____

____

____

S/N	Date (d/m/y)	Drilling hours	Drilled depth interval, m		Method of drilling*			Drilling fluid**	Drilling problem encountered	Solution given for the problem	Supervisor Name and Signature
			From	to	D. Method	Dia	Bit type				
1											
2											
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

* - Method of Drilling: 1) Mud rotary 2) Cable/Percussion 3) DTH 4) DTH/ Rotary 5) others ** Drilling fluids: Bentonite products or specify if other fluid is used.

3. DRILLING RECORD

Station:____

UTM E: __________m N: __________m G.el:________m

Drilling Commenced on: ____________________

Completed on: __________________________

Average Drilling Rate:

Well Diameter	Drilling Method	Drill Pipe no.	Depth Interval	Time to complete drill pipe

4. LITHOLOGY DESCRIPTION (Drilling date: from_______________to____________________)

S/N	Lithologic Descriptions	Depth, m		Remarks
		From	to	
1				
2				
3				
. . .	. . .	. . .	. . .	. . .

Described by:_____________________Checked by:______________________________

5. GEOPHYSICAL LOGGING

Depth. m	Resistivity logging		GAM(Nat)	SP COND	EC, μS/cm	Temp, °C	Others, specify			Remark

6. CASING ARRANGEMENT

Well depth interval from the surface		Casing material (steel, PVC)	Length/ Diameter (OD), inch	Wall thickness, inch	Casing Length, m	Casing Type		Number of Slot	Slot opening length / width, m	% of screen opening	Remark
from	to					Blind	Screen				

7. DRILLING AND WELL CONSTRUCTION

7.1 Drilling Diameters

SN	Drilling depth interval, m		Drilling diameter, inches	Drill bit type	Remark
	from	to			
1					
2					
. . .	. . .	. . .	. . .	. . .	. . .

7.2 Casing Installation (Date: from _________________to ___________________)
Total well depth: _____________ m Type of screen: _________________

7.3 Surface casing and Observation pipe

	Length (m)	Diameter (inches)
Permanent surface casing installed		
Observation pipe		

7.4 Gravel Pack and Well development

Gravel pack (Date :_____________________________)

Aquifer		Gravel Pack		Remark
Type	Grain size, mm	Size, mm	Volume, m3	

Well development (Date :________________________)

Development method	Duration, hours	Remark
Bailing		
Surging block		
Compressor development		
Chemical development		

8. PUMPING TEST

8.1 Preliminary pumping test

Pump Type: ________________Head(H) =___________m (Discharge) Q = ___________l/s
Pump position: ______________mMethod of Measurement for Q: _________________

Static water level (SWL): ____________m

Date	Time	Water level from the surface, m	Draw down, m	Electrical conductivity (EC), mS/cm	Temp, deg. C	Pumping rate, l/s	Turbidity, mg/l	Remark
	0							
	1							
	2							
	3							
	4							
	5							
	6							
	7							
	8							
	9							
	10							
	12							
	14							
	16							
	18							
	20							
	25							
	30							

Date	Time	Water level from the surface, m	Draw down, m	Electrical conductivity (EC), mS/cm	Temp, deg. C	Pumping rate, l/s	Turbidity, mg/l	Remark
	35							
	40							
	45							
	50							
	55							
	60							

8.2 Step pumping test

Pump type:____________________ Step test duration: ____________hrs

Method of measurement:_____________ (V-notch, volumetric) Pump position:_________ m

Date Time	Time(min) Since pumping Started	Step 1		Step 2		Step 3		Step 4		Recovery Observation
		Q1=______l/s		Q2=______l/s		Q3=______l/s		Q4=______l/s		
		WL, m	DD, m	WL, m	DD, m	WL, m	DD, m	WL, m	DD, m	WL, m
	0									
	1									
	2									
	3									
	4									
	5									
	6									
	7									
	8									
	9									
	10									
	12									
	14									
	16									
	18									
	20									
	25									
	30									
	35									
	40									
	45									
	50									
	55									
	60									
	70									
	80									
	90									
	100									
	110									
	120									

8.3 Constant pumping test

Constant Test Start Date: ______(d/m/y) Constant Test End Date: ________________________

Constant Test Duration: _________hours Pump type: ________________________________

SWL:_____________ Pump position: _______________m Q: _____________________l/s

Date	Time since pumping started, min	Water Level(m)	Draw Down(m)	Discharge Measurement		EC, µS/cm	Tem °c	Comment
				V-notch(mm)	Q(l/s)			
	0							
	1							
	2							
	3							
	4							
	5							
	6							
	7							
	8							
	9							
	10							
	12							
	14							
	16							
	18							
	20							
	25							
	30							
	35							
	40							
	45							
	50							
	60							
	70							
	80							
	90							
	100							
	120							
	140							
	160							
	180							
	210							
	240							
	270							
	300							
	330							
	360							
	420							
	480							
	540							

Date	Time since pumping started, min	Water Level(m)	Draw Down(m)	Discharge Measurement		EC, µS/cm	Tem °c	Comment
				V-notch(mm)	Q(l/s)			
	600							
	660							
	720							
	780							
	840							
	900							
	960							
	1020							
	1080							
	1140							
	1200							
	1260							
	1320							
	1380							
	1440							
	1500							
	1560							
	1620							
	1680							
	1740							
	1800							
	1860							
	1920							
	1980							
	2040							
	2100							
	2160							
	2220							
	2280							
	2340							
	2400							
	2460							
	2520							
	2580							
	2640							
	2700							
	2760							
	2820							
	2880							
	2940							
	3000							
	3060							
	3120							
	3180							
	3240							
	3300							

Date	Time since pumping started, min	Water Level(m)	Draw Down(m)	Discharge Measurement		EC, µS/cm	Tem °c	Comment
				V-notch(mm)	Q(l/s)			
	3360							
	3420							
	3480							
	3540							
	3600							
	3660							
	3720							
	3780							
	3840							
	3900							
	3960							
	4020							
	4080							
	4140							
	4200							
	4260							
	4320							

8.4 Recovery data

Recovery Start Date: __________________ (d/m/y) Recovery End Date: ____________________

Constant Test Duration: ______________________hours Pump type: ____________________

SWL:______________ Pump position: ________________m Q: ______________________l/s

Date	Time since Recovery started, min	Water Level(m)	Residual Draw Down(m)	Comment

9 . Water Quality Sampling

Station name	Rec_date	Sample reason	Sample technique	Sample class	Sample type	Sample name	Source	Sampled by

9.1 water Quality Analysis Result

Station name	Chemical name	Result value	Result Unit	Result comment	Result precision	WHO maximum allowable concentration (mg/l)

10. Other information

10.1 Instruction given to the contractor

Date and Time	Instruction given (orally or letter and content	Action taken by the Contractor

10.2 Any other activities not mentioned in this data sheet (like photographing of lithology log, developing, pumping test, etc), or any other activity:

____
____
____
____
____
____
____
____
____

SITE INSTRUCTION

Work order No.______________

Date: ______________

Instruction given to: Contractor________________________________
Instruction given by: ______________________________________
____

Reference:____

Work Description:____
____
____
____
____
____
____
____
____
____
____
____

On behalf of the supervisor
Name: _______________

On behalf of the contractor
____

Signature: ___________ ________________

APPENDIX III: Worked example on shallow groundwater study and Design

1.1 Summary

Following the contract award on October 05 2011, agreement was signed in November 2011, between Ministry of Agriculture (MoA, the Client) and Water Works Design and Supervision Enterprise (WWDSE, the lead Consultant) to conduct the consultancy on Fafen Jerer Sub Basins and the Adjacent Eastern Areas Groundwater Potential Assessment and Supervision of Test and Pilot Production Wells Drilling Project (FJAE), located in Somali National Regional State of Ethiopia. Subsequently, the lead consultant had signed association contract with Somali Design and Supervision Works Enterprise (SDSWE, associate consultant), in November 2011.

The main objective of the study was to delineate potential groundwater prospective areas for irrigation development.

The methodologies employed in preparation of the report include integration of the data and information obtained through detail geological mapping of the whole FJAE area; hydrological study; surface geophysical surveys (VES and Magnetic); water points inventory and water quality surveys as well as supervision on test / production wells drilling.

Employing the methodologies mentioned, the outcomes of phase I investigation has been presented.
Based on the analysis of available groundwater data and data generated through drilling and testing works by the project, the Upper Fafen Valley has been prioritized to qualify for phase II works. The prioritization and selection of Upper Fafen Sub basin for the next level of study has been done by using water quality, depth to water table, transmissivity and drawdown parameters. From estimations of annual dynamic recharge and static groundwater storage, it was concluded that about **60 MCM/yr**, or **164,380 m3/ day** or **1900 l/s** could be exploited from the alluvial aquifer of Upper Fafen Valley. The estimated annual groundwater recharge for Upper Fafen Sub Basin computed by Darcian approach was about **73 MCM** and by hydro-meteorological method was **70 MCM**. The yearly rate of dynamic recharge to the groundwater in Upper Fafen Sub basin was taken to be the average of the estimated methods by two methods (**71 MCM**). The static groundwater reserve estimated for the Upper Fafen Sub basin alluvial aquifer was **204 MCM.**
Based on the finding, about **1,900** ha of land could be irrigated in one time irrigation from the exploitable groundwater in Upper Fafen sub basin from the potential irrigable land of about **15,000 ha**. The annual irrigable land by the estimated exploitable groundwater could increase to more than **5000 ha** if three times irrigation per annum is considered in the area.

The Fafen River valley was selected from geological mapping and resistivity studies for further study. The valley shows indications of deeper sand layers and hence would be expected to have a higher potential of storing more groundwater. The bedrock is metamorphic rock mainly granitic and granodioritic gneisses which have been intruded by a dolerite dyke and pegmatite vein.

The present study implemented in areas surrounding Fafen valley in 2013/2014 budget year with the aim of identifying geological boundaries, geological structures and alluvial extent at the same time providing baseline data regarding the geometry of the alluvial fill.

1.2 Location and Accessibility

The project area can be reached by a ˜600 km Addis Ababa-Harer-Jijiga asphalt road. The Addis Ababa-Jijiga Ethiopian airline flights are also alternative transportation means to reach the project area in a short period of time. The study area accessed through the main asphalt road from Jijiga – Fafan and all weather gravel dry roads which emanates from the main asphalt road to different localities of the area and provide access during the field data collections. Since the study area is inaccessible due to poor road network as well as security issues at the time of field work, most traverses are accessed by precarious foot path.

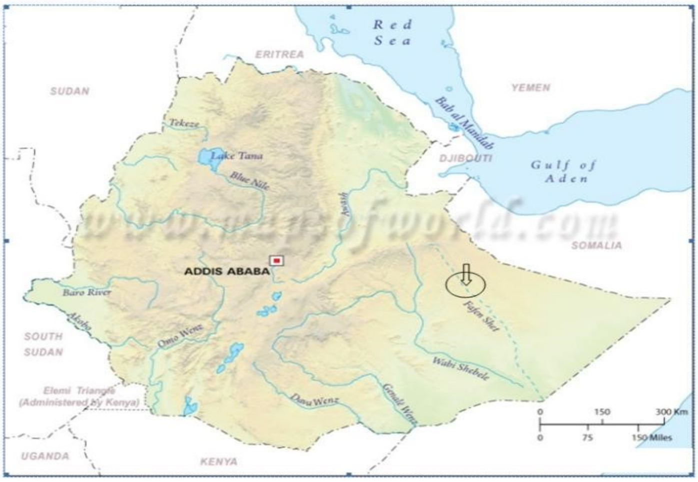


Figure A. Location map of the study area

1.3 Physiography

Ethiopia can be divided in to four major phsiographic regions, widely known as the Northwestern plateau and lowlands, Southeastern plateau and lowlands, the main Ethiopian rift system and the Afar depression. The Western and Eastern plateaus and associated lowlands are separated by the Rift valley system. The project area is located at the eastern margin of Eastern plateaus. The physiographic landscape of the study area is the result of tectonic activities, erosion and depositional events. From field observation and DEM analysis, three major physiographic regions were identified in the project area.

1.4 Previous Works

There have been a few studies of geology and hydrogeology in and around the study area; although no detail assessment of geological mapping to characterize the alluvial aquifers has yet been made, some works are used in this study to interpret the geological contact and the extent of flood plain alluvium of the area and their relationship with the tectonics structures.

Geological Map of Harer Sheet (NC38-9) at a scale of 1:250,000 by Yihune and Haro (2010); and other published articles on Ogaden Basin and surrounding area and reports of international Petroleum Exploration Companies. The report describes the distribution of a wide range of lithologies comprising high- and low-grade Precambrian basement rocks, Mesozoic sedimentary rocks, Tertiary volcanic rocks, and Quaternary sediments in the mapped area.

Geological Map of Ethiopia (Kazmin, 1972; Tefera et al. 1996): The geological map of Ethiopia (scale 1:2,000,000), first compiled by Kazmin (1972) and then revised by Tefera et al. (1996), a broad regional scale map. The paper outlines a general lithological distributions and structural setup of the country.
Geological Map of the Ogaden and surrounding Area (BEICIP, 1985): The geological map of the Ogaden and surrounding area (1:1,000,000). A regional scale map conducted by BEICIP (1985) covers the south-eastern corner of Ethiopia and describes the southern Ogaden Sedimentary Basin geological set up.
Geology of eastern Harer Sheet (NC38-9) by Hailemeskel (1992); the report describes the geological formations so as to produce the hydrogiological map of the area.

Groundwater in the Ogaden by Peter Hadwen et al., 1992. The paper describes groundwater distribution in the region.
Mengesha T., Tadios C. and Workineh H., 1996, explanation of the geological map of Ethiopia, 2nd edition (1:2,000,000). Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.the paper explains the geological and geochronological distribution of rocks in the country.

Merla, G., Abbate, E., Canuri, P., Sagri, M. and Tacconi, P. 1973: Geological map of Ethiopia and Somalia (1:2,000,000 scale). Regional scale map, describes geological units in the region.

Wabi-Shebele River Basin Integrated Development Master Plan Study Project – Geology (WWDSE, MCE and WAPCOS, 2004): The paper gives detailed account of the geology & economic mineral deposits that exist in the basin.

Water resource investigation in the Fafan valley – Geology by Habteab Zerai and Taddesse Desse (GSE, December 1987): The report deals with investigation of possible sources of water for irrigation and drilling purposes along the Fafan valley for oil and gas exploration project and geological map at 1:50000 scales.

1.5 Scopes and Objective of the Study

Understanding the nature and distribution of different geological units and their relationship with tectonic structures affecting the area is very important to understand and conceptualize the hydro-geologic system. Therefore in order to assess and evaluate the groundwater system in alluvial aquifer and identify potential well sites for groundwater exploitation, understanding of the nature, thickness, extent and geometry of alluvial fill in the area is mandatory. Hence, the main objective of the present study is to prepare geological map of the project area at a scale of 1: 250,000 accompanied with geological cross-section to model the groundwater resource potential of the associated alluvial aquifer and complete reports describing all important geological, structural and geomorphologic features.

Specific objectives are:

- To identify geological domains, lithologic contacts and major structural features.
- To interpret inter-relationship between geomorphology and tectonics.
- To identify, map and classify channel and flood plain alluvium
- To construct the litostratigraphy succession and alluvial history of the area

1.6 Methodology

In order to achieve the above mentioned objectives: to produce 1: 250,000 scales geological map of the entire project area of the present study, the following methods were applied:

1.6.1 Secondary data collection and interpretation (pre-field work)

acquisition and reviewing of previous reports and data
re-evaluation and revision of existing mapping using satellite imagery and topographic data
compilation of existing geologic mapping in an Arc GIS framework

1.6.2. Primary data collection (field work)

Primary field data on the lateral limits of Fafan river alluvium and the grain size, shape and type of the alluvium were collected every kilometer where access was permitted. Data collected include GPS waypoints, ground photos, and detailed field notes. River access generally is good, but GPS reception may be weak to nonexistent due to obstruction of satellite signal. In these reaches GPS control points were recorded where signal was available as near as possible to the river alluvium boundary. Detailed geological, structural and geomorphological notes and photos were recorded for the area and map was compiled using a combination of field collected data and high resolution Satellite images.

1.6.3 Analysis, Interpretation and Report Writing

Satellite images (Remotely Sensed Data) were mostly used in addition to satellite DEMs (Digital Elevation Models) derived from ASTER (Advanced Space born Thermal Emission and Reflection Radiometer), to identify linear trends of lithological contacts, ridgelines and lineaments that are often associated with the tectonic faults. Remote Sensing data used for this study include Landsat ETM (Enhanced Thematic Mapper) and SPOT with 5m spatial resolution.. ArcGIS 10 (a GIS software) was used for database creation and making maps. Satellite DEMs (Digital Elevation Models) i.e. 10-m ASTER (Advanced Spaceborn Thermal

Emission and Reflection Radiometer) were also used for the identification of geomorphic features of the study area. AutoCAD 7 was used for making x-section and Microsoft office 7also used for preparation and submission of report.

2. Geological Setting And Tectonics

2.1 Regional Geology

The basement rocks of Ethiopia are considered to be the interface between the Mozambique Belt (MB) in the south and the Arabian-Nubian Shield (ANS) to the north. The ANS (pan Africa 900 to 500 ma, characterized by low-grade volcano-sedimentary rocks with associated mafic to felsic intrusives, which is referred to as Upper Complex, all metamorphosed under green schist condition) and the MB (characterized by high-grade gneisses and migmatites are referred to as Lower Complex and generally consist of amphibolites facies (locally granulite facies) orthogenesis, parag-neisses, migmatites, granulite and amphibolite with bands of marble) collectively referred to as East African Orogen (EAO) (Stern, 1994). They are exposed in the northern, western, southern and eastern parts of the country.

The eastern Ethiopian Precambrian rocks of which the study area belongs are characterized by a three-fold division. These are: - (i) Lower Complex, comprised of high-grade gneiss and migmatites, (ii) the Boye Group (Middle Complex of Kazmin, 1972), comprising meta-arkose, metapelite, quartzite and marble, and (iii) the Soka Group (Upper Complex of Kazmin, 1972), consisting phyllite, chlorite schist, metavolcanics and lenses of ultramafic rocks. Geochronological investigations suggest that the Precambrian basement of eastern Ethiopia is much older (Archean and Paleoproterozoic) than the other Precambrian exposures in the country (Teklay et al., 1998).

The sedimentary regions of Ethiopia cover a significant portion of the country and comprise five distinct sedimentary basins; namely: the Ogaden, Abay (Blue Nile), Mekele, Gambela and southern Rift Basins. The development of most these basins is related to the extensional tectonic events that have take place intermittently since the late Paleozoic and continued up to Tertiary. The Ogaden, Abay and Mekele basins are presumed to be intracontinental rift basins formed as a result of extensional stresses induced by the breakup of Gondwanaland in Upper Paleozoic.

The Ogaden Basin, located in the southeastern part of Ethiopia, and its occupies an area of about 350,000 km^2 area extending from the east to southeast part of the country, is constituted of triaxially rifted troughs trending NW-SE,N-S,AND ENE-WSW. The basin’s formation is related with the Permo-Triassic breakup of the mega continent, Gondwanaland. The sedimentary succession reaches a thickness of over 10000m (in deeper part), and is comprised of non-marine to deep marine clastics, very thick, shallow to deep marine carbonates (in complex association with Argillaceous clastics) and evaporites. The succession ranges in age from late Paleozoic to Early Tertiary.

Fragmentation of Gondwanland mass, in the late Paleozoic led to the separation of southern continents. Initial rifting (Karroo (type locality South Africa) rift)) was followed by extensive marine incursion on the eastern part of Africa. According to Tamirat et al. (1992), Karoo is broad term applied mainly to continental rift sediments, deposited widely in what was eastern Gondwanaland during late Paleozoic to lower Jurassic. The Karoo sediments are all subsurface and include Calub Sandstone, Bokh Shale, Gumburo Sandstone. These phenomena deposited marginal clastics and shelf carbonates. The marginal to continental deposits formed the Adigrat Formation and the marine phases deposited the Hamanlei Limestone Formation.

The Adigrat Sandstone was deposited in the Triassic Period and the Hamanlei limestone during the Jurassic Period. This thick sequence of Mesozoic sedimentary succession which is believed to be Triassic to lower Jurassic in age, is uncomformably underlain by Pre-cambrian unit.
The NW-SE trending Karamara ridge is in line with Marda-Fault-Belt (Mohr, 1963; Kazmin 1972; Blacket al. 1974; Merla et al.1979; Senbeto et al. 1981; Mengesha et al. 1996). This fault belt occurred in the Oligocene and produced fissural basaltic volcanism in the area. These basalts covered Karamara, Ejersa Goro and

Afgugu areas. The Tertiary rocks cap both the Precambrian basement and Mesozoic – Cenozoic sedimentary successions along the Karamara mountain.

Quaternary rocks in the region have superficial origin. These sediments are of alluvial deposits of unconsolidated gravels, sands and silts which form fluvial terraces and alluvial deposits.

2.2 Local Geological Setting

The study area is located in the Ogaden basin and is divisible into four structural domains. The domain I covers the area to the north, east and west of the fafan River. This domain comprises Precambrian basement rocks and Mesozoic formations. The eastern part of the Structural Domain I, near Karamara contains a NW-SE oriented structure called Marda Fault. The Marda fault has Mesozoic sedimentary successions at its western limbs and is cored by the Precambrian basement formation. The Structural Domain II comprises a major Quaternary surficial deposits cored by Fluvial terraces, with the Precambrian basement on its limbs. The Structural Domain III is composed of modern alluvial deposits within the flood plain. This domain therefore forms deposits adjacent to active channels. The Structural Domain IV forms part of modern stream channel deposits. The local geology of the Upper Fafen Valley has been shown in figure B.

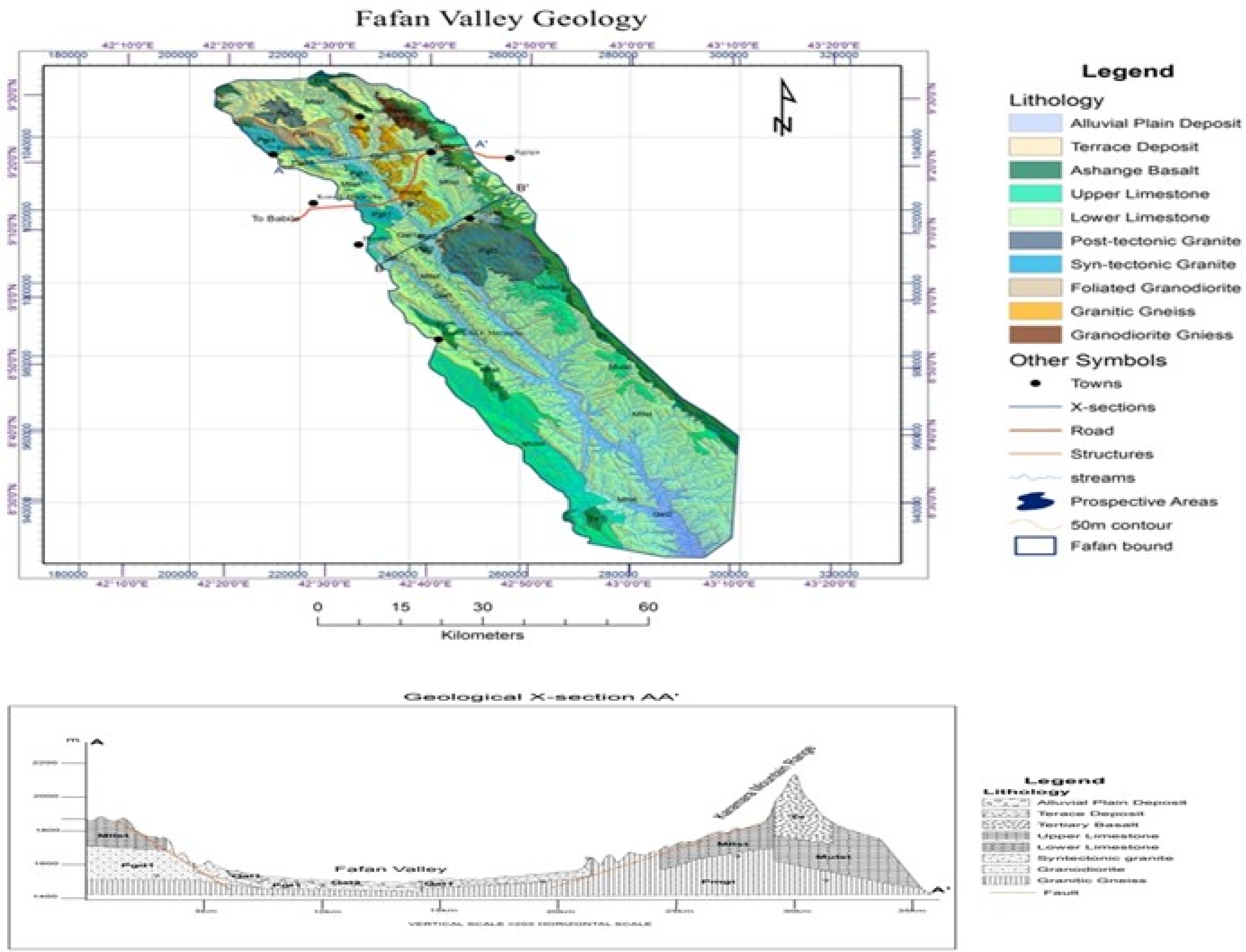


Figure B : Geological map of the study area

3. Hydrological Study

The hydrological study here focuses on the Hydro-climatological method of recharge estimation for the upper Fafen sub basin. The sub basin considered has a total surface area of **1382.16Sq.km** and is formed dominantly of basement rocks. Other rock types that make up the catchment area include Messozoil sandstone, Hamanlei limestone, basalt and alluvial sediments fig C.

The major sources of groundwater recharge for Upper Fafen valley aquifer are subsurface seepage from the fracture openings of the basement rocks from the surface catchment, seepage from run off flowing through the alluvial deposits and infiltration from precipitation that takes place in the valley plain alluvial aquifer.

3. 1 Hydro-climatological method

The main recharge to the ground water in the Upper Fafen Valley aquifer may be contributed from three major sources as portrayed in the schematic diagram of figure D.

Infiltration of rainfall that falls along fractured and faulted basement rocks of the surface catchment (subsurface inflow)
Seepage of runoff that is generated from the surface catchment

Infiltration of Rainfall that falls on valley plain alluvial aquifer area.

The total groundwater recharge of the sub basin basin could be estimated by the following relation:

$$GWR = \alpha_b A_b P_b + \alpha_R (C_b A_b) P_b + \alpha_a A_a P_a$$

Where, GWR: Groundwater recharge in MCM/year

α_b: Coefficient of groundwater recharge along fractured and faulted basement rocks of the surface catchment

α_R: Coefficient of recharge from run off

C_b: Coefficient of runoff of the basement rock

α_a: Coefficient of groundwater recharge from precipitation in the Valley plain aquifer

A_b: Area of basement rocks of the catchment (m^2)

A_a: Area of valley plain alluvial aquifer of the catchment (m^2).

P_b: Average precipitation in the surface catchment of basement rocks (m)

P_a: Average precipitation in the valley plain area (m).

The data used for the calculation of recharge by the above formula are summarized in the following table I.

TABLE I: Estimated Average Parameters for calculation of Recharge

No	Parameters	Value	Remark
1	α_b	2%	Estimated coefficient of infiltration for basement rock (2% of the rainfall)
2	α_R	20%	Estimated
3	C_b	50%	Estimated for basement rocks with steep slope
4	α_a	20%	Estimated for coarse and medium grained alluvial aquifer in plain topography
5	A_b	875.46Km^2	
6	A_a	85.13Km^2	
7	P_b	0.533m/yr	
8	P_a	0.533m/yr	

The total recharge by hydro meteorological method applying the above formula and data in table I is estimated to be **70 MCM/year (70 Million Cubic meters per year).**

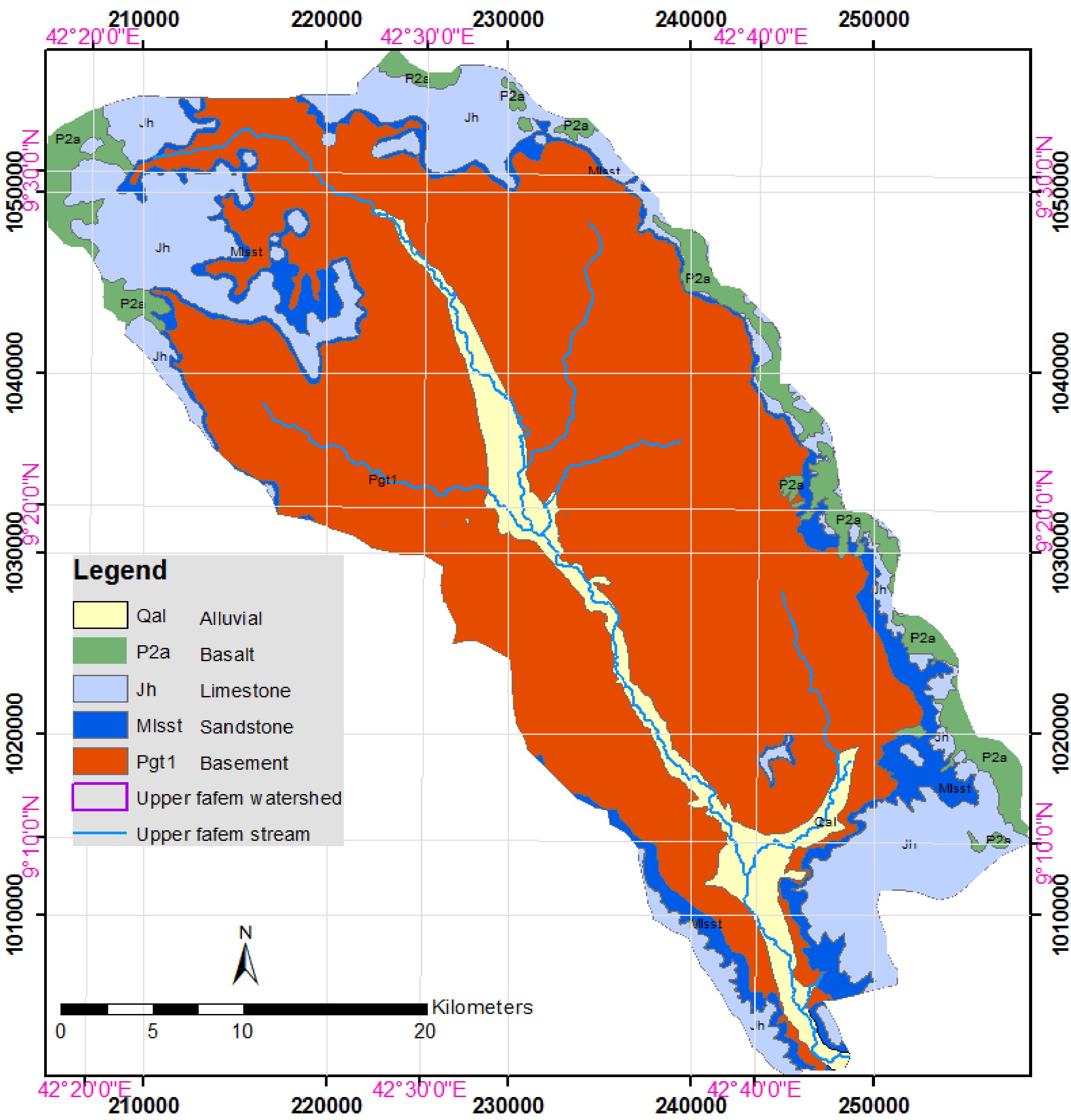


Figure C: Geological classification of upper fafen river catchment

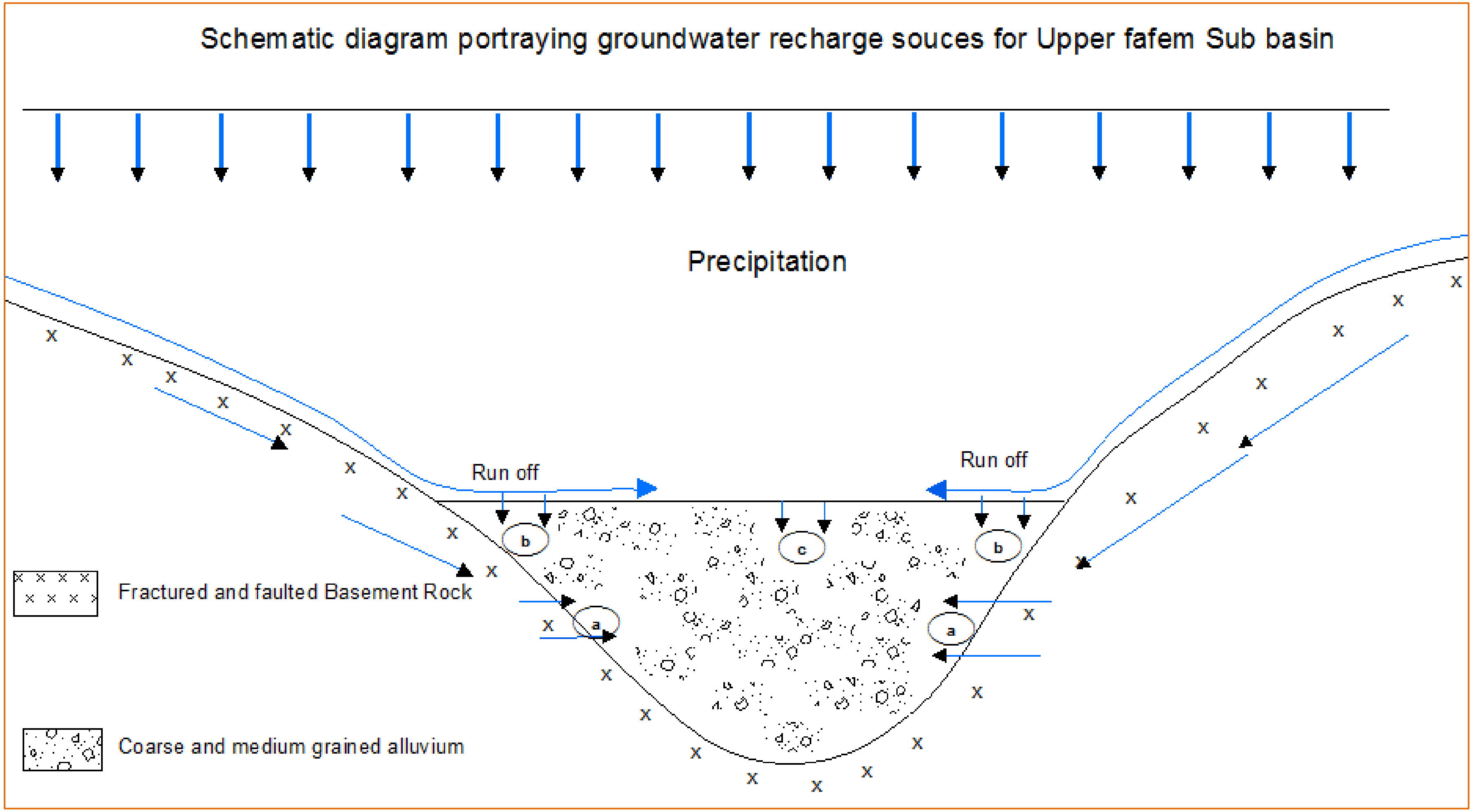


Figure D: Schematic diagram conceptualizing the groundwater recharge sources in Upper Fafen sub baisn

4. Geophysical Surveys

Geophysical surveys namely, Vertical Electrical Sounding Survey and Magnetic Survey were carried out in conjunction with Geological and Hydrogeological studies at the Fafen sub basins. Totally 126 VES points and nearly 57.4 km line of Magnetic survey were carried out in the project areas. Out of the total VES conducted 101 VES were carried out in Fafen-Jerer sub basins and the remaining 25 VES were conducted in the adjacent eastern areas.

5. Hydrogeological Survey and Investigation

The following hydrogeological survey and investigation were carried out to assess the groundwater resource of the project area. The major activities include water point inventory, water quality survey, geophysical investigation, test wells drilling and pumping test. The next sections describe the results of the hydrogeological surveys and investigation conducted in the area.

5.1 Water Point Inventory

5.1.1 Introduction and Field Work

The water point inventory has been commenced at office level by collecting all available information and data from different organizations. These information in the form of reports and data were evaluated to identify the data gap and plan what has to be done next. Hence, most of the obtained information and data were found to be incomplete, lacking co-ordinate, well log and other relevant well and aquifer parameters. Thus, the water point's inventory was planned to collect hydrogeological information and directly measured data such as co-ordinates, dynamic or static water level, and field water quality measurements.

5.2 Water Quality

A total of 80 groundwater samples were collected for the water quality analysis of the Fafen Sub basin groundwater potential assessment project. Among the 80 groundwater samples, 32 are hand dug wells dug in the alluvial formations of the Fafen valleys. Generally these hand dug wells' depths range between 3m and 15 meters. The majority of these hand dug wells depth range between 3 to 6m. The rest 48 groundwater samples are boreholes where the majority of the boreholes' depth is greater than 70 m. These boreholes mainly penetrate the Alluvial, Jessoma, Hamanlei, Adigrat and the Basement Formations.

The groundwater quality was analyzed for physical and chemical analysis. In this study it is attempted to classify the various types of water types in the different geological formations and compared with different standards to evaluate their quality for drinking and irrigation purposes.

5.2.1 Water Samples Collection

As stated above totally 80 groundwater samples were collected and analyzed during the Phase I program and for the preparation of this report. The physico-chemical analysis is used for classification and comparison with standards. The conventional hydrochemical techniques were applied to study groundwater quality and classify the water samples. AquaChem V.4.0 software by Waterloo Hydrogeologic Inc. was utilized for data processing, archiving and the production of hydrochemical plots. The water quality parameters considered for the hydrochemical analysis are physical and chemical characteristics.

The main physical characteristics considered for the analysis are

Color , turbidity, taste and odor

Temperature

The main chemical analysis are done by considering the following parameters:

Major cations (NH^+, Na^+, K^+, Mg^{+2}, Ca^+ ,total iron, and Manganese)

Major anions (Cl^-, NO_2^-, NO_3^-,F^-, HCO_3^-, SO_4^{-2}, and PO_4^{-3})

Total alkalinity as mg/l of $CaCO_3$ and

Total Hardness as mg/l of $CaCO_3$

Electrical conductivity @ 25 ^oC

Total dissolved solids @ 105^oC

PH @ 25 ^oC

The laboratory data are encoded in the Fafen_Jerer Sub basins database and checked for correctness by comparing the sum of anions and cations and by correlation of the electrical conductivity with total dissolved solids (TDS).

Groundwater quality comprises the physical, chemical and biological quality of groundwater. Since most groundwater is colorless, odorless, tasteless, and the biological quality of groundwater are not related with the geological and hydro geological environments, it is appropriate to concentrate on the chemical quality aspect. The chemical composition of groundwater is mainly attributed to weathering and erosion of rocks and soil, solution or precipitation reactions occurring below in the sub surface and by the influence of anthropogenic activities. Some of the chemical parameters that give a clue for the evaluation both the drinking and irrigation water qualities are given high emphasis.

5.3 Drilling of Test wells

To evaluate the groundwater resources potential, a total of 10 pilot and test wells had been drilled in Fafan valley.

The main purposes of the test wells are to calibrate the surface geophysics interpretation and determine preliminary aquifer parameters of the potential formation. The drilling, construction and pumping test works were contracted out in for Modern Corporation for Drilling Water Wells (MCDWW).

MCDWW has finished drilling and construction of 6 test wells out of 10. The remaining four wells were drilled and constructed by Aqua Boreholes PLC which was given as sub contract. The pumping test activities for the four wells were carried out by the MCDWW while the rest six wells were given to Somali Regional Water Works Construction Enterprise (SRWWCE) given as sub contract. However; only 3 of them were completed and the remaining 3 wells were given as a sub contract to IDMS and completed the pumping test activities.

During the evaluation of the drilling work progress of the contractors, the performance of both MCDWW and SRWWCE were too far behind the schedule for execution of the drilling, construction and pumping test activities.

The result of test wells drilling has been summarized hereunder.

The main purposes of drilling of test wells are:

To understand aquifer productivity and water quality variations in depth and lateral

To acquire subsurface data to calibrate the geophysical investigation results

To obtain aquifer parameters

The distribution of test boreholes was planned to test the potential of the Upper Fafen Valley alluvial and weathered and fractured basement aquifers.

The drilling, construction and testing of the test wells in Fafen Sub basin have been completed successfully. The test wells drilled in Fafen valley have well IDs FPW3, FPW4, FPW6, FPW7, FPW8, FPW10, FPW12', FPW13', FPW18 and FPW19.

These test wells have been drilled by mud rotary method using 17 ½ inch tricon rock bit from the surface to 12 m depth followed by 12 inch diameter tricon rock bit from 12 m to the final depths. 14 inch diameter steel surface casings were installed and 8 inch production line steel casings were lowered in all these test wells.

The maximum depth of these test wells is 99m (FPW4) and the minimum depth is 52.5m (FPW10). The static water level ranges from 1.37m bgl (FPW7) to 18.31m bgl (FPW4). The test wells have been tested with test pump discharges during constant rate pumping test varying from 4.9 LPS (FPW4) to 33.7 LPS (FPW7) for a constant rate pumping duration from 32 hrs to 72hrs. The summary of the test wells results have been presented in table II and the water quality test results of the water samples collected from these test / pilot production wells shown in table III.

TABLE II: Summary of test wells drilling results

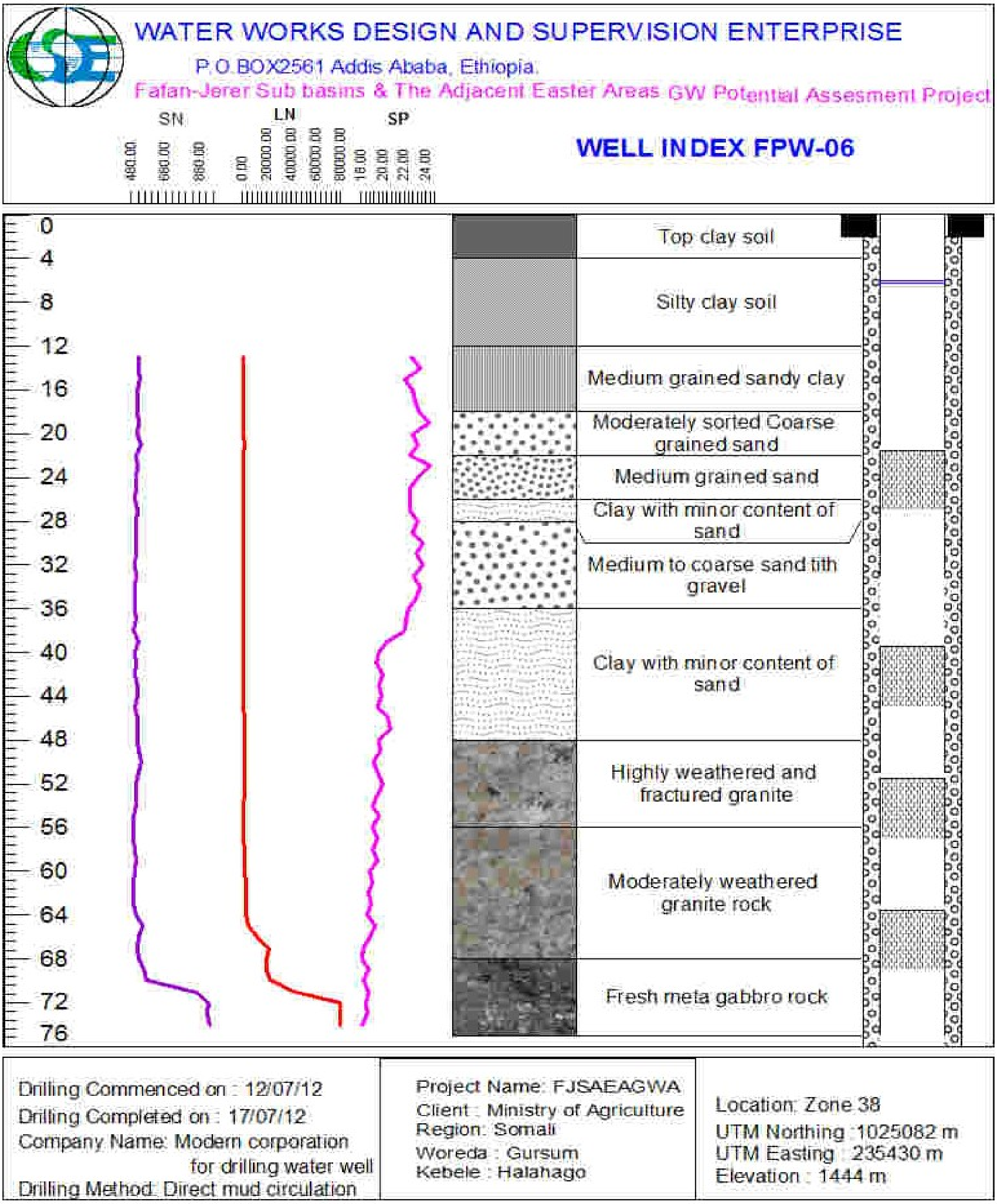
Locations & Coordinate							*Other Information*							
Water Point Index	Location	UTME	UTMN	Elevation	Depth, m	SWL, m	Discharge, l/s	Draw Down, m	Specific Capacity, l/s/m	Transmissivity, m^2/day	Driller	Drilling started	Drilling completed	Remark
FPW-03	*Halhago*	*230859*	*1031666*	*1493*	*65*	*4.68*	*13*	*25.84*	*0.50*	*36.3*	*MCDWW*	*06/06/12*	*16/06/12*	
FPW-04	*Halhago*	*233964*	*1027059*	*1469*	*99*	*18.31*	*4.9*	*34.64*	*0.14*	*77.5*	*MCDWW*	*06/06/12*	*16/06/12*	
FPW-06	*Halhago*	*235430*	*1025082*	*1444*	*75*	*5.51*	*19.6*	*7.98*	*2.46*	*263*	*MCDWW*	*12/07/12*	*17/07/12*	
FPW-07	*Degahale*	*236396*	*1022638*	*1432*	*72*	*1.37*	*33.7*	*3.54*	*9.52*	*1290*	*MCDWW*	*10/11/12*	*23/11/12*	
FPW-08	*Degahale*	*238613*	*1020135*	*1420*	*59.70*	*2.6*	*15.1*	*7.4*	*2.02*	*295*	*AQUA Boreholes*	*30/04/13*	*01/05/13*	
FPW-10	*Batey*	*238613*	*1020135*	*1416*	*52.5*	*5.04*	*10*	*19.4*	*1.98*	*132*	*AQUA Boreholes*	*15/04/13*	*18/04/13*	
FPW-12'	*Degahale*	*235950*	*1023167*	*1433*	*53*	*4.35*	*19.6*	*2.77*	*7.08*	*2180*	*AQUA Boreholes*	*25/05/13*	*26/05/13*	
FPW-13'	*Batey*	*238182*	*1020820*	*1418*	*58.5*	*2.89*	*15.5*	*10.03*	*1.55*	*304*	*AQUA Boreholes*	*15/05/13*	*16/05/13*	
FPW-18	*Dufeyis*	*239157*	*1017669*	*1401*	*82.5*	*6.8*	*27.86*	*10.42*	*2.67*	*501*	*MCDWW*	*19/09/12*	*04/10/12*	
FPW-19	*Tohada kesis*	*238777*	*1018737*	*1409*	*76.5*	*5.45*	*25.88*	*2.74*	*9.45*	*1200*	*MCDWW*	*17/08/12*	*24/08/12*	

TABLE III: Summary of Water Quality Analysis Results

ID	*Depth*	*TDS*	*EC*	*ph*	*NH3*	*Na*	*K*	*Hardness CaCo3*	*Ca*	*Mg*	*Fe*	*Mn*	*F*	*Cl*	*No2*	*No3*	*Alkalinity CaCo3*	*Co3*	*HCo3*	*So4*	*Po4*	*Date of Analysis*
FPW-03	*65*	*10900*	*1661*	*6.89*	*1.08*	*148*	*5.8*	*619.5*	*201.6*	*27.72*	*0.06*	*0.14*	*0.74*	*101.93*	*0.02*	*0.28*	*352*	*-*	*429.44*	*352.64*	*0.41*	*23/03/13*
FPW-04	*99*	*1394*	*2140*	*7.6*	*0.37*	*290*	*4.3*	*446.5*	*152*	*15.96*	*0.07*	*0.098*	*2.17*	*256.48*	*0.02*	*29.07*	*320*	*-*	*390*	*455.53*	*1.37*	*02/01/05*
FPW-06	*75*	*1288*	*1981*	*7.25*	*0.48*	*130*	*4.5*	*784.7*	*235.6*	*46.97*	*0.03*	*0.07*	*0.61*	*209.16*	*0.08*	*13.68*	*350*	*-*	*427*	*432.21*	*11.14*	*02/01/05*
FPW-07	*72*	*1700*	*2580*	*7.64*	*2.35*	*206*	*4.1*	*910*	*292*	*43.2*	*0.03*	*0.42*	*0.82*	*337.64*	*0.11*	*30.81*	*323*	*nil*	*394.06*	*570*	*0.94*	*01/12/12*
FPW-08	*59.7*	*1226*	*1855*	*7.08*	*0.91*	*148*	*1.1*	*738*	*132*	*97.92*	*0.05*	*--*	*0.78*	*201.13*	*0.04*	*2.78*	*360*	*Nil*	*439.2*	*566.08*	*1.02*	*16/02/15*
FPW-10	*52.5*	*1368*	*1990*	*7.26*	*0.68*	*208*	*1.7*	*716*	*170*	*69.60*	*0.15*	*--*	*0.7*	*159.27*	*0.12*	*4.24*	*464*	*nil*	*415.35*	*460.68*	*2.04*	*16/02/15*
FPW-12'	*53*	*1036*	*1524*	*7.28*	*1.07*	*114*	*3.1*	*600*	*128*	*67.2*	*-*	*--*	*0.71*	*187.48*	*0.03*	*3.19*	*214*	*nil*	*261.08*	*311.13*	*0.58*	*20/05/14*
FPW-13'	*58.5*	*1236*	*1881*	*7.09*	*0.87*	*182*	*2*	*716*	*168.8*	*70.56*	*0.03*	*--*	*0.62*	*166.55*	*0.278*	*5.88*	*430*	*nil*	*524.6*	*424.22*	*2.93*	*16/02/15*
FPW-18	*82.5*	*1140*	*1701*	*6.88*	*2.59*	*104*	*3.1*	*750*	*208*	*55.2*	*0.01*		*0.65*	*150.17*	*0.01*	*9.7*	*456*	*Nil*	*556.32*	*294.88*	*0.17*	
FPW-19	*76.5*	*1080*	*1603*	*6.9*	*1.63*	*101*	*3*	*714*	*239.40*	*27.72*	*0.02*	*0.03*	*0.65*	*162*	*0.02*	*18.98*	*356*	*nil*	*434.64*	*257.83*	*0.3*	

5.4 Design of Test / Pilot Production wells

The actual well designs of the test/ pilot production wells drilled and constructed in upper fafen valley of Somali national regional state have been portrayed as follows in figure E and the spacing of these wells in the well field of upper fafen valley have been shown in figure F.



WATER WORKS DESIGN AND SUPERVISION ENTERPRISE

P.O.BOX2561 Addis Ababa, Ethiopia.

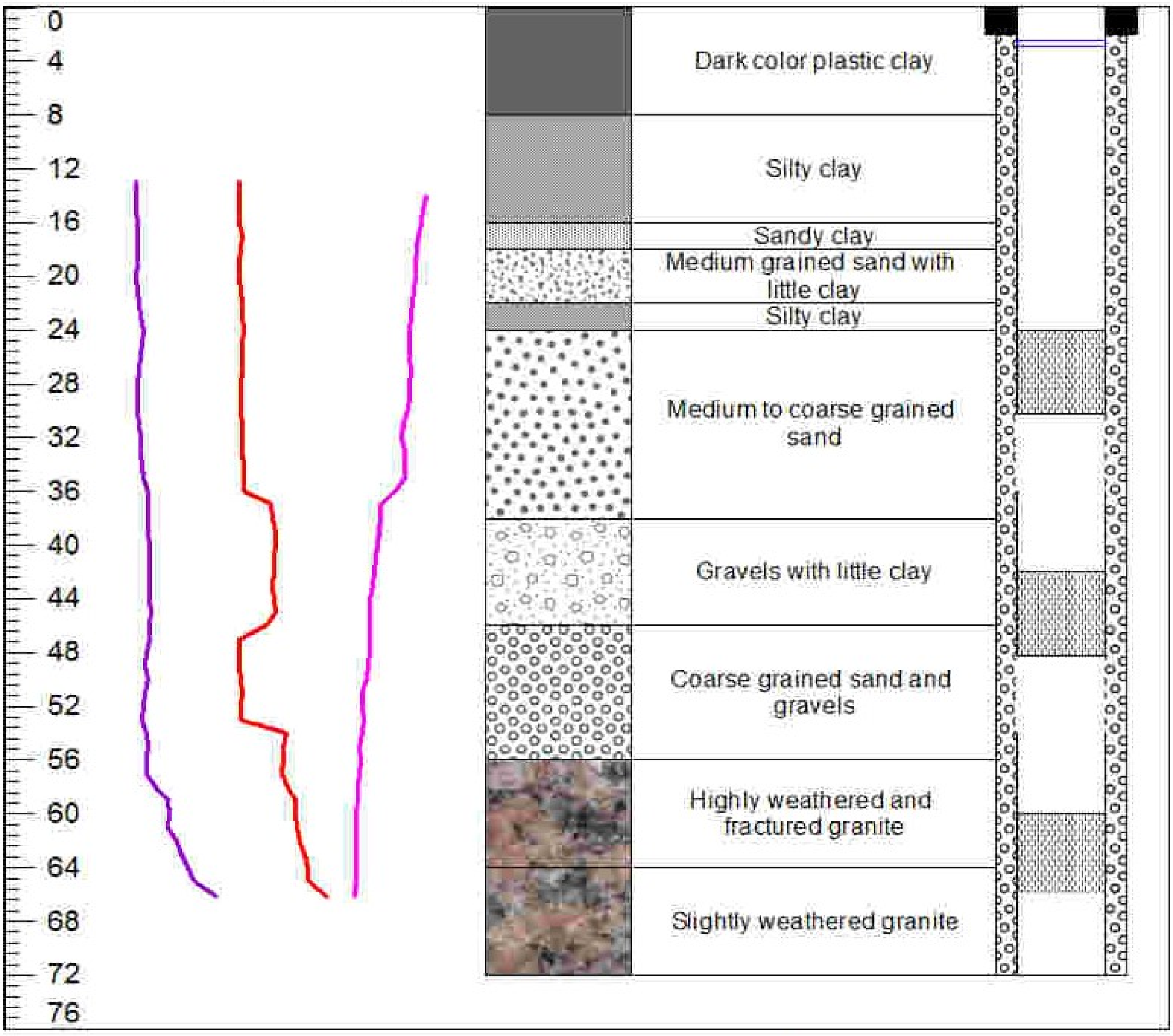
Fafan-Jerer Sub basins & The Adjacent Easter Areas GW Potential Assesment Project

SN: 10.00, 60.00, 110.00, 160.00

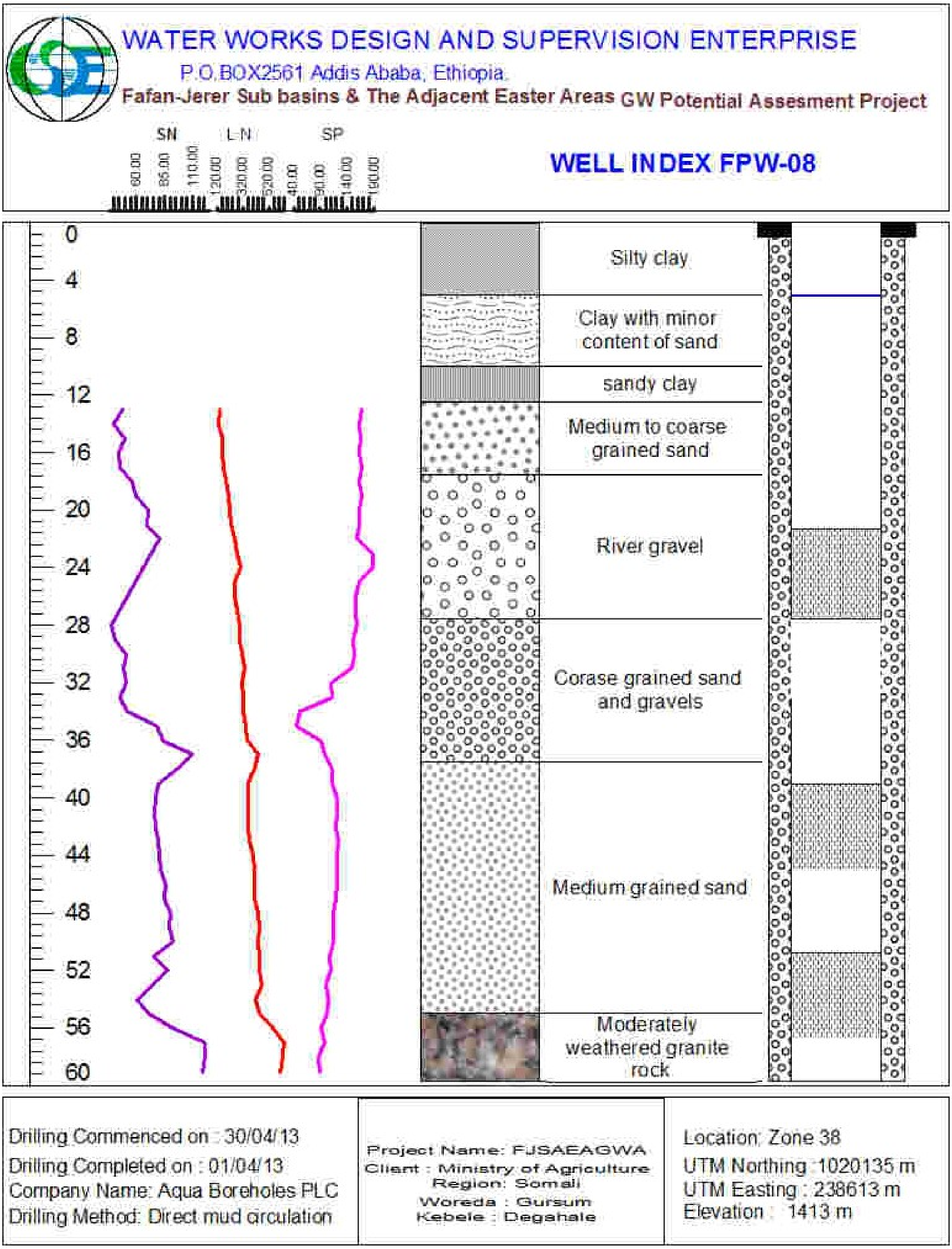
LN: 50.00, 300.00, 550.00, 800.00, 1050.00

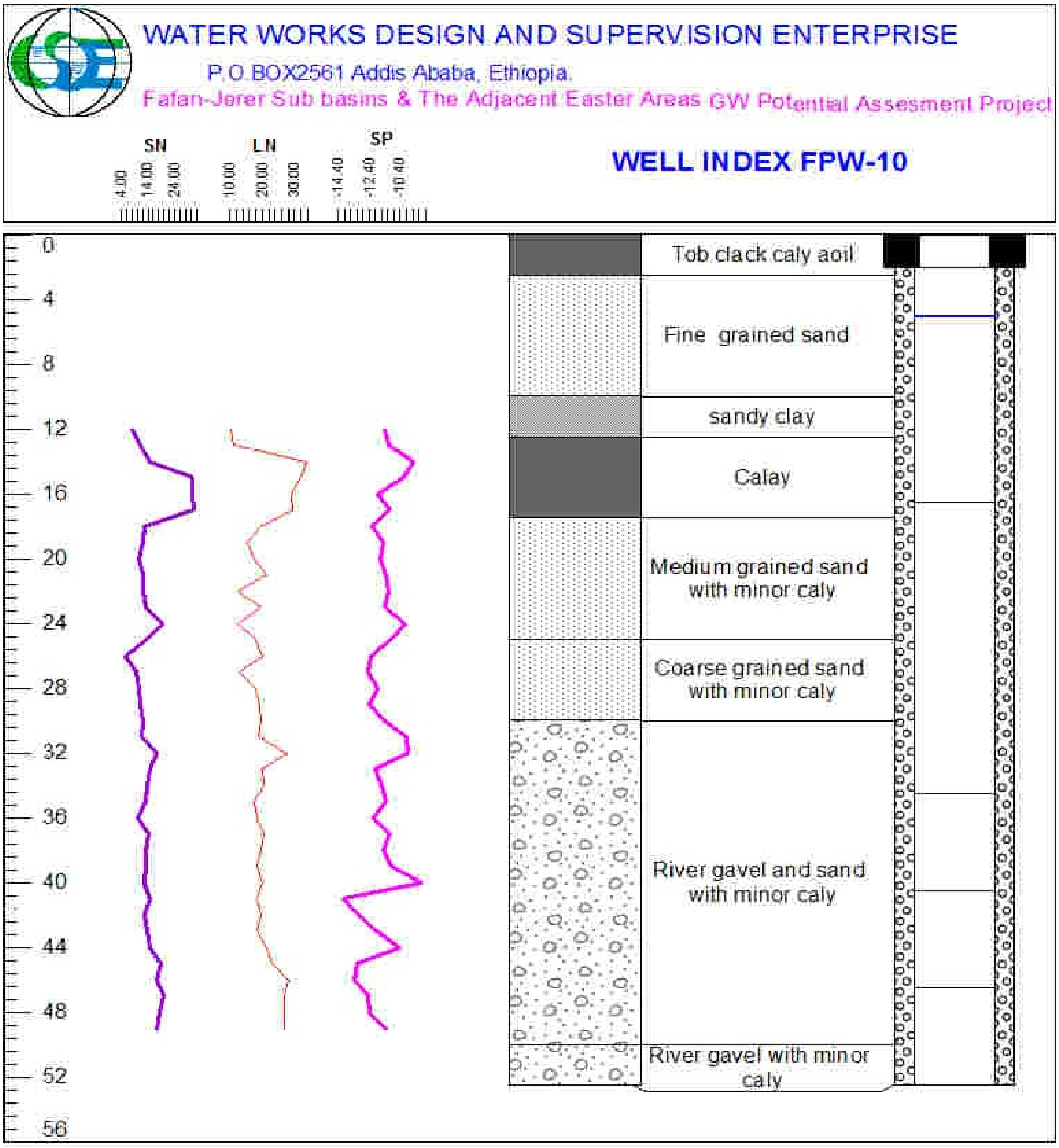
SP: 0.00, 50.00, 100.00, 150.00

WELL INDEX FPW-07



Drilling Commenced on : 10/11/12 Drilling Completed on : 23/11/12 Company Name: Modern corporation for drilling water well Drilling Method: Direct mud circulation	Project Name: FJSAEAGWA Client : Ministry of Agriculture Region: Somali Woreda : Gursum Kebele : Degahale Locality : Fafan	Location: Zone 38 UTM Northing :1022638 m UTM Easting : 236396 m Elevation : 1078 m


WATER WORKS DESIGN AND SUPERVISION ENTERPRISE
P.O.BOX2561 Addis Ababa, Ethiopia
Fafan-Jerer Sub basins & The Adjacent Easter Areas GW Potential Assesment Project
SN
LN
SP
WELL INDEX FPW-08
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
Silty clay
Clay with minor content of sand
sandy clay
Medium to coarse grained sand
River gravel
Corase grained sand and gravels
Medium grained sand
Moderately weathered granite rock
Drilling Commenced on : 30/04/13
Drilling Completed on : 01/04/13
Company Name: Aqua Boreholes PLC
Drilling Method: Direct mud circulation
Project Name: FJSAEAGWA
Client : Ministry of Agriculture
Region: Somali
Woreda : Gursum
Kebele : Degahale
Location: Zone 38
UTM Northing :1020135 m
UTM Easting : 238613 m
Elevation : 1413 m



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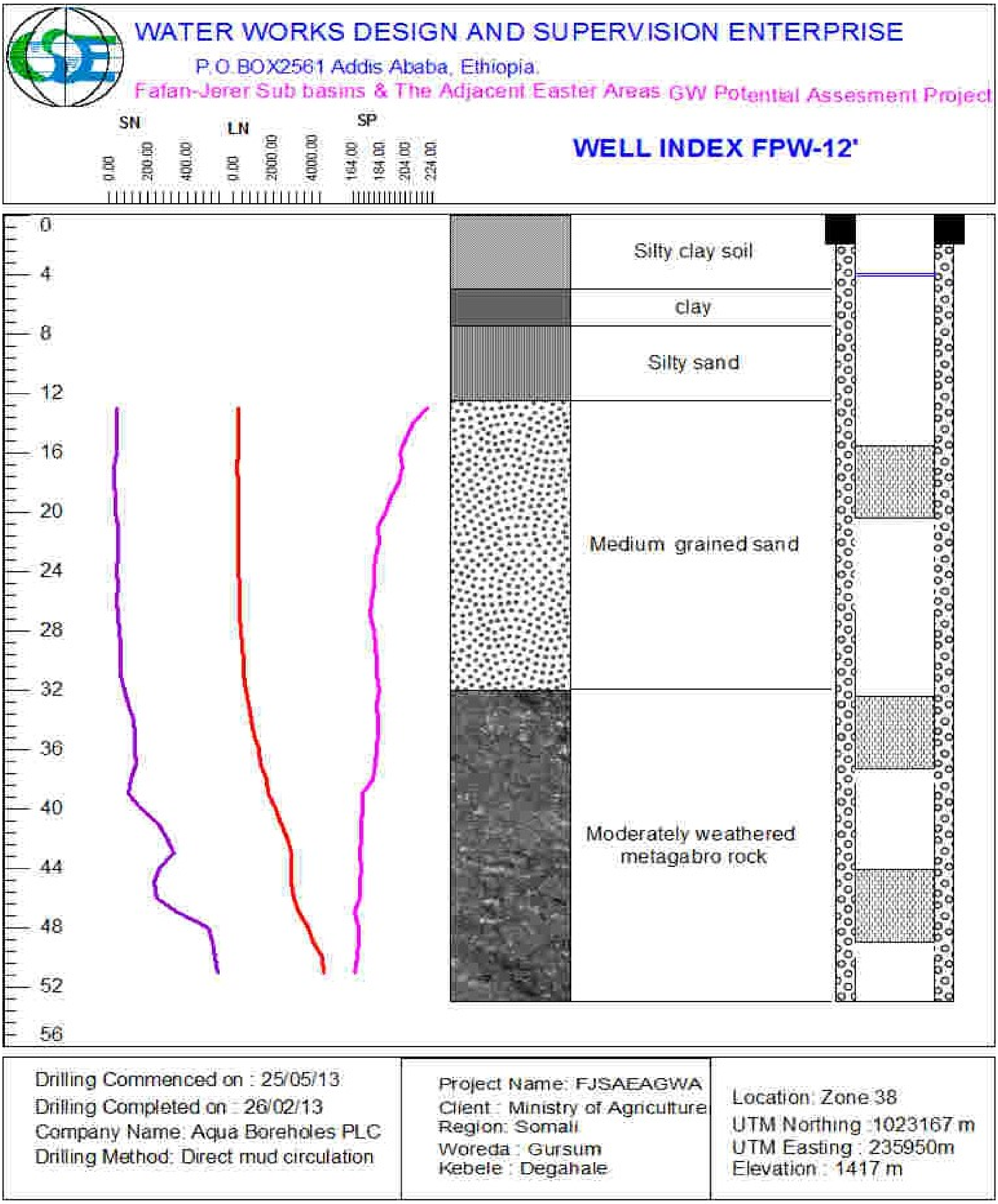
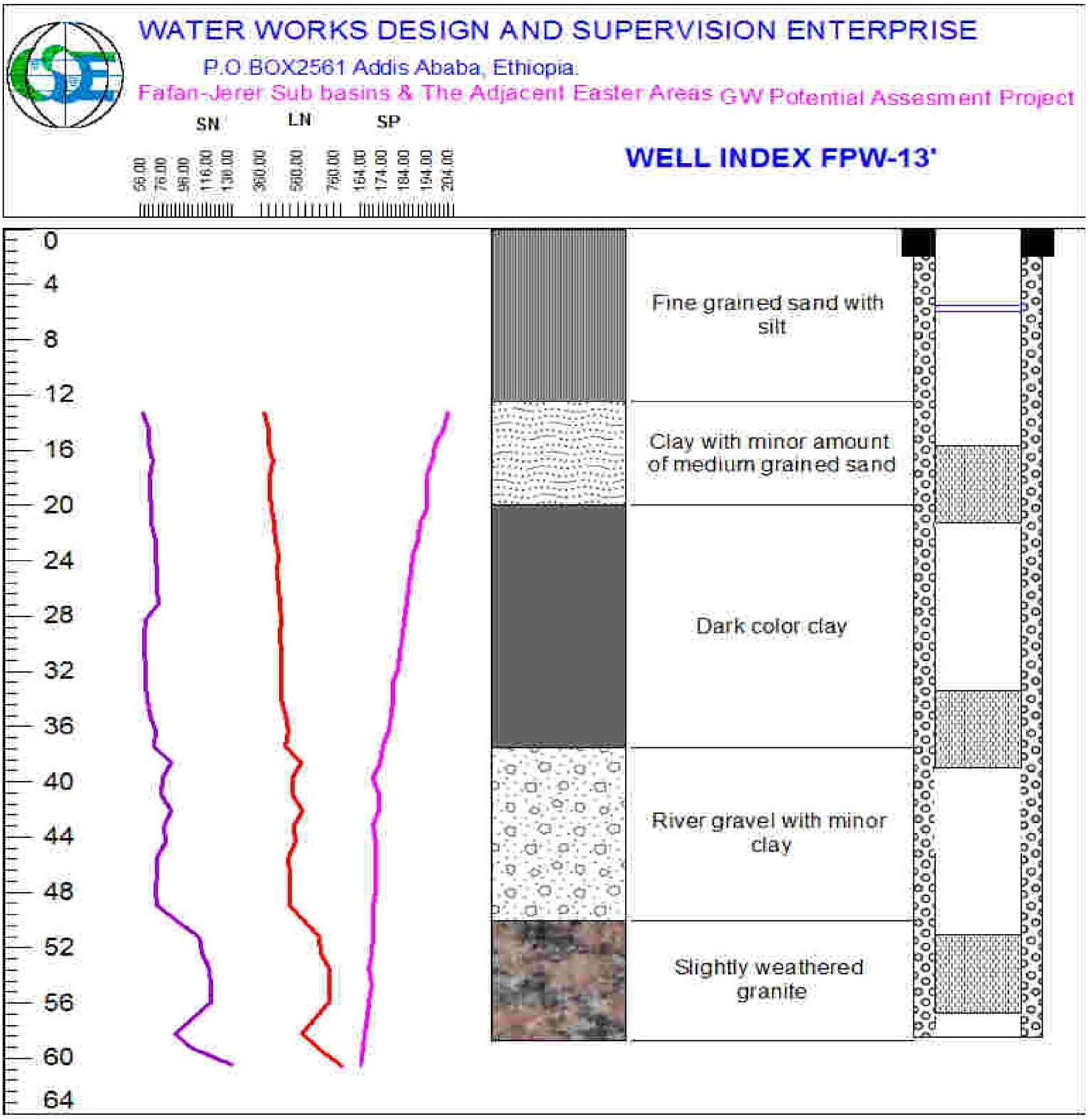
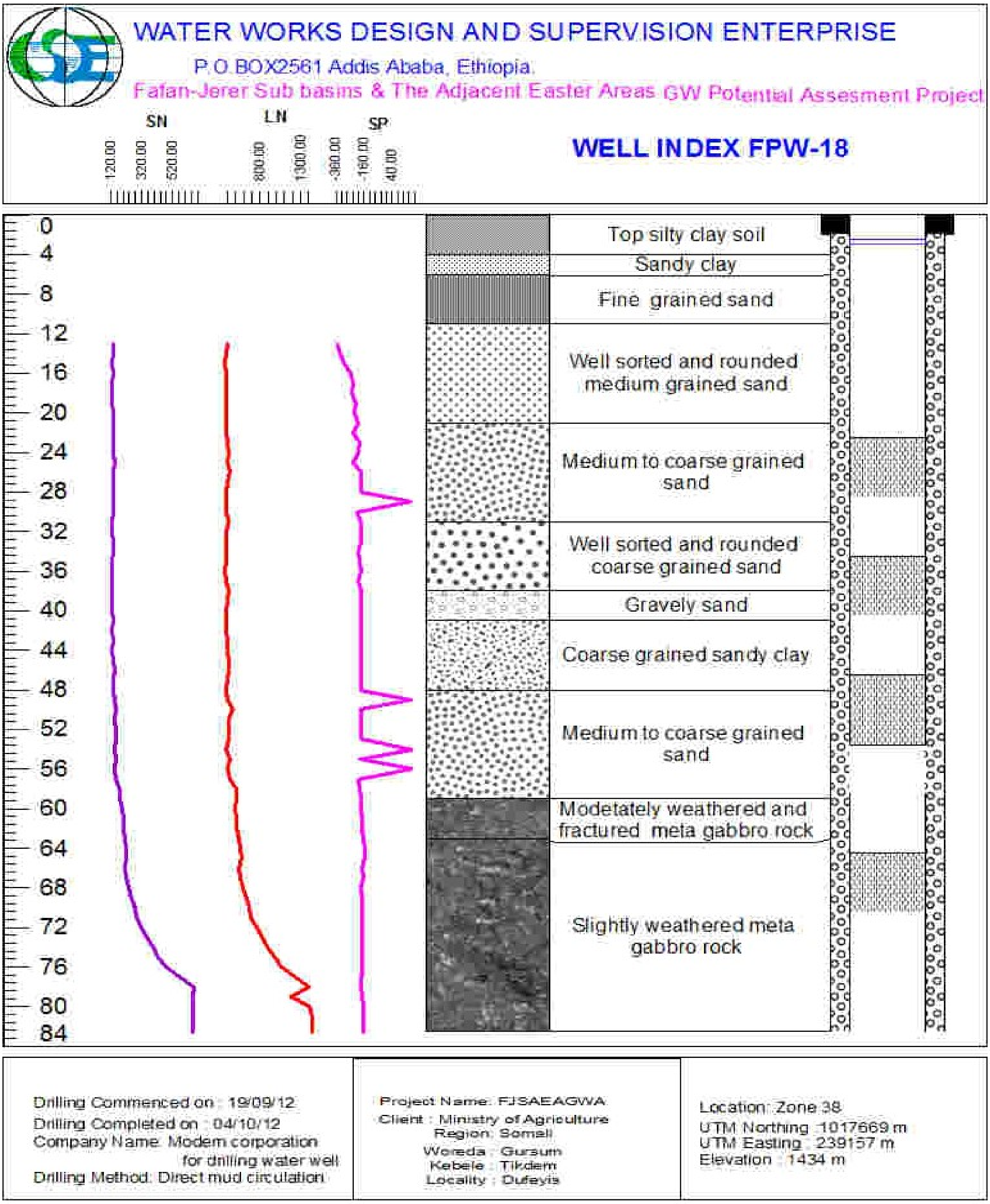

WATER WORKS DESIGN AND SUPERVISION ENTERPRISE
P.O.BOX2561 Addis Ababa, Ethiopia.
Fafan-Jerer Sub basins & The Adjacent Easter Areas GW Potential Assesment Project
WELL INDEX FPW-12'
SN
LN
SP
0.00
200.00
400.00
0.00
2000.00
4000.00
164.00
184.00
204.00
224.00
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
Silty clay soil
clay
Silty sand
Medium grained sand
Moderately weathered metagabro rock
Drilling Commenced on : 25/05/13
Drilling Completed on : 26/02/13
Company Name: Aqua Boreholes PLC
Drilling Method: Direct mud circulation
Project Name: FJSAEAGWA
Client : Ministry of Agriculture
Region: Somali
Woreda : Gursum
Kebele : Degahale
Location: Zone 38
UTM Northing :1023167 m
UTM Easting : 235950m
Elevation : 1417 m



Drilling Commenced on : 15/05/13 Drilling Completed on : 16/05/13 Company Name: Aqua Boreholes PLC Drilling Method: Direct mud circulation	Project Name: FJSAEAGWA Client : Ministry of Agriculture Region: Somali Woreda : Gursum Kebele : Batey	Location: Zone 38 UTM Northing :1020820 m UTM Easting : 238182m Elevation : 1411 m


WATER WORKS DESIGN AND SUPERVISION ENTERPRISE
P.O.BOX2561 Addis Ababa, Ethiopia.
Fafan-Jerer Sub basins & The Adjacent Easter Areas GW Potential Assesment Project
WELL INDEX FPW-18
SN
LN
SP
120.00
320.00
520.00
800.00
1300.00
-360.00
-160.00
40.00
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
Top silty clay soil
Sandy clay
Fine grained sand
Well sorted and rounded medium grained sand
Medium to coarse grained sand
Well sorted and rounded coarse grained sand
Gravely sand
Coarse grained sandy clay
Medium to coarse grained sand
Modetately weathered and fractured meta gabbro rock
Slightly weathered meta gabbro rock
Drilling Commenced on : 19/09/12
Drilling Completed on : 04/10/12
Company Name: Modern corporation for drilling water well
Drilling Method: Direct mud circulation
Project Name: FJSAEAGWA
Client : Ministry of Agriculture
Region: Somali
Woreda : Gursum
Kebele : Tikdem
Locality : Dufeyis
Location: Zone 38
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UTM Easting : 239157 m
Elevation : 1434 m

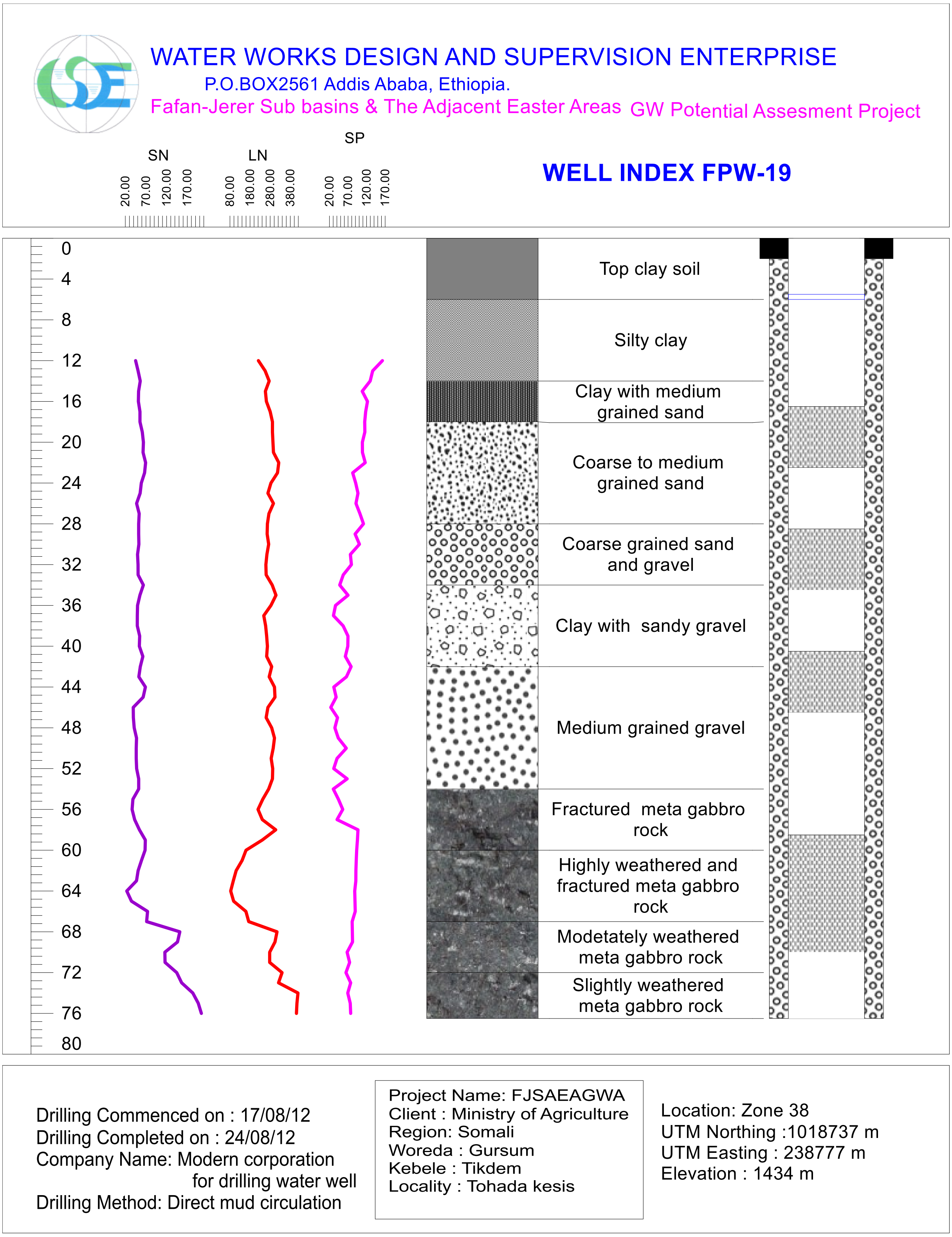

Figure E : Well Designs of the test/ pilot production wells which are ready for irrigation

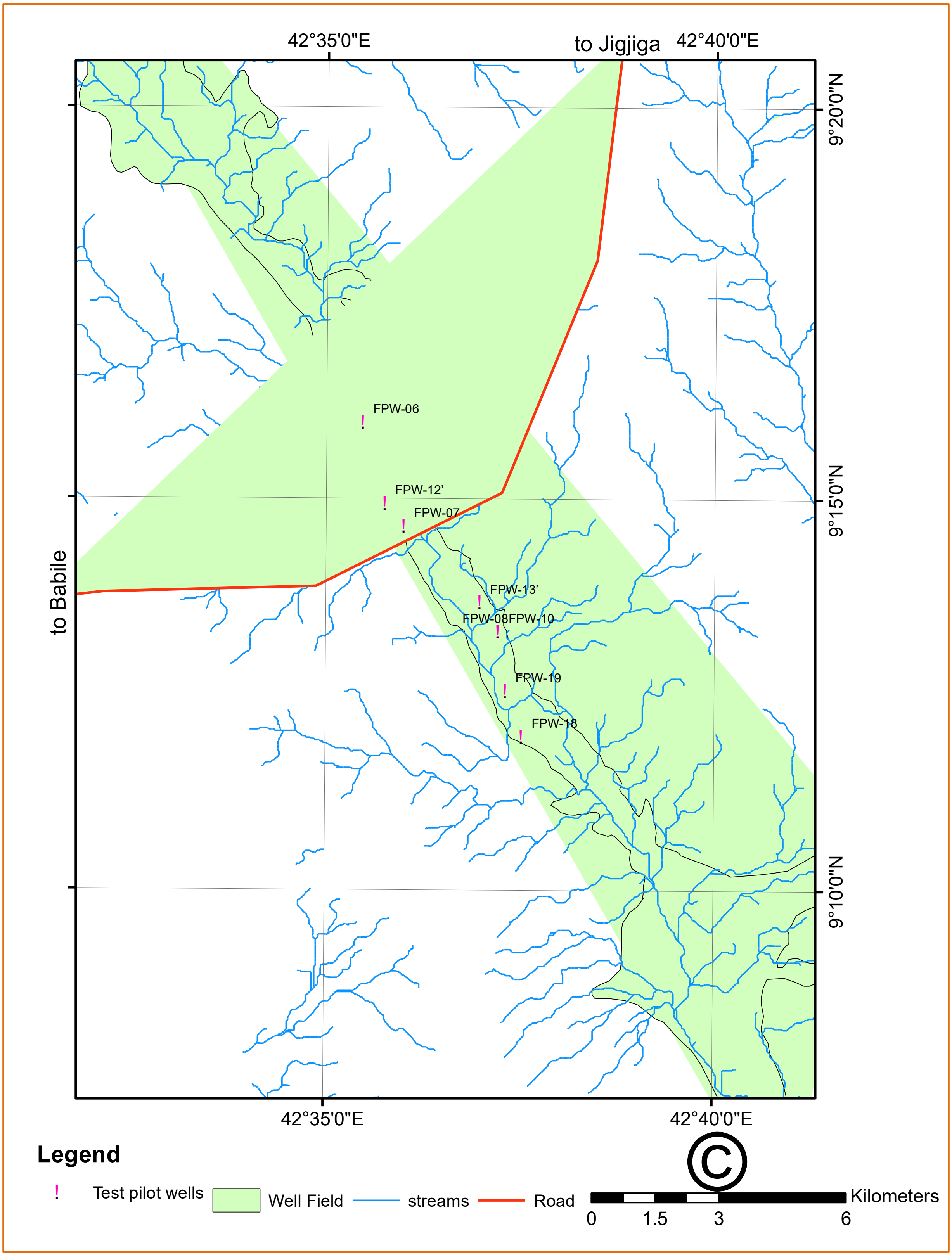

Figure F : Distribution and spacing of the test and Pilot production wells ready for irrigation in the well field of Upper Fafen Valley

SSIGL 7

Prepared by

GIRDC