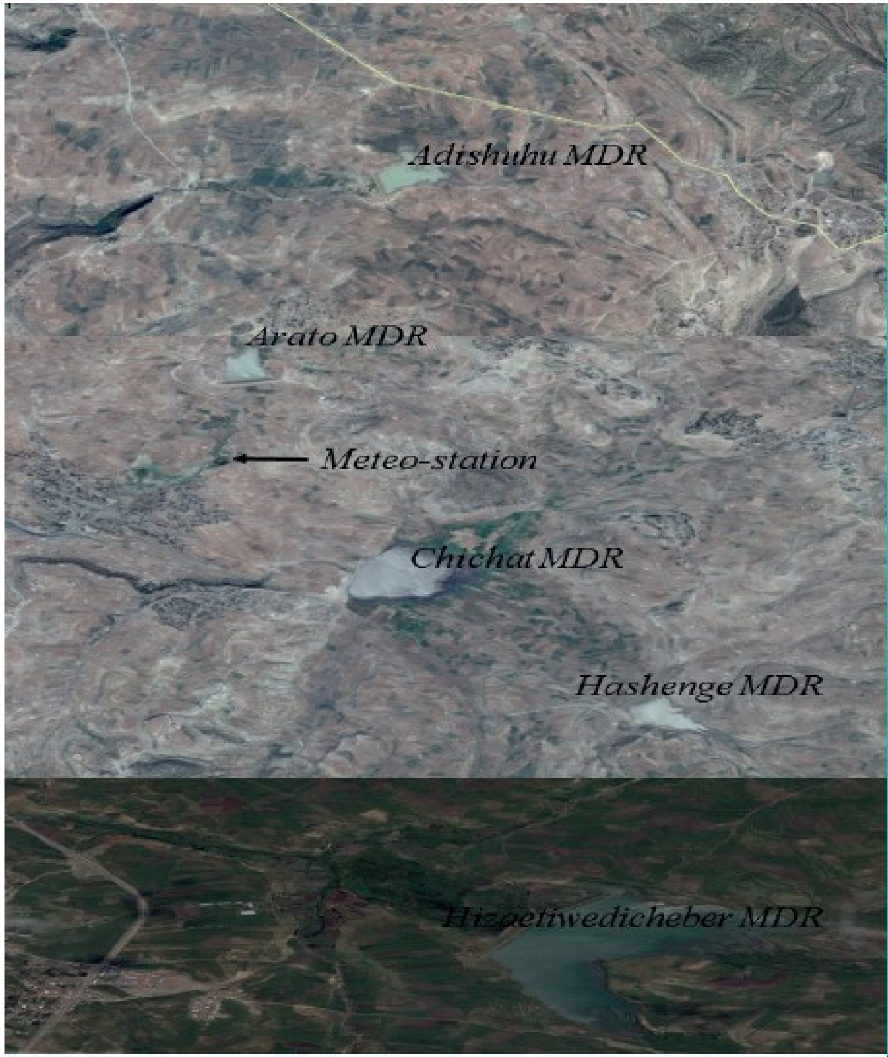

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MICRO-DAM RESERVOIR LEAKAGE AND HYDROGEOLOGICAL SETTING IN TIGRAY, NORTHERN ETHIOPIA

Ghebremedhin Berhane Reda

2016

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FACULTY OF SCIENCES
DEPARTMENT OF GEOLOGY
LABORATORY FOR APPLIED
GEOLOGY AND HYDROGEOLOGY

UNIVERSITEIT GENT

FACULTEIT WETENSCHAPPEN
VAKGROEP GEOLOGIE
LABORATORIUM VOOR TOEGEPASTE
GEOLOGIE EN HYDROGEOLOGIE

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Front cover photographs:

Arato micro-dam reservoir as background (a view from right abutment toward left abutment) and different field photos showing some of the techniques used in this study ©Gebremedhin Berhane

Back cover: *Google Earth^{TM}*

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Micro-Dam Reservoir Leakage and Hydrogeological Setting in Tigray, Northern Ethiopia

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Ghent University
Faculty of Sciences

Thesis submitted in fulfillment of the requirements for the award of Degree of Doctor (PhD) in Sciences: GEOLOGY

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DEDICATION

This PhD dissertation is dedicated:

- To my father “Melake Tsehay” Berhane Reda Abera and my mother Zewditu Tesfahun Weldu,
- To my wife Berhan Kasahun and my beloved daughters Saron, Sina and “Mitu”
- To the rest of my family members

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A work with such an extended scope is never completed in isolation. Thank you to all who contributed in one way or another toward this research output.

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Above all, I give glory to God, Father of Lord Jesus Christ, for my ability, strength and everything!

Gebremedhin Berhane
April 2016
Ghent, Belgium

SUMMARY

Water scarcity is a key factor in food security and sustainable livelihood in sub-Saharan Africa, particularly in East Africa. Reliable water supply is fundamental to human health, wellbeing, industrial development and food security. Dams for storing water for the purpose of electricity, irrigation, domestic water supply and flood control have been constructed for more than a century.

The agricultural sector in Ethiopia contributed about 52% of the country's GDP in 2001, 46% in 2006 and 47% in 2007 and accounts for about 80% of employment. The vast majority (80%) of Ethiopia's population subsists on rainfed agriculture, and thus their welfare and economic productivity are linked to the volatile and erratic rains. The rainfall regime in Ethiopia and in Tigray in particular is irregular, unreliable and unevenly distributed. There are few perennial rivers and exploitation of groundwater remains limited. Furthermore, the country is subjected to periodic extreme events of droughts and floods; this problem is very critical in the northern part of the country (Tigray, Afar and Amhara regions). Limiting the consequences of recurring droughts has always been high on the development agenda of the government and has notably underpinned considerable investments in hundreds of small ponds, diversion weirs, Micro-dam reservoirs (MDRs), etc. that support livelihood including water use in agriculture, for livestock and domestic use. Construction of MDRs in Ethiopia started in the late seventies to combat drought and increase food security. However, the construction of dams increased in recent years. Over the last 20 to 30 years, about 92 dams were constructed in Tigray region. Despite the various socio-economic benefits and livelihood impacts, many of the dams found in Tigray have many threatening problems affecting their sustainability. Worrying is the fact that the construction of MDRs is continuing without being supported by research. Many scholars conducted investigations on some of the problems, like sedimentation, hydrology, ecology and health, but none or very limited research has been conducted related to leakage problems of the MDRs.

The subject of this PhD dissertation is to evaluate the MDRs in Tigray in the context of their engineering and geo-hydrological problems in general and to study in detail the mechanisms and causes of leakage on selected MDRs. From an inventory of 92 MDRs during the period of field survey (2012/13), 56 (61%) have siltation problem, 49 (53%) leakage, 23 (25%) structural dam body damage, 21 (23%) inflow problem and 19 (21%) have spillway route erosion. The main problems highlighted, siltation and leakage, are found to be highly linked to geological factors. These problems are found to be very high in MDRs located in sedimentary rocks. Siltation is found to be more significant in areas where shale is the dominant rock type; on the other hand leakage is more common in areas where limestone predominates.

The available hydrogeological information and integrated studies concerning the limestone-shale-marl intercalation unit confirm it to be the main water bearing formation in the area in the form of a multi-layer aquifer system and responsible for leakage problems of most MDRs in the study area. This conclusion was verified using geological, geotechnical, geo-hydrological, hydrogeochemical, geophysical and water balance techniques. The limestone-shale-marl intercalation unit at all study sites was found to be leaky using field observation and in-situ (packer) tests at selected sites. The field observations and packer test results on this unit at different sites were in harmony. The dolerite unit on the other hand acts as aquitard/aquiclude at almost all considered sites where dolerite exists (Hashenge and Arato MDRs). Yet, the dolerite unit has an impact on the hydraulic conductivity of the limestone-shale-marl intercalation unit and other rock units along its contact due to the baking effect during the time of intrusion. This is an important feature that should be taken into account during site investigation for any water harvesting structures and groundwater exploration in the area and other regions with similar geological settings.

The groundwater recharge for Arato MDR catchment was estimated using different approaches. The natural annual recharge was estimated at 104 mm, 92.8 mm and 100 mm using Soil Moisture Balance (SMB), Chloride Mass Balance (CMB) and Water Table Fluctuation (WTF) methods, corresponding to some 1.41×10^{6} m^{3}. The annual runoff was estimated using the SCS-Curve Number (CN) and water balance approaches. The result from SCS-CN was about 0.71×10^{6} m^{3}, while from the water balance approach based on diver data logger, it was about 0.64×10^{6} m^{3}. It was possible to estimate the leakage from the reservoir, using the water balance model approach, for the observed first part of the dry period, to be 13.2 mm/day or 112,300 m^{3} for the 83 days of observed dry period (1353 m^{3}/day).

Future planning, design and construction of MDRs in the area shall be based on sound understanding of the geomorphology/topography, geology, geo-hydrology and engineering geology of the site. Manual or automatic sensors are recommended for further monitoring of the leakage rate and reservoir and groundwater levels. These long-term data could be used to validate the study over a longer period.

A proposed large water supply dam, Geba, with detailed surface and subsurface data (mapping, drilling, pressure tests, and laboratory tests) was investigated and the data were interpreted. The results were compared with the conclusions drawn from post-construction investigations of four leaking MDRs with limited or no drilling, pressure tests and laboratory tests. Conclusions were comparable, and we could thus identify the minimum study requirements for a conclusive site-assessment for MDR, prior to construction. By considering this as a baseline, a practical engineering geological approach is proposed for MDRs for the area. The approach gives more weight to geology and geomorphology before proceeding to selected drilling and other expensive subsurface investigation techniques.

According to the proposed approach detailed geomorphological, lithological and discontinuity mapping along with electrical resistivity prospection and test pits, etc. are recommended during the initial preliminary investigation phase which result in a conceptual engineering geological model. This is followed by the main site investigation and design phase with higher resolution geophysical investigation and/or selected geotechnical drilling and in-situ tests. These observations allow to update the conceptual engineering geological model. The updated model can be used as a base for the design of the MDR. The proposed approach implies that monitoring should continue during and after construction, to validate the conclusions drawn at design phase and to obtain feedback to update the approach.

SAMENVATTING

Waterschaarste is een bepalende factor inzake voedselzekerheid en duurzame leefbaarheid in sub-Sahara Afrika, vooral in Oost-Afrika. Betrouwbare watervoorziening is onontbeerlijk voor de menselijke gezondheid en welzijn, industriële ontwikkeling en voedselzekerheid. Stuwdammen voor wateropslag ten behoeve van elektriciteitsproductie, irrigatie, huishoudelijke watervoorziening en beheersing van overstromingen worden al meer dan een eeuw gebouwd.

De landbouwsector in Ethiopië vertegenwoordigde ongeveer 52% van het BNP in 2001, 46% in 2006 en 47% in 2007, en is verantwoordelijk voor 80% van de tewerkstelling. De overgrote meerderheid (80%) van de bevolking van Ethiopië leeft van regenwater-afhankelijke landbouw, en hun welvaart en economische productiviteit zijn dus verbonden aan de onvoorspelbare en onregelmatige neerslag. Het neerslagregime in Ethiopië en in Tigray in het bijzonder is onregelmatig, onbetrouwbaar en ongelijk verdeeld. Er zijn weinig permanente rivieren en grondwaterexploitatie blijft beperkt. Bovendien is het land onderworpen aan periodieke extreme droogtes en overstromingen; dit probleem is uiterst kritiek in het noordelijk gedeelte van het land (Tigray, Afar en Amhara regio's). Het beperken van de gevolgen van de weerkerende droogtes heeft altijd hoog op de ontwikkelingsagenda van de overheid gestaan, en dit heeft geleid tot aanzienlijke investeringen in honderden kleine wateropslagvijvers, aftappingen van oppervlaktewater, microdam reservoirs (MDRs), enz., die de leefbaarheid en het watergebruik in de landbouw ondersteunen, voor gebruik door de mens en de veestapel.

De bouw van MDRs in Ethiopië begon in de late jaren 1970 om de droogte te bestrijden en de voedselzekerheid te verhogen. Maar de bouw van MDRs is sterk toegenomen in recente jaren. Tijdens de laatste 20 tot 30 jaar werden ongeveer 92 MDRs gebouwd in Tigray. Ondanks de belangrijke socio-economische voordelen en impact op de leefbaarheid, zijn er vele van deze stuwdammen die kampen met ernstige problemen die hun duurzaamheid bedreigen. Zorgwekkend is het feit dat de bouw van MDRs doorgaat zonder te zijn ondersteund door voorafgaand onderzoek. Vele onderzoekers hebben studies uitgevoerd over de vastgestelde problemen, zoals sedimentafzetting, hydrologie, ecologie en gezondheid, maar weinig of geen onderzoek werd doorgevoerd over het probleem van lekkage van de MDRs.

Het onderwerp van deze PhD verhandeling is de MDRs in Tigray te evalueren in de context van hun ingenieurs- en geohydrologische problemen in het algemeen, en geselecteerde MDRs in detail te bestuderen aangaande de mechanismen en oorzaken van lekkage. Van de inventaris van 92 MDRs opgemaakt tijdens het terreinonderzoek (2012/2013), vertonen er 56 (61%) een sedimentatieprobleem, 49 (53%) lekken, 23 (25%) hebben een structureel probleem van schade aan het damlichaam, 21 (23%) vertonen een probleem van onvoldoende instroming en 19 (21%) vertonen erosie aan de overlaat. De belangrijkste problemen, sedimentatie en lekkage, zijn duidelijk gekoppeld aan geologische factoren. Deze problemen zijn heel groot in MDRs in sedimentaire gesteenten. Het sedimentatieprobleem is belangrijker in gebieden waar kleisteen het dominant gesteentetype vormt, terwijl lekkage meer algemeen is in gebieden waar kalksteen overheerst.

De beschikbare hydrogeologische informatie en geïntegreerde studies betreffende de kalksteen-kleisteen-mergel intercalatie-eenheid bevestigen dat dit de belangrijkste watervoerende formatie is in het gebied en een meerlagig aquifersysteem vormt, en verantwoordelijk is voor het lekkageprobleem van de meeste MDRs in het studiegebied. Dit besluit werd geverifieerd met geologische, geotechnische, geohydrologische, hydrogeochemische, geofysische en waterbalans-technieken. De kalksteen-kleisteen-mergel intercalatie-eenheid werd op alle bestudeerde sites als lekkend bevonden, aan de hand van terreinwaarnemingen en in-situ (packer) tests op geselecteerde sites. De veldwaarnemingen en packer test resultaten voor deze eenheid stemden overeen op de verschillende sites. De doleriet eenheid, anderzijds, gedraagt zich als een aquitard/aquiclude op bijna alle beschouwde sites waar doleriet aanwezig is (Hashenge en Arato). Nochtans heeft deze doleriet eenheid een impact op de hydraulische doorlatendheid van de kalksteen-kleisteen-mergel intercalatie-eenheid en andere gesteenten, door zijn verstorend effect op het moment van de intrusie. Dit is een belangrijk kenmerk dat in aanmerking moet worden genomen bij site-onderzoek voor wateropvangstructuren en grondwaterverkenning in het gebied en in andere gebieden met vergelijkbare geologische gesteldheid.

De grondwatervoeding van het bekken waarin Arato MDR zich bevindt, werd ingeschat met verschillende methodes. De jaarlijkse natuurlijke voeding werd begroot op 104 mm, 92.8 mm en 100 mm respectievelijk aan de hand van de bodemvochtbalansmethode, de chloride-massabalansmethode en de watertafel-fluctuatiemethode, overeenstemmend met zowat 1.41 x 10^6 m^3. De jaarlijkse runoff werd ingeschat met de SCS Curve Number methode en de waterbalans-benadering. Het resultaat met SCS-CN was 0.71 x 10^6 m^3, terwijl de waterbalans-benadering op basis van diver datalogger-gegevens, 0.64 x 10^6 m^3 opleverde. De lek vanuit het reservoir kon met de waterbalans-methode worden afgeleid voor het opgemeten eerste deel van de droge periode, en bedraagt 13.2 mm/dag of 112.300 m^3 voor de 83 dagen die opgemeten werden van de droge periode (1353 m^3/dag).

Toekomstige planning, ontwerp en constructie van MDRs in het gebied zou moeten gebaseerd zijn op grondig begrip van de geomorfologie/topografie, geologie, geohydrologie en ingenieursgeologie van de site. Manuele of automatische sensoren worden aanbevolen voor verdere monitoring van de lekhoeveelheden en waterniveaus in reservoir en grondwater. Deze lange-termijn gegevens kunnen gebruikt worden om de studie te valideren over een langere periode.

Een geplande grote stuwdam, Geba dam, waarvan gedetailleerde oppervlakkige en ondergrondse gegevens (kartering, boringen, druktesten, laboratoriumtesten) beschikbaar zijn, werd onderzocht en de gegevens geïnterpreteerd. De resultaten werden vergeleken met de besluiten getrokken uit onze (post-constructie) studies van vier lekkende MDRs met beperkte of geen boringen, drukproeven en laboratoriumtesten. De besluiten waren vergelijkbaar, en we konden dus de minimale onderzoeksvereisten definiëren, nodig voor een degelijke site-beoordeling voor een MDR, die voor de aanleg zou moeten worden uitgevoerd. Steunend op deze basis kon een praktische ingenieur-geologische benadering worden voorgesteld voor MDRs in het gebied. Deze benadering legt meer de nadruk op de geologie en geomorfologie alvorens over te gaan tot selectief boren en andere dure onderzoekstechnieken van de ondergrond.

Volgens de voorgestelde benadering wordt gedetailleerde geomorfologische, lithologische en discontinuïteitskartering voorgesteld, samen met verkennende elektrische resistiviteitsprospectie en testputten, enz., tijdens de initiële fase van verkennend onderzoek, die moet resulteren in het conceptueel ingenieur-geologisch model. Dit moet gevolgd worden door de hoofdfase van site-onderzoek en ontwerp, met hogere-resolutie geofysisch onderzoek en/of geselecteerde geotechnische boringen en in-situ proeven. Deze observaties moeten toelaten het conceptueel ingenieur-geologisch model te updaten. Het bijgestelde model zal gebruikt worden als basis voor het ontwerp van het MDR. De voorgestelde benadering gaat ervan uit dat de monitoring wordt voortgezet gedurende en na de bouw, om de besluiten getrokken bij de ontwerpfase te valideren, en de feedback te gebruiken om de benadering te updaten.

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μ: kinematic viscosity of water

λ: dimensionless parameter

ρ_a: apparent resistivity

ΔV_R: change in Volume of water in Reservoir

ΔSW: change in soil water storage

ΔV: electric Potential difference between electrodes

ΔWL_R: change/variation in Reservoir Water Level

A and B: designation for Current Electrodes in electrical resistivity survey

a: separation between each pair of successive electrodes in Wenner array

Ac: Area of catchment

AET: Actual Evapotranspiration

AP: Arato electrical Profile

APWL: Accumulated Potential Water Loss

A_R: Average Reservoir Area

A_{Rf}: Reservoir Area at final time

A_{Ri}: Reservoir Area at initial time

ASHDW/AHDW: Arato Shallow Hand Dug Well

ASP: AdiShuhu electrical resistivity Profile

ASTM: American Society for Testing and Materials

AS-VES: Adishuhu-Vertical Electrical Sounding

BH: Borehole

BoFED: Bureau of Finance and Economic Development of Tigray

CIGR: International Commission of Agricultural Engineering (Commission Internationale du Génie Rural)

Cl_{gw}: constant Chloride concentration of groundwater

Cl_P: Chloride concentration of precipitation

CMB: Chloride Mass Balance

CN: Curve Number

CoSAERT: Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray

CSA: Central Statistics Agency of Ethiopia

D:	Depth for vertical BH, but for inclined or near hill sides=minimum lateral coverage
DCG:	Drylands Coordination Group
DEM:	Digital Elevation Model
e:	average joint aperture
EMA:	Ethiopian Mapping Agency
ER:	Evaporation loss from reservoir
ERP:	Electrical Resistivity Profile
ETo:	Reference Evapotranspiration
E-W:	East-West
FAO:	Food and Agricultural Organization of the United Nations
FC:	Field Capacity
FEMA:	United States Federal Emergency Management Agency
g:	gravitational acceleration
GDP:	Gross Domestic Product
GPS:	Geographic Position System
GSE:	Geological Survey of Ethiopia
GWP:	Global Water Partnership
h:	water-table height (change in water level)
HWC:	Hizaetiwedicheber
HWCP:	Hizaetiwedicheber electrical resistivity Profile
HWC-VES:	Hizaetiwedicheber-Vertical Electrical Sounding
I:	Electric current injected into the ground through current electrodes
I_a:	Initial abstraction
IAEG:	International Association for Engineering Geology and the Environment
ICOLD:	International Commission on Large Dams
ISRM:	International Society for Rock Mechanics
IWMI:	International Water Management Institute
EIGS:	Ethiopian Institute of Geological Survey
ILRI:	International Livestock Research Institute
J:	Joint
k:	geometric factor in resistivity survey
K:	Hydraulic Conductivity
L:	separation between current electrodes in resistivity survey

l:	Separation between potential electrodes (for Schlumberger array)
L:	test section of a borehole in Lugeon test
Leak:	water loss due to Leakage
Live:	Livestock water consumption
LL:	Liquid Limit,
LU:	Lugeon Unit/value
M and N:	designation for Potential Electrodes in electrical resistivity survey
MDR:	Micro-Dam Reservoir
MoWR:	Ministry of Water Resources of Ethiopia
NBCBN-RE:	Nile Basin Capacity Building Network-River Engineering
NE-SW:	North East-South West
NNE-SSE:	North North East-South South East
NP:	Non-Plastic
N-S:	North-South
NW-SE:	North West-South East
ODNR:	Ohio Department of Natural Resources
Out:	water released through Outlet
P:	Precipitation or rainfall
P_A:	Atmospheric Pressure (
PAW:	Plant Available Water
P_{eff}:	Effective Precipitation
PI:	Plasticity Index,
PL:	Plastic Limit
P_{MAX}:	Maximum Pressure in Lugeon test
P_P:	Water Pressure in Packer/Lugeon test
PR:	direct Rainfall on Reservoir water surface
P_{ucs}:	Maximum axial load applied in a rock speciemen
P_{rise}:	Cumulative Rainfall responsible for groundwater level rise at ASHDW till it overflows
P_T:	Total Pressure (in water level sensor measurement)
P_w:	Water Pressure (in water level sensor measurement)
PWP:	Water content at Permanent Wilting Point
q:	flow rate or intake in water pressure/Lugeon test
RQD:	Rock Quality Designation

RC:	Runoff Coefficient
RMS:	Root Mean Square error
Rech:	Groundwater Recharge/deep drainage
REST:	Relief Society of Tigray
RI:	direct Input on Reservoir surface
RO:	Runoff
S:	average Spacing of joint
S:	Potential maximum retention
SCS-CN:	Soil Conservation Service-Curve Number
SHDW:	Shallow Hand Dug Well
SHW:	Shallow Well
SI:	Saturation Index
SMB:	Soil Moisture Balance
Spill:	water released through Spillway
SRTM:	Shuttle Radar Topography Mission
S_y:	Specific yield
t:	time
TBoARD:	Tigray Bureau of Agriculture and Rural Development
TNRS:	Tigray National Regional State
T_{out}:	Outlet operation time (days or hours)
T_{total}:	Total number of days (observation period)
TR:	Trench (shallow hand dug)
TP:	Test Pit (shallow hand dug)
TWRDB:	Tigray Water Resource Development Bureau
TWRMEB:	Tigray Water Resources, Mines and Energy Bureau
TWWCE:	Tigray Water Works Construction Enterprise
UK:	United Kingdom
UNESCO:	United Nations Educational, Scientific and Cultural Organization
UNEP:	United Nations Environment Protection
UNPD:	United Nations Population Division
UNICEF:	United Nations Children's Emergency Fund
USCS:	Unified Soil Classification System
UCS:	Unconfined Compressive Strength
USA:	United States of America

USDA: United States Department of Agriculture

USGS: United States Geological Survey

USSD: United States Society of Dams

UTM: Universal Transverse Mercator

VES: Vertical Electrical Soundings,

V_{Rf}: Reservoir Volume at final time

V_{Ri}: Reservoir Volume at initial time

WCD: World Commission on Dams

WHO: World Health Organization

WHS: Water Harvesting Structures

WIC: Walta Information Centre

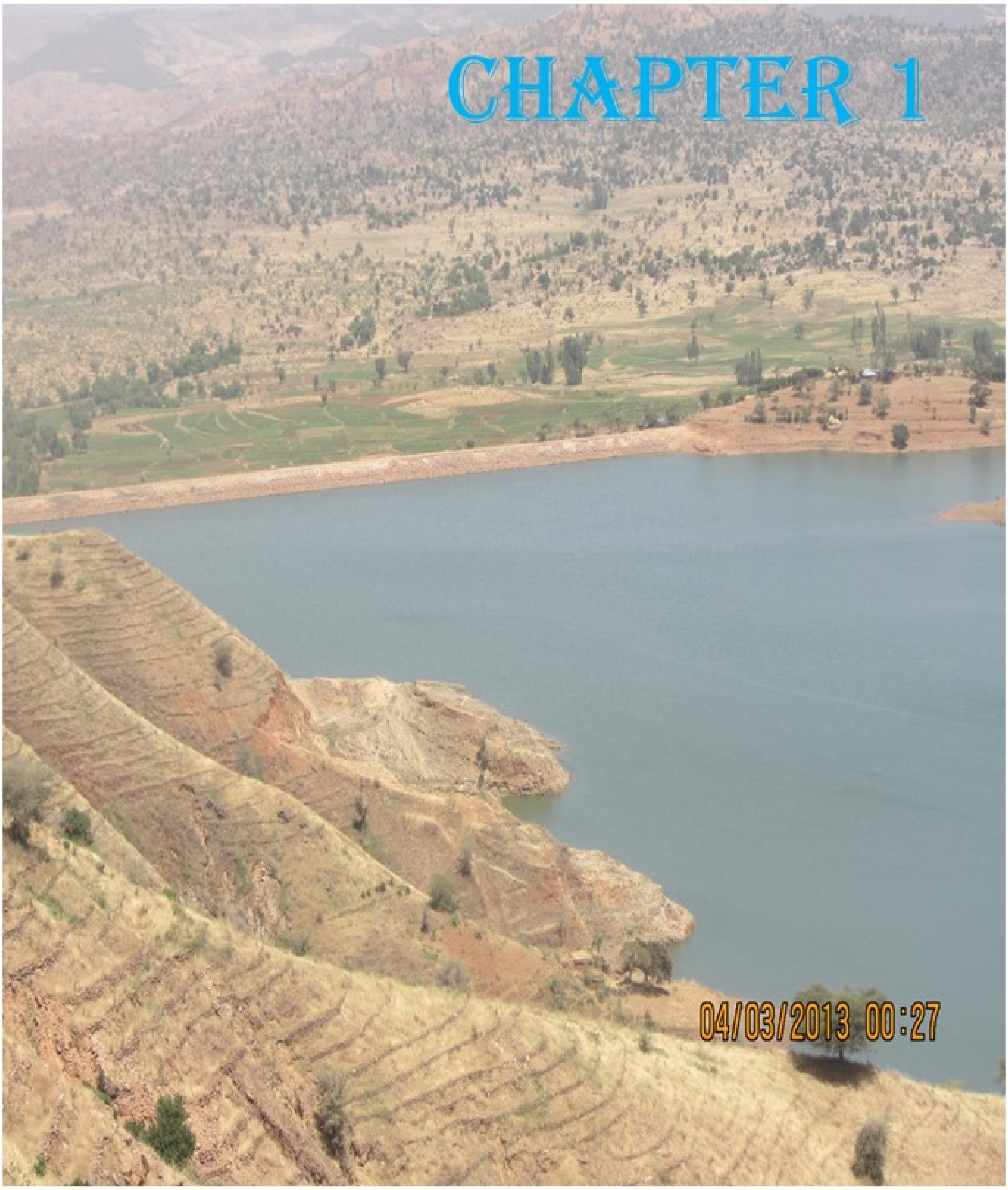
WNW-ESE: West North West-East South East

WSDP: Water Sector Development Program

WTF: Water Table Fluctuation

WWAP: United Nations World Water Development Report

WWDSE: Water Works Design and Supervision Enterprise



Mai-Demu MDR (411770 mE, 1561110 mN): one of the successful reservoirs (but spillway route was failed/eroded and maintained), currently under utilization for Shire-Endaselassie town. The author was part of the study and design team at identification and reconnaissance phases @2013 Gebremedhin Berhane

CHAPTER 1

General introduction

BACKGROUND

Ethiopia is one of the largest countries in Africa, having the second largest population in Sub-Saharan Africa (SSA) with a population of about 94 Million (United Nations, 2012; Central Statistical Agency (CSA), 2007), covering a land area of about 1.13 million km^2 and lies in the northeastern part of the Horn of Africa (HA) (Fig. 1.1). It is located in the tropics between 3° N and 18° N latitude; and 33° E and 48° E longitude. Ethiopia's topographical diversity encompasses high and rugged mountains, flat-topped plateaus, and deep gorges with rivers and rolling plains with altitudes ranging from 120 m below sea level at the Danakil Depression in the northeast to over 4,650 m above sea level in the Simien Mountains in the north (Cherent, 1993; FAO, 2005).

Water is one of the highly valuable natural resources and its importance for the existence of life has always been recognized by mankind. Globally, water is an increasingly scarce resource requiring careful economic and environmental planning and management. In developing countries the situation is exacerbated by rapid population growth, land degradation/erosion and urbanization. The demand for water for domestic use, agriculture and industry has escalated and is being escalating (World Bank, 2000).

Water has always played a central role in Ethiopian society. Water plays the central role for sustainable development including industry, irrigation for crop production, health, etc. A safe, adequate and accessible water supply is a prerequisite for socio-economic development. It is an input, to a greater or lesser extent, to almost all production. It is also a force for destruction. In

Ethiopia, as in all societies, there has always been a struggle to reduce the destructive impacts of water and increase its productive impacts. This struggle has intensified over the past century as the population has grown dramatically and the government aspires to reach middle income status over the next decade (http://www.worldbank.org/en/country/ethiopia/overview). Today, Ethiopia's development is seriously constrained by a complex water resources legacy and a lack of access to, and management of, these water resources (World Bank, 2006). Agriculture is often hampered by the lack of easily accessible water resources, low rainfall and often unpredictable rainfall patterns.

The economy has experienced strong and broad based growth over the past decade, averaging 10.7% per year in 2004/05−2011/12 compared to the regional average of 4.9%. Ethiopia was the 12th fastest growing economy worldwide in 2012 and managed to grow faster than African countries such as Rwanda, Mozambique, Zambia, and Ghana, as well as China and India (World Bank, 2013a, b).

The country has a vast hydrological potential, having a long rainy season in most parts between July and October, and a shorter rainy season between April and May. The surface water resource potential is impressive, but little developed (FAO, 2005). Thus, with proper management, the water supply should be sufficient throughout the year. The country possesses twelve major river basins (Fig. 1. 2) and 22 lakes, which form four major drainage systems (Nile, Rift Valley, Shebelle−Juba and North-East Coast). The annual runoff from these Ethiopian river basins is about 122 billion cubic meters (Table 1.1). Renewable groundwater resources are estimated to be about 2.6 billion cubic meters per year (MoWR, 2002a). Although less than 2 percent of these resources are diverted for use, the current estimated per capita renewable freshwater resource of 1,900 cubic meters per year (MoWR, 2002b) indicates an abundance of water (World Bank,

2006) compared to the resources currently utilized or no stress, but close to the threshold value (1,700 m^3 per year) of Falkmark water stress index (Falkenmark, 1989).

Figure 1.1. Location map of Ethiopia and East Africa (modified from http://www.Worldatlas .com/ and , accessed/visited on 25/03/2016). Nile Basin water divide is shown in red line.

Irrigation is one means by which agricultural production can be increased to meet the growing food demand in Ethiopia (Awulachew *et al*., 2005). However, irrigated production is far from satisfactory (Woldeab, 2003). While the country's irrigation potential is about 3.7 million hectares (WSDP, 2002), the total irrigated area was 190,000 ha in 2004, which was only 4.3% of the potential (FAO, 2005).

It was claimed that Ethiopia cannot assure food security for its population with rain fed agriculture alone without a substantive contribution of irrigation. Thus, the government of Ethiopia has prepared a water sector development program to be implemented in 15 years between 2002 and 2016. This program assigned a prominent role to the development of irrigation in the country for food production (MoWR, 2001). Hence, construction of water harvesting schemes (Micro-Dam Reservoirs (MDRs), ponds, diversions, etc.) is one intervention area to intensify and increase irrigation practice.

Water harvesting has been used for thousands of years to supplement scarce water resources in moisture deficit or dry areas (Sharma and Baranwal, 2005; Watanabe *et al*., 2012). Millions of people throughout the world depend on dam reservoirs for domestic water supply. Construction of MDRs in Ethiopia started in the late seventies to combat the recurrent drought in the country (Tiruneh, 2005). Construction of MDRs by the Cuban engineering team had been carried out from 1978-1982 after the agreement made on the collaboration between the Ethiopian and the Cuban Governments, started just after the visit made by the Cuban President Fidel Castro Ruz to Ethiopia in September 1978. The dams were constructed by the team that had been working together with Ethiopian experts from the Water Resource Authority. During their stay in Ethiopia, they studied, designed and constructed four micro-dams. These are, Belbela, Wedecha, Tolly and Chichat dam. The first three are in the Awash River basin and the fourth one is in the Tekeze River basin (Michael, 2004).

Table 1.1. Area and annual runoff by river basin in Ethiopia (FAO, 2005).

Major drainage system	River basin	Area[1] (ha)	As % of total area (%)	Annual runoff (km^3/yr)	As % of total runoff (%)
Nile Basin (Ethiopia)		**36, 881,200**	**32.4**	**84.55**	**69.0**
	Abbay (Blue Nile)	19,981,200	17.6	52.60	42.9
	Baro-Akobo	7,410,000	6.5	23.60	19.3
	Setit-Tekeze/Atbara	8,900,000	7.8	7.63	6.2
	Mereb	590,000	0.5	0.72	0.6
Rift Valley		**31,764,000**	**27.9**	**29.02**	**23.7**
	Awash	11,270,000	9.9	4.60	3.7
	Danakil	7,400,000	6.5	0.86	0.7
	Omo-Gibe	7,820,000	6.9	17.96	14.7
	Central/Rift Lakes	5,274,000	4.6	5.60	4.6
Shebelle-Juba		**37,126,400**	**32.7**	**8.95**	**7.3**
	Wabi-Shebelle	20,021,400	17.6	3.15	2.6
	Genale-Dawa	17,105,000	15.1	5.80	4.7
North East Coast		**7,930,000**	**7.0**	**0.00**	**0.0**
	Ogaden	7,710,000	6.8	0.00	0.0
	Aysha/Gulf of Aden	220,000	0.2	0.00	0.0
Total		**113,701, 600**	**100.0**	**122.52**	**100.0**

[1] The areas are estimates and the total area is slightly different from the total area of the country.

The need to conserve water resources through technologies has resulted in the use of small earth micro-dams, constructed by the local governments, non-governments and local communities themselves, as sources of water supply for the development of irrigated agriculture, domestic use and water livestock. However, it should be pointed out at the outset that the development of micro-dams for different uses is being threatened by (1) sedimentation problems arising from the degradation of catchment areas shown by four pressure indicators namely agricultural production, rapid population growth, poverty and wood energy demands, (2) inappropriate runoff estimation methods resulting in over sizing or under-sizing of dams, and (3) excess leakage through mainly foundation, abutment and sometimes through the dam body itself.

In the last two to three decades 92 MDRs have been constructed in northern Ethiopia to be used for irrigation and water supply purposes. Most of them were designed under inadequate, a non existent hydrological and geological data condition. For example their stream flows or tributary flows were not gauged and lack detailed geological and engineering geological data.

Consequently, some of the reservoirs failed to deliver the design yields. Some of them filled-up in few years with sediments and some failed due to excessive leakage.

A systematic study on existing MDRs that have been successful and failed and their causes of success and failure has not been performed. This study addresses this research gap by first inventorizing existing MDRs in Tigray National Regional State. This was followed with assessment and analysis of the conditions of the inventorized MDRs. Furthermore, analyses were made on the assessed data to identify problem areas and detailed investigations were carried out at the selected MDRs.

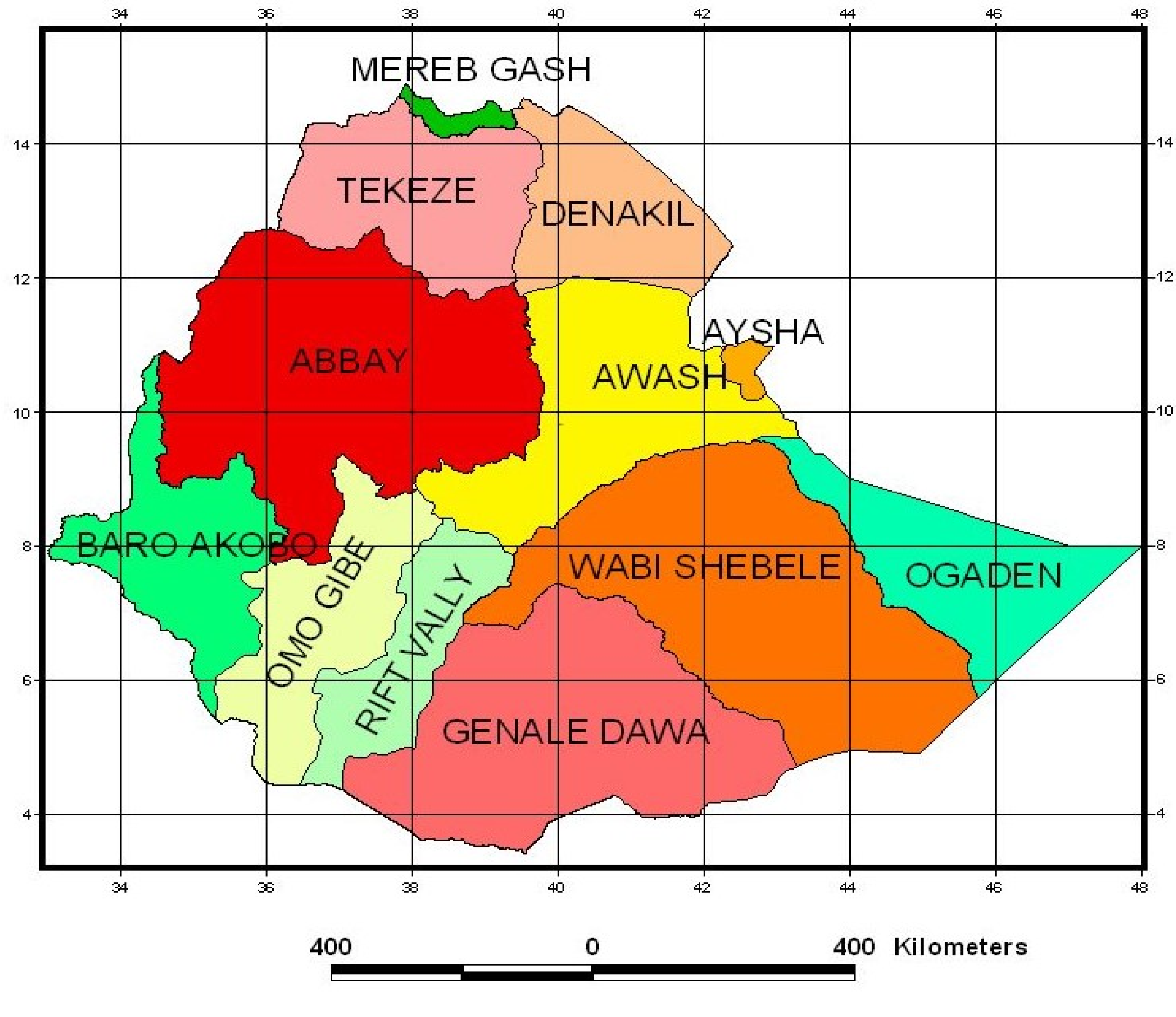


Figure 1. 2. Figure 1.2. River basins of Ethiopia (Source: Ministry of Water Resources of Ethiopia). Latitudes and longitudes are in degrees.

CLIMATE AND GEOLOGY

Climate

The fact that Ethiopia is located in the tropics, latitude 3° N to 18° N, combined with the high range of altitude, -120 m to +4650 m, and the pressure and air flow pattern determine the tremendous differences in climate which prevail in different parts of the country (Cherent, 1993).

Ethiopia has a tropical monsoon climate with wide topographic-induced variation. Three climatic zones can be distinguished: a cool zone consisting of the central parts of the western and eastern section of the high plateaus (above 2,400 m above sea level), a temperate zone between 1,500 m and 2,400 m, and the hot lowlands below 1,500 m. Mean annual temperature varies from less than 7−12ºC in the cool zone to over 25ºC in the hot lowlands (Fig. 1.3). Mean annual potential evapotranspiration varies between 1,700−2,600 mm in arid and semi-arid areas and 1,600−2,100 mm in dry sub-humid areas. Average annual rainfall for the country is 848 mm, varying from about 2,000 mm over some pocket areas in southwest Ethiopia to less than 100 mm over the Afar lowlands in the northeast (Fig. 1.4). Rainfall in Ethiopia is highly erratic, and most rain falls intensively, often as convective storms, with very high rainfall intensity and extreme spatial and temporal variability. The result is that there is a very high risk of annual droughts and intra-seasonal dry spells (FAO, 2005).

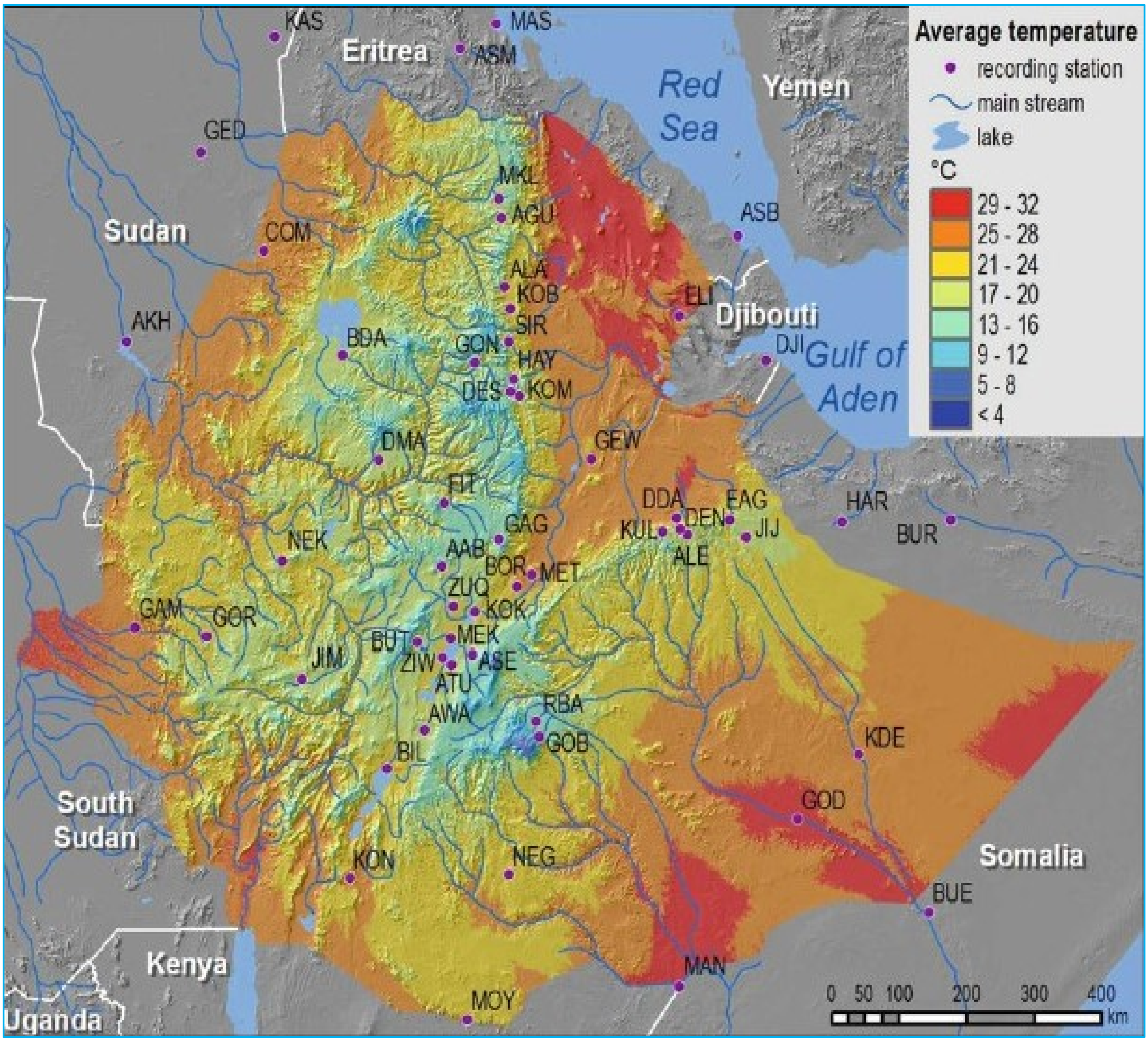


Figure 1.3. Mean annual temperatures over Ethiopia (Fazzini *et al*., 2015).

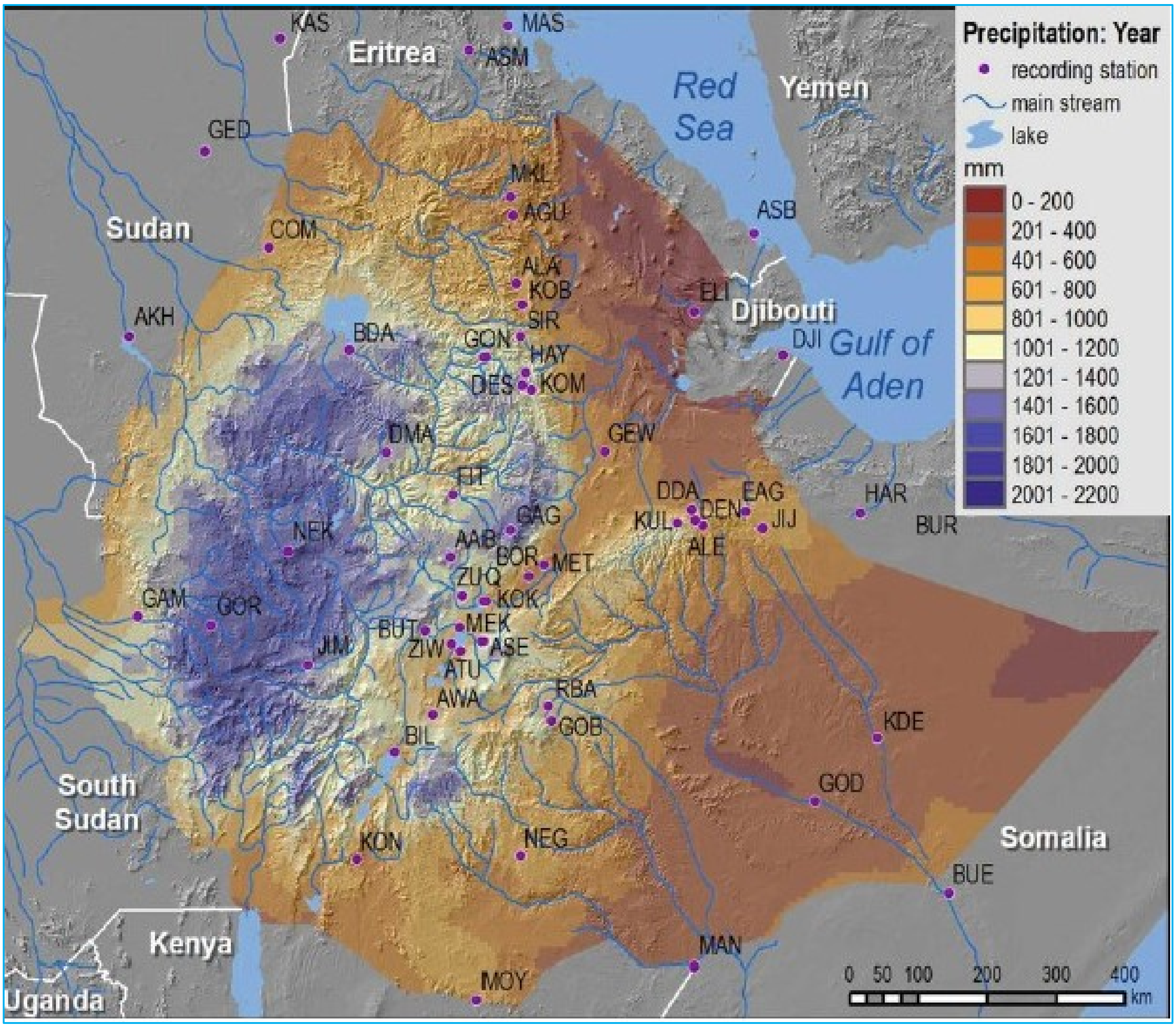


Figure 1.4. Distribution of annual precipitation (Fazzini *et al*., 2015).

Geology and hydrogeology

Ethiopia is located at the northern end of the East African Rift System and is characterized by a wide variety of landscapes and landforms (Billi, 2015) with elevated and flat-topped plateaus and deeply incised valleys. These contrasting features were developed by a complex of tectonic, erosive, and depositional processes acting on and shaping the rocks.

Several authors investigated and documented the geology of Ethiopia in general and northern Ethiopia in particular (Alene et al., 2006; Arkin *et al*., 1971; Asrat *et al*., 2001,2003; Beyth, 1971, 1972a, b; Bosellini *et al*., 1997; Beyth and Shachnai, 1970; Dow *et al*., 1971; Dubey *et al*., 2007; Garland, 1980; Kazmin, 1972a, b, 1975; Levitte, 1970a, b; Merla *et al*., 1973; Tadesse, 1996; Tadesse *et al*., 2003; Worash and Valera, 2001; Wolela, 2008) mainly at a regional scale, that may not of help for specific project scale. Recently, the geology of Geba catchment, which covers part of the Mekelle Outlier, has been compiled by Gebreyohannes *et al*. (2010). The Mekelle Outlier is a near circular area about 8000 km^2 large (Beyth, 1972a, b), where Mesozoic sedimentary succession has been preserved from erosion and sourrounded by older metamorphic rocks. According to several authors (e.g. Kazmin, 1975), Ethiopia is covered by the following major rock types: metamorphic basement (Precambrian), Palaeozoic sediments, Mesozoic sediments, volcanic and intrusive types and young sediments. Precambrian metamorphic and associated syn-to post-tectonic intrusive rocks cover 23% of the country (Tadesse *et al*., 2003) and include rocks such as quartzites, granitoids, granodiorite gneisses, hornblende-biotite gneisses, diorites, schists, marbles, metasediments and metavolcanics. Thick successions of Palaeozoic and Mesozoic sediments (33%) overlie the Precambrian rocks. These include limestone, shale, mudstone and sandstone. A large part of the country is covered by Paleo-Plistocene and Quaternary volcanic rocks (44%) (Wolela, 2008; Kazmin, 1972a, b, 1975). According to Wolela (2008), about 33% of the surface area of Ethiopia is covered by sedimentary rocks in five major basins (the Ogaden Basin, the Blue Nile Basin, the Gambela Basin, the Southern Rift Basin and the Mekelle Outlier).

Rocks of Precambrian age (with ages of over 600 million years) underlie large parts of western and northern Ethiopia and smaller areas in the south and east of the country. Paleozoic, Mesozoic, and Cenozoic sediments occupy the eastern, central, and northern part of the country. Voluminous piles of mainly Cenozoic volcanic rocks occur in large parts of central and western Ethiopia. The rift valley is covered with relatively young lacustrine sediments and volcanics (Merla *et al*., 1973).

The basement (Precambrian), upon which all the younger formations were deposited, contains the oldest rocks in the country. They are exposed in areas where the younger cover rocks have been eroded away. The Precambrian contains a wide variety of sedimentary, volcanic and intrusive rocks which have been metamorphosed to varying degrees. At the end of Precambrian times uplift occurred, which was followed by a long period (for more than 85 million years) of erosion. Any sediments which were deposited during the Paleozoic interval, which lasted some 375 million years, have been largely removed by erosion, except for shale and deposits partly of glacial origin laid down in northern Ethiopia towards the end of this period (Kazmin, 1972a, b). Figure 1.5 shows a simplified geological map of Ethiopia.

Subsidence occurred in the Mesozoic, which began some 225 million years ago, and a shallow sea spread initially over the Ogaden (in the south eastern Ethiopia and Somalia) and then extended farther north and west as the land continued to subside. During Triassic–Jurassic sand, now sandstone, was deposited on the old land surface. Deposition of mudstone and limestone followed as the depth of water increased (Kazmin, 1972b).

Extensive fracturing due to rifting occurred early in the Cenozoic, the earliest rocks of which are dated at 65 million years, although major displacement along the fault systems which approximate to the alignment of the Red Sea, Gulf of Aden and East African rift including the main Ethiopian rift systems (Fig. 1.6), did not occur until later in the Paleo-Pliocene (Paleo-Neogene). Faulting was accompanied by widespread volcanic activity and the two processes, which are partly related, have largely determined the form of the landscape in the western half of Ethiopia and in the Afar Depression (Fig. 1.6). The outpouring of vast quantities of basaltic lava over the western half of the country was accompanied by, and alternated with, the eruption of large amounts of ash and coarser fragmental material, forming the Trap Series (Kazmin, 1972b).

The geology of northern Ethiopia is mainly characterized by low grade metamorphic (Precambrian) rocks, Paleozoic-Mesozoic sedimentary rocks, Paleo-Pliocene basalt and Quaternary deposits (basalt and alluvial and lacustrine sediments). The metamorphic rocks mainly consist of meta-volcanic and meta-sedimentary rocks and mafic/ultramafic to felsic intrusions which are grouped as Upper Complex (Kazmin, 1972b). The Paleozoic sedimentary rocks in Tigray known as Enticho Sandstone and Edaga Arbi Tillites are typically exposed in Enticho and Edaga Arbi villages (between Mekelle and Axum). These rocks are also sparsely exposed in different localities while in other parts they are covered by Mesozoic sedimentary rocks. Table 1.2 presents the generalized stratigraphy of northern Ethiopia.

The Mesozoic sedimentary sequence unconformably overlies the Precambrian basement. The Mesozoic sequence is composed of a horizontal Triassic basal clastic unit (Adigrat Sandstone), a Jurassic carbonate-marl-shale succession (Antalo Supersequence or Antalo and Agula Shale Formation), and an early Cretaceous Sandstone (Amba-Aradam Formation). The flood basalt of Paleo-Pliocene age unconformably overlies the sedimentary rocks, which in places are intruded by a network of dolerite sills and dykes (Bosellini *et al*., 1997). Among the Quaternary deposits, alluvial deposits and some carbonate precipitates (travertine) are common (Gebreyohannes *et al*., 2010).

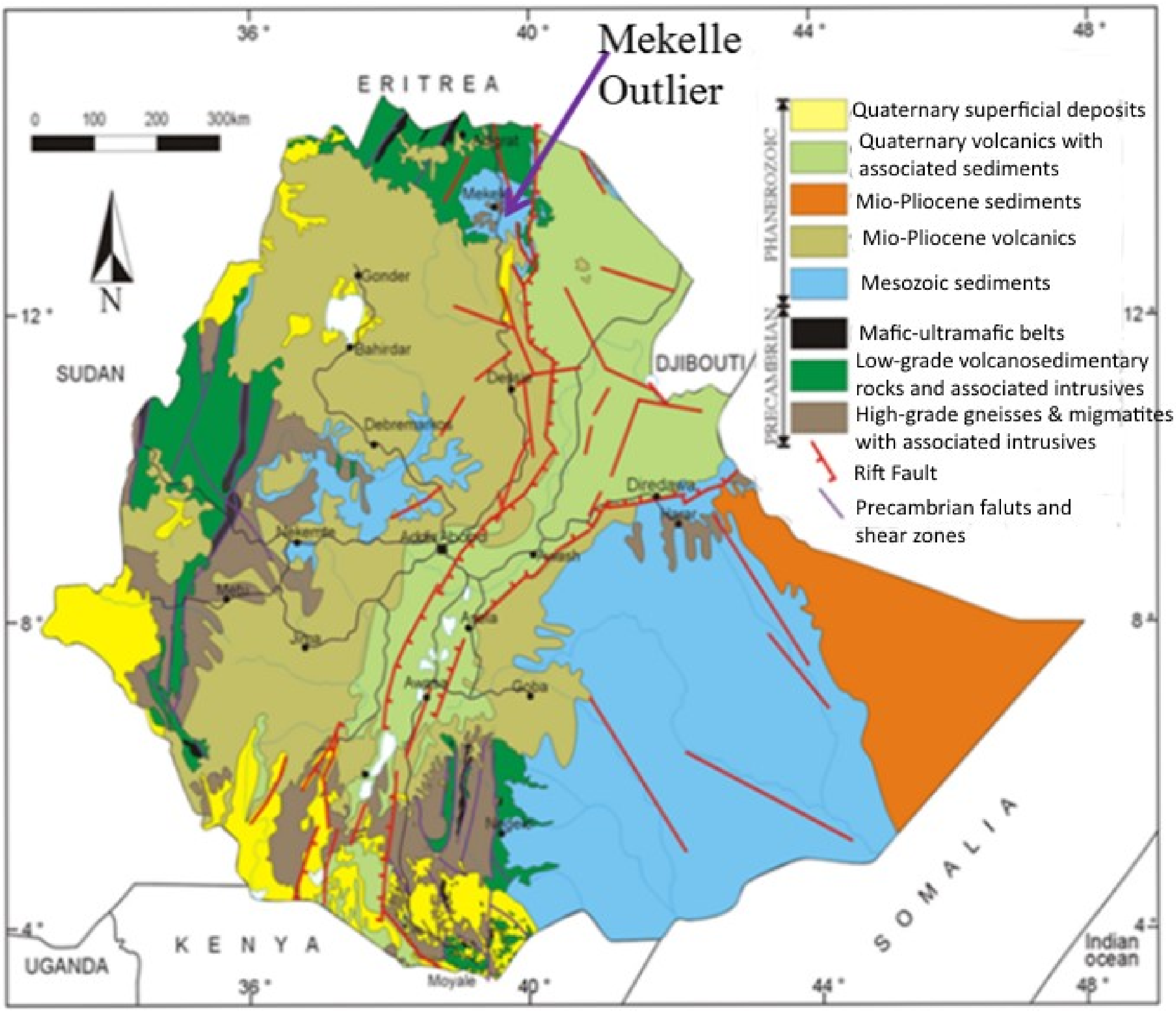


Figure 1.5. Simplified general geological map of Ethiopia (GSE, 1973; Tefera *et al*., 1996; http://spilpunt.blogspot.be/2007 /04/ethiopia_13.html). Mekelle Outlier is indicated toward the northern part of the country.

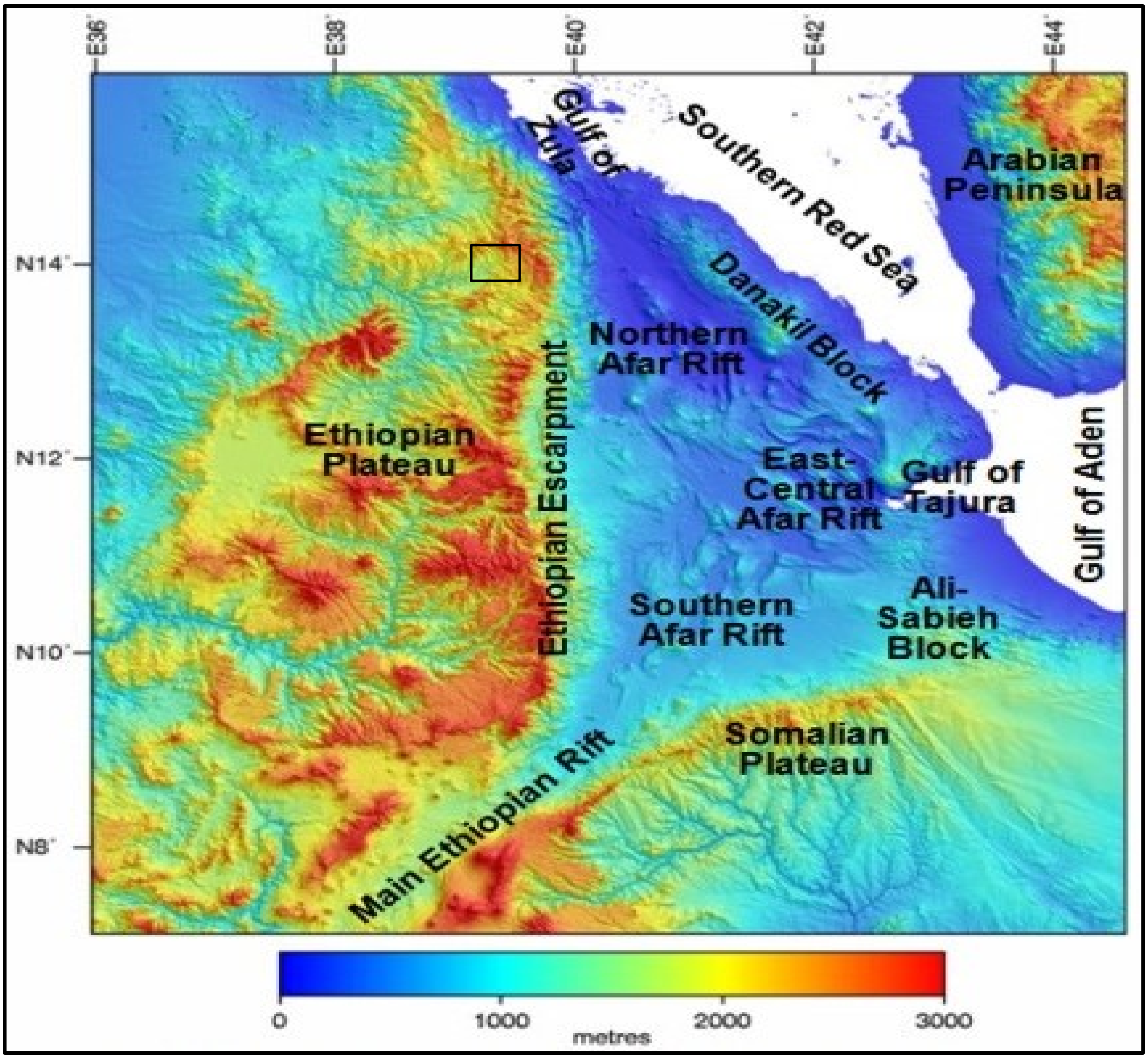


Figure 1.6. DEM of the Afar and surrounding area showing geomorphological and structural divisions. Black square (not to scale) shows location of the study area (modified from: http://www.see.leeds.ac.uk/afar/websitepages/structurepages/structuregeol.htm, visited on 21/02/2014).

Table 1.2. Generalized geologic stratigraphic units of Tigray (Northern Ethiopia) (modified after Arkin *et al*., 1971, Gebreyohannes *et al*., 2010 and Wolela, 2008).

Era		Period/Epoch	Geologic unit	Common Rock/Lithologic Types
Cenozoic		Quaternary/ Recent (present-10,000 years	Alluvium	- Silt, sand and gravel
		Paleo-Pliocene /Palaeo-Neogene (~2.588-66 million years)	Mekelle Dolerite	- Dolerite sills, dykes and small batholiths
			Trap Volcanics	- Amygdaloidal basalts, dolerite sills and dykes
Mesozoic		Cretaceous (~66-145 Million years)	Amba Aradam (Upper Sandstone)	- consists of fluviatile sandstone and shale, and is compact and variegated
		Jurassic (~145-201 million years)	Agula Shale	- Marl and shale with minor black limestone and thin gypsum and dolerite beds
			Antalo Limestone	- Limestone, marl, shale, gypsum intercalations, in places fossiliferous
			Adigrat Sandstone (Lower Sandstone)	- Fine to coarse sandstone, cross-bedded, siltstone, minor calcareous sandstone, ferruginous silt and clay
Palaeozoic		Ordovician (~443-485 million years)	Edaga Arbi Glacial deposits	- Tillite with granite boulders, siltstone
			Enticho Sandstone	- Calcareous sandstone with conglomerate and tillite lenses
		Lower Palaeozoic/Cambrian (~485-541 million years)	Mareb Granite	- Porphyritic granite with aplitic dykes and pegmatite veins
			Forestage Diorite	- Quartz diorite with andesite dykes
Precambrian	Proterozoic	Upper Proteozoic/Neo-proterozoic (>~600 million years)	Tambien Group	- Pebbly slate and limestone alternation - Matheos black limestone with veins - Dedikama dolomite and black marble
			Tsaliet Group (metavolcanics)	- Green schist, quartzite, black limestone, tuffaceous sediments

The engineering geological and geotechnical aspect of the Mekelle Outlier is almost untouched except few fragmented and localized studies (Berhane, 2010a, b; Berhane and Ayenew, 2010).

Beyth (1971) also studied the structure and tectonics of the sedimentary rocks in the Mekelle Outlier and in the escarpment and identified two main fault systems. The two main fault systems are WNW-ESE running fault belts (Wukro, Mekelle, Chelekot and Fuicea Mariam) and the

NNE-SSE Rift Valley fault system forming the escarpment and the Danakil depression. The longest of these faults in the study area is the Mekelle Fault which forms a 65 km long escarpment. Faulting brings the lower most part of the Antalo Formation against its uppermost part and in places against the overlying Agula Formation, near Mekelle City, implying a throw of at least 400 m (Bosellini *et al*., 1997; Levitte, 1970a, b). The Mekelle fault belt cross-cuts Hashenge MDR and reservoir area of Geba proposed water supply dam and Chelekot fault cross-cuts Hizaetiwedicheber MDR. The faults are mostly sealed by dolerite intrusions along their length. The intrusions in the study area are dykes and sills (Kuster *et al*., 2005).

The hydrogeological conditions of the country are linked with the occurrence and distribution of the various hydrostratigraphic units, the topography, the recharge and discharge conditions which, in turn are related to the spatial and temporal variation of rainfall. These hydrostratigraphic units include the Precambrian basement, Paleozoic and Mesozoic sedimentary rocks, Paleo-Neogene and Quaternary volcanics, and Quaternary sedimentary rocks and sediments (Pavelic *et al.*, 2012).

The Mesozoic sedimentary rocks are widely distributed in the present study area (around Mekelle City). Mesozoic sedimentary rocks possess both primary and secondary permeability that play important role in the occurrence and movement of groundwater. The Mesozoic sedimentary rocks can make good aquifers when they are found under favorable climatic and topographic conditions.

Groundwater in the Mekelle Outlier is mainly associated with fracturing and joints (faults) and impact of dolerite intrusion on country rock. The major faults, joints and sedimentary bedding planes play an important role in groundwater occurrence and movement. Beyth (1971) reported that in the area there are two major fault systems, NW-SE and NE-SW trending faults. Girmay *et al*. (2015) indicated three groundwater flow systems (shallow/local, intermediate and deep/semiregional). The shallow groundwater flow is localized in highland plateau areas. Agula Shale and dolerite are characterized by shallow and localized groundwater flow systems.

PROBLEM DEFINITION

In the northern part of the country, Tigray region, though agriculture plays an important role in the regional economy, crop production and productivity are limited at low level due to various reasons. Some of the reasons are recurrent droughts, erratic and uneven rainfall distribution, and poor or no experience in modern water harvesting techniques. To alleviate these critical problems, an organization (Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSAERT)), was established by the government of Ethiopia some 20 years ago with a main objective of constructing MDRS, ponds and river diversions in the region. Before the establishment of CoSAERT, practice of constructing water harvesting structures was almost none existent in the region.

In the region about 92 MDRs have been constructed in the last 15-20 years (mainly beteen 1992 and 2012, chapter 2) by CoSAERT and other organizations. But due to technical and operational problems most of the MDRs and ponds are not serving as planned (out of 92 MDRs about 61% are facing serious siltation problems, 53% leakage, 22% inflow problems, 25% structural damages on dam body and 21% damages on spillway route). Out of the constructed MDRs , a considerable number (about 53%) have failed to contain water due to various reasons, out of which perhaps the most probable would be inadequate hydrogeological, engineering geological and geotechnical investigations. Even though a number of efforts have been made in tackling the problems, it is still not addressed because of lack of comprehensive scientific research in this area. People are suffering from shortage of food and water and decision makers are looking for a holistic research output to help them for future strategies and directions. Specific problems that should be solved through detailed research work are summarized below.

Construction of MDRs in Tigray region

Agriculture depends entirely on seasonal rainfall which is characterized as erratic showing high variability resulting in moisture deficit. Micro-dam construction was considered as one solution to introduce modern irrigation by storing runoff water. After its establishment, CoSAERT was planned to construct a large number of earth MDRs in a short period of time. Most of the constructions were executed with limited understanding of the constraints, minimum of machinery and a maximum of manpower. This leads to a number of technical and operational problems including inappropriate siting, and poor or no geological and engineering geological/hydrogeological investigations.

Reservoir leakage

In general, leakage from reservoir is a trouble. During the study of leakage possibilities, attention is very essential to the patterns of joints, seams, and vertical and inclined channels; their frequency and degree of openness; together with general topography and geology of the locality (Krynine and Judd, 1957). Palaeozoic-Mesozoic sedimentary formations with intrusion of dolerites make up large portion of the area (Beyth, 1972a, b) with some MDRs on Precambrian basement (slate and meta-volcanic). These rocks are affected by weathering and tectonic activities and some karstification in the limestone-shale-marl sequences. Hence, leakage problems may be expected, although their detection and identification need detailed studies and there is no detailed and systematic research work in this regard.

Poor understanding of hydrogeological conditions at the dam sites

In dam and reservoir sites a careful study should be made of the position and depth of the water table, location of springs and their discharge. Engineering geological and hydrogeological mapping of dam and reservoir sites requires more detailed investigations (Golze, 1977).

In all aspects of the investigation for MDRs, the groundwater situation is an important parameter and should be continually monitored. This involves the location and monitoring of seepage points during surface mapping, recording of groundwater inflows into pits and trenches, and the monitoring of groundwater levels during drilling. Measurement of seepage and flow rates, recording of rainfall, evaporation, and water levels in exploration drill holes give a broad indication of the proportion of infiltrating rainfall, the response of the groundwater to storms, and areas where high groundwater flow rates may be expected and provide a useful indication of mass permeability (Robin *et al*., 1992). These measurements were not conducted during the study, construction and operation period of the existing MDRs. Lack of these data and poor understanding of the hydrogeological conditions bring about failure and unwanted maintenances after construction. Therefore, locating reservoir and dam in a geologically complex terrain needs critical and comprehensive considerations of hydrogeological and engineering geological parameters.

OBJECTIVES

Main objective

This research project aims to investigate the peculiar characteristics of the geology and hydrogeology that have to be taken into consideration for the construction of effective and sustainable dam reservoirs in different geological settings in Tigray. In line with this, it aims to study the geological, hydrogeological and engineering geological conditions of selected existing MDRs and their intricate relations, hydrodynamic interactions and pinpoint the causes for their failures. It will therefore develop proper investigation methods or procedures for water harvesting structures in the area.

Specific objectives

1. Characterize and analyse the geological and engineering geological properties of the rocks and soils from dam construction and reservoir siting perspectives.
2. Investigate and determine the main hydrogeological and engineering geological features that cause an excessive leakage problem.
3. Characterization of interacting processes of hydrogeochemistry of surface/reservoir and groundwater, their trend and implications to leakage.
4. Based on the overall integrated data analysis, working methods/procedures will be setup for future MDR studies and other water harvesting possibilities in the area.

Questions for research include the following:

1. How is leakage occurring in micro-dams founded on sedimentary rock succession?
2. Why do some MDRs perform well while others get empty within a short period after the rainy season?
3. Which are the hydrogeological and environmental impacts of these MDRs in the area?

THESIS OUTLINE

The findings of this comprehensive and pioneering study are presented in six chapters, excluding the general introduction (chapter 1) and the final synthesis and outlook (chapter 8). The dissertation is presented in article format. The contribution of each co-author will be explained in table format, with the explanation of the role of each co-author in the study at the end of each of the six chapters. Figure 1.7 shows organization and structure of the dissertation.

The dissertation begins with providing a panel introduction on climate, geology and the problem and objective definitions in the **first chapter**. Then the **second chapter** provides an overview of MDRs and other water harvesting structures in northern Ethiopia with emphasis to geological constraints and associated geotechnical and geo-hydrological problems. In **chapter 3** a detailed account of the water leakage study of two MDRs (Hashenge and Arato) is presented. Geological, engineering geological, geophysical and drilling techniques were used to understand the Mesozoic sedimentary sequences with intruded dolerite and their hydraulic properties. **Chapter 4** deals with a detailed study and integrated approach to detect leakage path of Arato MDR. Electrical resistivity (profiling and vertical electrical sounding) and hydrogeochemistry were used in addition to conventional geological and hydrogeological approaches. **Chapter 5** focuses on detailed experimental and monitoring results of reservoir water level and groundwater level and their interaction or connectivity at Arato MDR. Diver data recorder, and manual rain gauge and minimum-maximum temperature recording thermometer were used to collect site water level and meteorological data respectively. **Chapter 6** presents geological and geophysical study results at two MDRs, namely Adishuhu and Hizaetiwedichebr, in view of leakage in the limestone-shale-marl intercalation unit in the absence of dolerite. The **seventh chapter** discusses geological challenges in construction of large dam in Mesozoic sedimentary sequences in northern Ethiopia with a focus on proposed Geba water supply dam site. The **final part** of the dissertation summarizes the main conclusions and recommendations on future researches and implementation of MDRs and proposed investigation approach. The data collected to answer the various questions raised in the main six chapters (chapter 2 to 7) are summarized in Table 1.3.

Except the first and last chapters, all other chapters are designed to present a specific theme linked to geology with their own abstract, introduction, methodology, results and discussions, conclusions and implication of the findings and references.

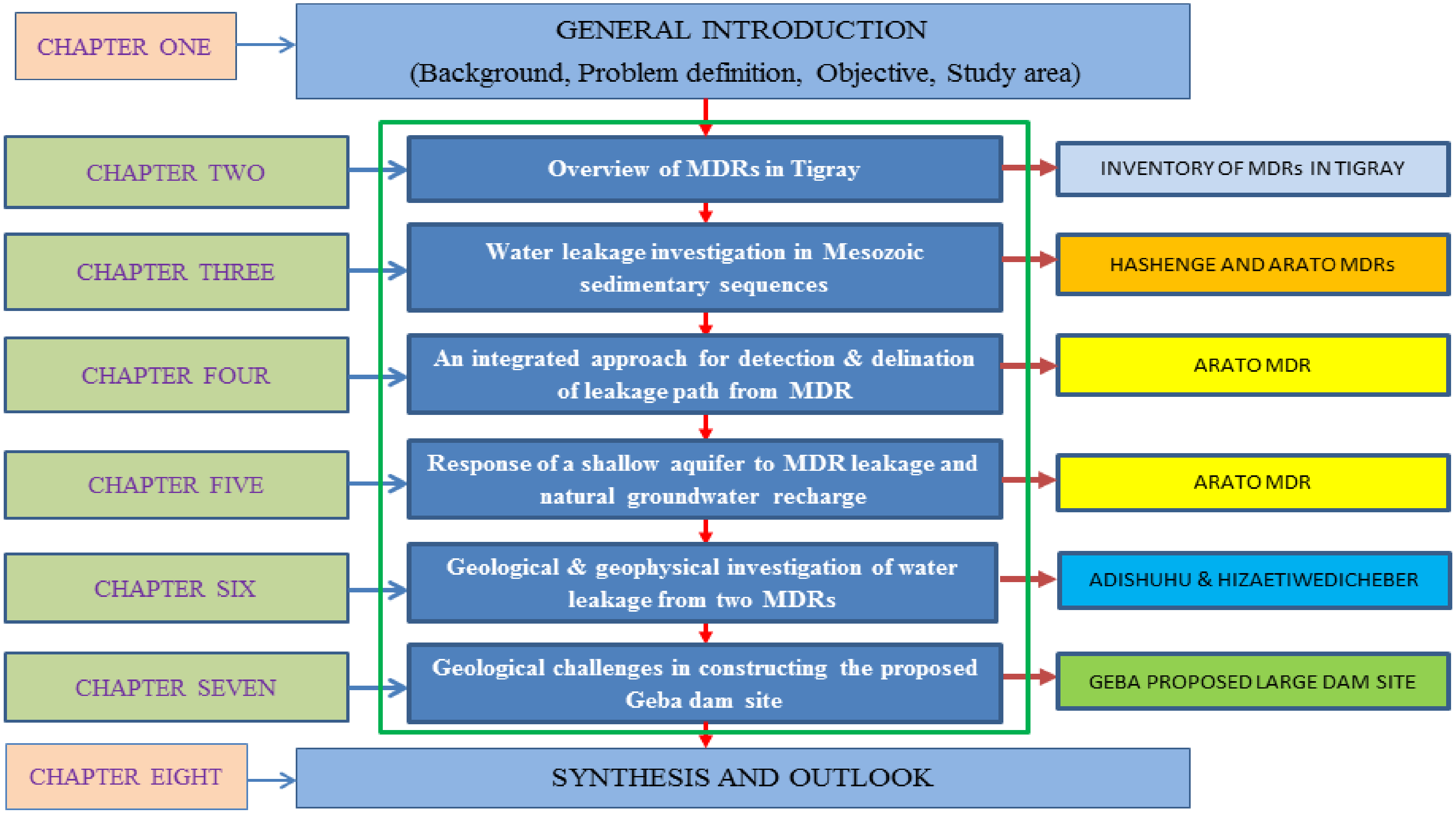


Figure 1.7. Organization and structure of the dissertation.

Table 1.3. Summary of the data collected.

Collected Data	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
MDR inventory; historical construction of MDRs; dam height; crest length; catchment and reservoir capacities; catchment, foundation and reservoir geology; observed problems, etc.	x		x	x	x	
Geology, rock discontinuity, geotechnical drilling (log, RQD, packer test, etc.), engineering geology, etc.		x				x
Geophysical survey (VES & electrical profiling), geology and hydrogeology, test pit (soil description), etc.			x		x	x
Hydro-geochemistry (reservoir, groundwater and stream water chemistry)			x			
Diver data loggers (reservoir water and groundwater level), rainfall, Min-Max. temperature, land use, soil grain size, etc.				x		

STUDY AREA AND METHODOLOGY

Study area

Tigray is one of the regional states of the Federal Democratic Republic of Ethiopia located in its northern part (Fig. 1.8). The population of Tigray reaches 5.1 million and the area is about 84, 722 km^2 (http://www.citypopulation.de/Ethiopia.html). The study area covers most part of Tigray regional state, mainly within the Tekeze river basin and partly in Mereb and Danakil/Afar river basins. It covers 31 woredas (=districts), most of which drain to the Tekeze river and finally to Nile basin. The study area is characterized by lack/shortage of potable water and poor water harvesting activities and utilization in modern irrigation practices although significant progress has been made in the last two decades.

Climatically, Tigray is classified as arid and semiarid region. The average annual rainfall varies from 350 to 900 mm and in most parts of the region, about 50 to 70% of the annual rainfall comes in the months of July and August only. Due to this climatic condition, most of the rivers draining the area are dry or intermittent and the need of water harvesting scheme construction (e.g. MDR, pond, etc.) is indispensable. The mean annual temperature ranges between 16 $^{\circ}$C and 38 $^{\circ}$C and the altitude varies from about 600 in the western lowlands to 3000 m (a. s. l.) in the highlands of Atsbi (northeast) (Gebreyohannes *et al*., 2010). Most streams and tributaries are controlled by geological structures and underlying geology.

Methodology

The overall working procedure and flow is schematically presented in Fig. 1.9. When every data were missed or/and additional data were needed during the course of the whole activities (processing and interpretations) the missing or/and additional data were gathered back again from field, archives of organizations, etc. (broken line in Fig. 1.9). In this section, the main approaches and methods used are described. However, the detailed techniques and methods used are described in respective chapters.

Figure 1.8. Location of Tigray Regional State (showing all regional states of the Federal Democratic Republic of Ethiopia). River networks and lakes are shown in the background (modified from http://www.fao.org/nr/water/aquastat/countries_regions/eth/ETH-mapdetailed.pdf visited on 16/12/2015).

The intitial step in the investigation of leakage problem from a reservoir is obtaining geological/engineering geological and hydrogeological information as a base to establish possible senarios or hypothesis and for selection of specific study techniques. The techniques commonly used for the investigation of leakage at reservoirs (also at lakes) are summarized in Table 1.4. Generally, combined use of diverse techniques is desirable to solve problems and detect leakage paths (Plata and Araguas, 2002). Among the techniques listed in Table 1.4 those listed under serial numbers 1, 2, 4, 5, 7 and 9 were used in this study.

Specifically the general approaches and methods used in this research include: 1) literature review, 2) data collection from archives, organizations, collection of field data, etc. 3) laboratory analysis, and 4) data organization, processing and interpretation. During the fieldwork the following main techniques were used (Fig. 1.9): 1) conventional geological mapping, 2) geophysical survey (electrical resistivity), 3) drilling and test pit analysis, 4) water level measurements using diver (automatic data logger), 5) daily rainfall and temperature measurements, and 6) water sampling for laboratory analysis.

An inventory of 92 MDRs in Tigray was established during the initial stage of the research (Figs. 1.7 and 1.10). Based on evaluation of the results, including the geological setup and observed leakage problems, four MDRs were selected as experimental post construction evaluation study sites. One proposed large scale dam site with more subsurface geological data and in-situ test results was selected as comparison and validation to the results obtained from the four MDRs.

Table 1.4. Summary of leakage investigation techniques (Plata and Araguas, 2002).

S.No.	Lekage investigation techniques	Simplifid description of the techniques
1	Geological, engineering geological and hydrogeological	Geological, engineering geological and hydrogeological information of the area should always be the initial step of the investigation and gives a clue and possible scenarios about the leaky formation and locality.
2	Permeability tests	Conducted in boreholes, test pits or any excavation. They are of different types: constant head, variable head, Packer/Lugeon test, etc.
3	Geophysical well-logging	Including: natural gamma rays, self-potential and resistivity, ultrasonic techniques, magnetic induction, etc.
4	Geophysical techniques on the ground	Including: self-potential, resistivity, seismic, magnetic, gravity, etc.
5	Water balance of reservoir	Common in water management issues, but can be applied to leakage investigation, it can tell the amount of leakage in a specified period but may not answer from where, how, etc. questions.
6	Relationship between reservoir water level and flow rate of springs located downstream (Leakage or filtration law)	Generally for concentrated leakage the discharge is proportional to the hydraulic gradient (when it is not turbulent), provides valuable information on the elevation interval inside the reservoir where the infiltration of the emerging water at the springs it taking place.
7	Piezometric levels measurement at boreholes (at dam site and surrounding)	Plotting maps with piezometric contour lines, relationship between the changes of water level at the reservoir and the piezometric levels in boreholes, changes in piezometric levels produced during drilling
8	Use of temperature as a natural tracer of water	Temperature variation with time in the reservoir and springs/boreholes, etc. for the determination of the elevation in the reservoir from which water infiltrates into the terrain

9	Measurement of physical and chemical parameters in boreholes and springs	Temperature and conductivity profiles, distribution of temperature, conductivity and other chemical parameters in reservoir, springs, boreholes and other discharge points. Chemical analysis of major ionic components (Cl^{-}, SO_4^{2-}, HCO^{-}_3, NO^{-}_3, Na^{+}, K^{+}, Ca^{2+} and Mg^{2+}), sometimes SiO_2 and Fe (total) and other minor components may be used
10	Measurement of environmental isotopes	Stable isotopes such deuterium and oxygen-18, carbon and the radioactive isotopes of hydrogen and tritium are commonly used
11	Artificial tracers	Measurement of flow properties along a vertical profile in boreholes, interconnection experiments between the reservoir (or boreholes) and the discharge points (or boreholes) located downstream, infiltration experiments inside the reservoir, etc.
12	Detection and measurement of flow in the reservoir (identify point or area of infiltration)	Using floating devices and float drogues, migration of tracer cloud
13	Identification of areas of preferential infiltration in the reservoir	Using specially designed devices such as infiltrometers

Conclusions were drawn from the four MDRs, and counterchecked by the conclusions from the detailed subsurface investigations at the proposed large scale dam. Figure 1.10 shows the simplified interlink between the MDRs and the proposed large-scale dam. Typical characteristics of the experimental MDRs and the proposed large-scale dam site are presented in Table 1.5, while Fig. 1.11 portrays the location of all five study sites.

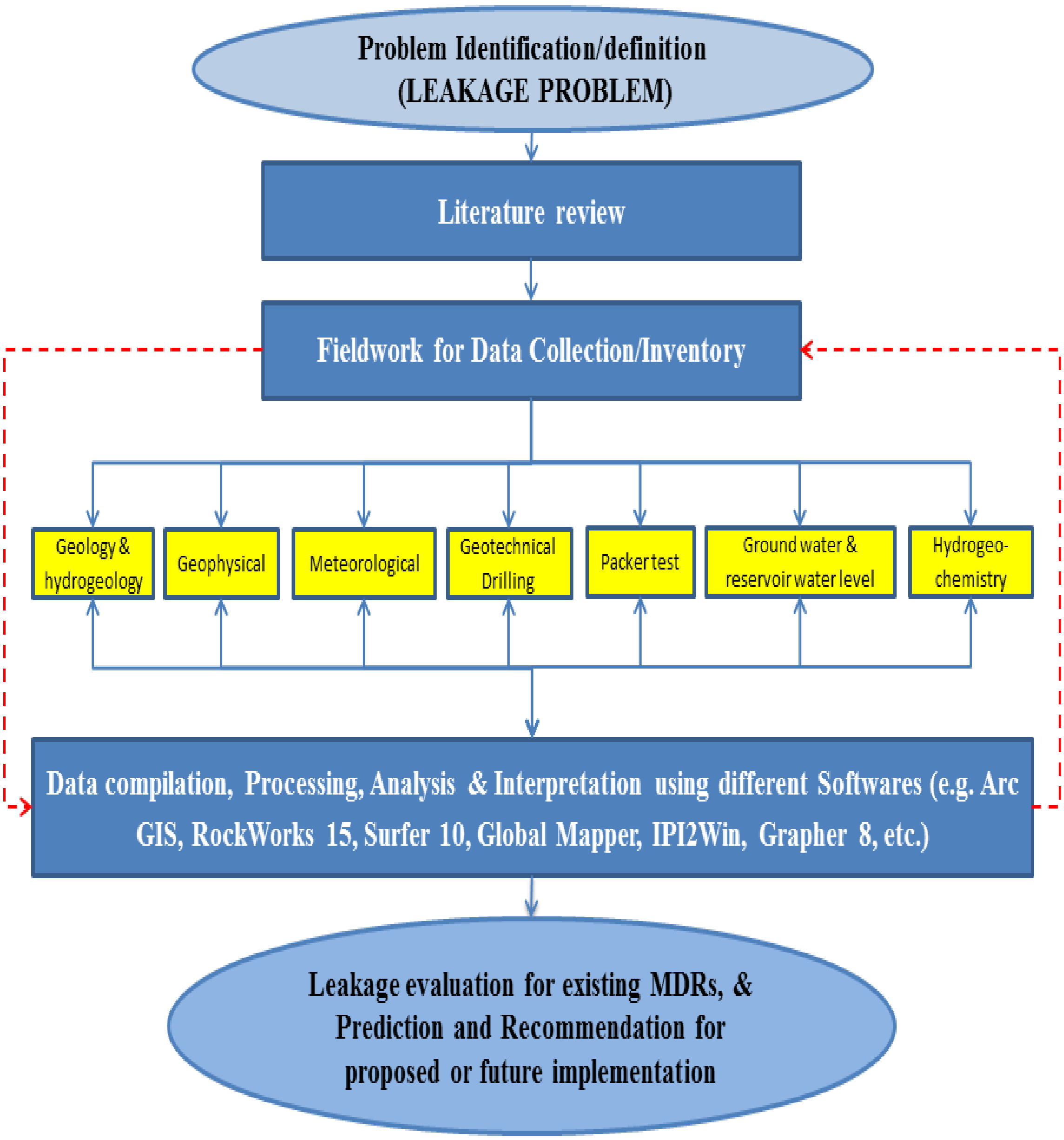


Figure 1.9. Simplified working procedure and flow of the research.

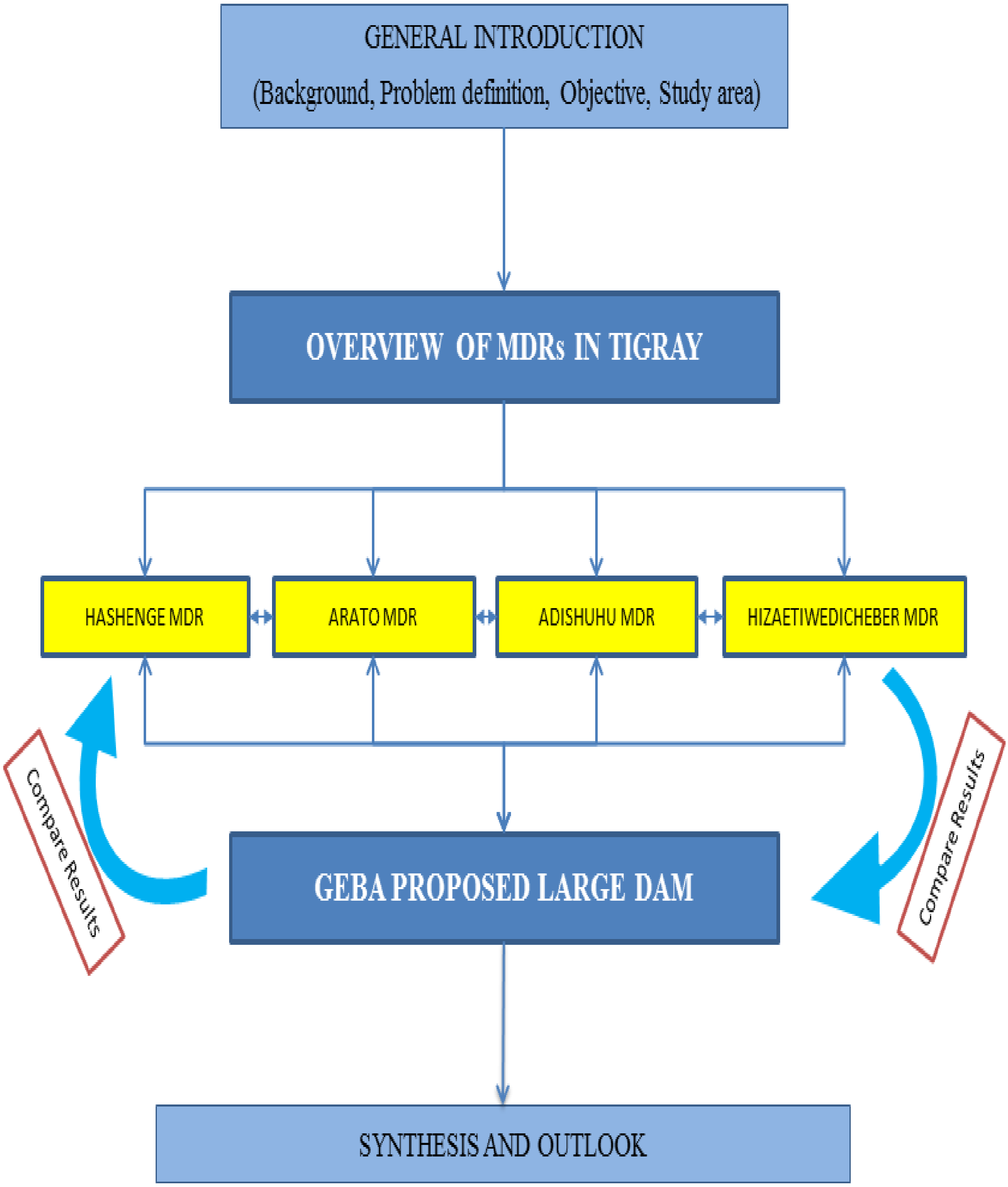


Figure 1.10. Interlink of the four MDRs and Geba proposed large-scale dam.

Table 1.5. Characteristics of the experimental MDRs and the proposed large-scale water supply dam site (HWC=Hizaetiwedicheber).

Parameters	**Hashenge**	**Arato**	**Adishuhu**	**HWC**	**Geba**
Location (mE and mN)	572850, 1489900	570198, 1494180	574937, 1508567	558645, 1477362	542243, 1504348
Elevation (m.a.s.l.)	2400	2424	2301	2235	1750
Dam height (m)	19.0	20	10.6	15.5	80
Crest length (m)	373	447	495	598	1000
Reservoir gross capacity (10^6 m^3)	2.23	2.59	1.0	1.24	350
Designed command area (ha)	120	120	40	80	n.a.
Catchment area (km^2)	19.3	20.7	9.4	33	2540
Year of construction	1996	1997	1997	1997	n.a.
Central foundation geology	dolerite	l-s-m[1]	l-s-m	l-s-m	l-s-m
Left abutment geology	l-s-m/ dolerite	l-s-m	l-s-m	l-s-m	l-s-m
Right abutment geology	dolerite	dolerite	l-s-m	l-s-m	l-s-m
Reservoir geology	l-s-m/ dolerite	l-s-m/ dolerite	l-s-m	l-s-m	l-s-m
Catchment geology	l-s-m/ dolerite	l-s-m/ dolerite	l-s-m	l-s-m	l-s-m/ dolerite

[1]l-s-m: limestone-shale-marl intercalation

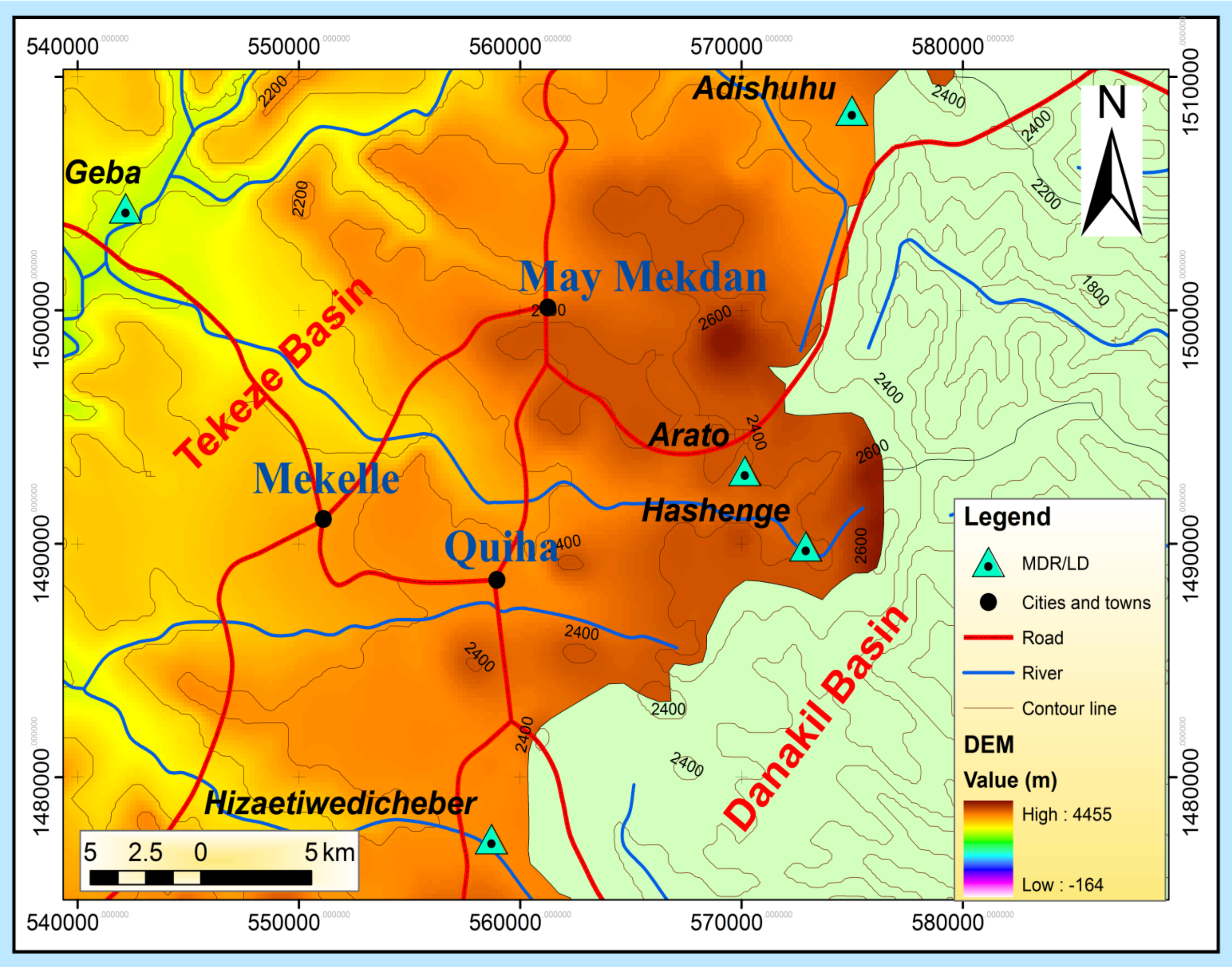
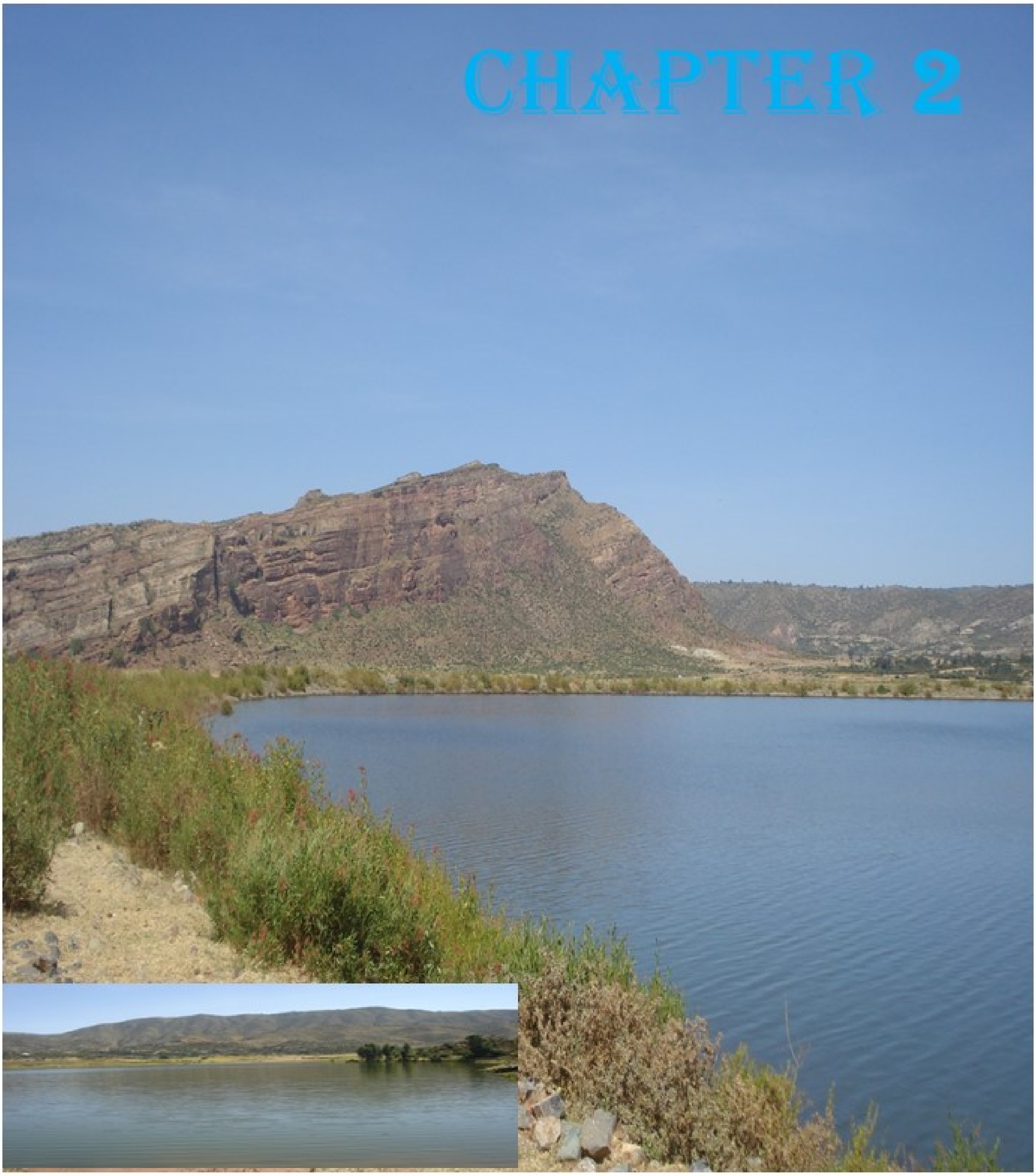


Figure 1.11. Location map of Hashenge, Arato, Adishuhu and Hizaetiwedicheber MDRs and Geba proposed water supply dam site. Mekelle City (capital city of Tigray region) is shown in the center-left side of the map. (DEM data source from ETHIO-GIS DATA sets (SRTM) http://dds.cr.usgs.gov/ srtm/version2 _1/SRTM3/Africa/).



View of Laelay-Wukro MDR (one of the successful MDRs in Tigray). The author was part of the study and design team of this project @2012 Gebremedhin Berhane.

CHAPTER 2

Overview of Micro-Dam Reservoirs (MDRs) in Tigray (Northern Ethiopia): Challenges and benefits

This chapter is based on Gebremedhin Berhane, Tesfamichael Gebreyohannes, Kristine Martens, Kristine Walraevens (in press). Overview of Micro-Dam Reservoirs (MDRs) in Tigray (Northern Ethiopia): Challenges and benefits. Journal of African Earth Sciences. DOI: 10.1016/j.jafrearsci.2016.07.022.

ABSTRACT

Water scarcity is a key factor in food security and sustainable livelihood in sub-Saharan Africa, particularly in East Africa. The problem is severe in many parts of Ethiopia where water plays a central role in the country's economy. To alleviate and curb water scarcity different water harvesting technologies were introduced in Ethiopia during the last two decades; nevertheless, their sustainability and livelihood impacts are not well addressed. For the first time, a complete and comprehensive inventory of micro-dam reservoirs (MDRs) in Tigray has been established including the geological background and currently observed problems. The inventory of 92 MDRs in Tigray was conducted using the direct field observational method, selected interviews and secondary data, to understand the overall situation of the schemes from engineering geological and geo-hydrological perspectives and its implication to sustainability and water availability. Analysis of the inventory shows that sustainability and livelihood impact of the water harvesting schemes are threatened by siltation, leakage, insufficient run-off, poor water management and structural damages on the dam body as well as on irrigation infrastructure and spillway. Basic statistical analysis showed that 61% of them are found to have siltation problems, 53% suffer from leakage, 22% from insufficient inflow, 25% have structural damages and 21% have spillway erosion problems. Furthermore, nearly 70% of the MDRs are founded on carbonate dominant sedimentary terrain at places with intrusion of dolerite sills/dykes and the problems of siltation and leakage are found to be extremely high in the MDRs located in such geological setting, as compared to those on crystalline metamorphic rocks. Lack of proper water management was observed in most of the reservoirs with irrigation practices. Future research and analysis on the causes of the bottlenecked problems and monitoring surveillance are recommended.

INTRODUCTION

Water scarcity is a key factor in food security (Behailu and Haile, 2002) and sustainable livelihood in sub-Saharan Africa, particularly in East Africa. Reliable water supply is fundamental to human health, wellbeing, industrial development and food security. Over the previous centuries, mankind has tacitly assumed that water is readily available, inexpensive and plentiful. However, more recent times have shown that the abundance of clean, unlimited supplies of inexpensive water is becoming a myth. There is an increasing pressure worldwide to develop new strategies and methods to meet the growing demands of water to maintain the current standards of living.

Dams for storing water for the purpose of electricity, irrigation, domestic water supply and flood control have been constructed for more than a century (WCD, 2000; Bird and Wallace, 2001; Tefera, 2006). Now, in the 21st century, one-third of the countries in the world rely on hydropower for more than half of their electricity supply (dams generate 19%) and some 30-40% of the 271 million hectares irrigated worldwide rely on dams (WCD, 2000; Bird and Wallace, 2001).

The agricultural sector in Ethiopia contributed about 52% of the country's GDP in 2001 (Teshome, 2003), 46% in 2006 (World Bank, 2008) and 47% in 2007 (von Braun and Olofinbiyi, 2007) and accounts for about 80% of employment (World Bank, 2008). The rainfall regime in Ethiopia and in Tigray in particular is irregular, unreliable and unevenly distributed. Furthermore, the country is subjected to periodic extreme events of droughts and floods; this problem is very critical in the northern part of the country (Tigray, Afar and Amhara regions). Limiting the consequences of recurring droughts has always been high on the development agenda of the government and has notably underpinned considerable investments in hundreds of small ponds, diversion weirs, MDRs, etc. that support livelihood including water use in agriculture, for livestock and domestic use.

In Ethiopia water is an input, to a greater or lesser extent, to almost all production (World Bank, 2006). Ethiopia's extreme hydrological variability is echoed in its economic performance. The vast majority (80%) of Ethiopia's population subsists on rain fed agriculture, and thus their welfare and economic productivity are linked to the volatile and erratic rains.

Rainfall across much of the country is exceptionally variable and unpredictable, both in time (within and between years) and in space (Yazew, 2005). According to Webb *et al*. (1992) (cited in Teshome, 2003), Tigray region is characterized by erratic rainfall and frequent droughts. Regional projections of climate models do not only predict a substantial rise in mean temperatures over the 21st century but also suggest an increase in rainfall variability (World Bank, 2008). With highly vulnerable watersheds and almost no investment in water storage, the consequences of this hydrological variability are endemic, and unpredictable droughts and floods (World Bank, 2006). Construction of micro-dams in Ethiopia started in the late seventies (Tiruneh, 2005) to combat drought and increase food security. However, the construction of dams increased in recent years. Over the last 15-20 years (mainly beteen 1992 and 2012) about 92 dams were constructed in Tigray region (Fig. 2.1) and currently three dams are under construction and another four are at the study and design phases.

Despite the various socio-economic benefits and livelihood impacts (Teshalle, 2001; Behailu, 2002), many of the dams found in Tigray have many threatening problems affecting their sustainability. Worrying is the fact that the construction of MDRs is continuing without being supported by research. Many scholars conducted investigations on some of the problems, like sedimentation, hydrology, ecology and health (e.g. Abdulkadir, 2009; Berhane, 2010; Desta, 2005; Dejenie *et al*., 2008, 2009; Gonzalez-Quijano, 2006; Girmay *et al*., 2009; Haregeweyn *et al.*, 2005, 2006, 2008a, b, 2013; Nedaw and Walraevens, 2009, Yazew, 2005 and others). Haregeweyn *et al*. (2006) provided general characteristics and problems of 54 micro-dam reservoirs and a detailed sediment survey on 10 selected micro-dam reservoirs. Awulachew *et al*. (2005) also indicated that 18 out of 44 micro-dams are reported as non-functional schemes and 9 additional schemes were reported to have different problems (e.g. high seepage). Moreover, 7 out of 11 micro-dams constructed by the Relief Society of Tigray (REST) were reported to have problems (e.g. catchment degradation and seepage).

In Ethiopia in general and in its northern part in particular, soil erosion is considered catastrophic (Awulachew *et al*., 2005; Tamene *et al*., 2005; Wolka, 2012 and others), even though many efforts are being made to curb severe soil erosion which resulted in some achievements in the region (Alemayehu *et al*., 2009; Descheemaker *et al*., 2006a, b, 2009; Gebremichael *et al*., 2005; Mekuria *et al*., 2007, 2009; Nyssen *et al*., 2004, 2006, 2008b, 2009; Tamene *et al.,* 2005, 2011; Vancampenhout *et al*., 2006 and others). None of the above papers dealt with detailed characteristics and causes of leakage and geotechnical/engineering geological related problems of the MDRs in Tigray. The role of geological background to erosion and leakage was not well addressed.

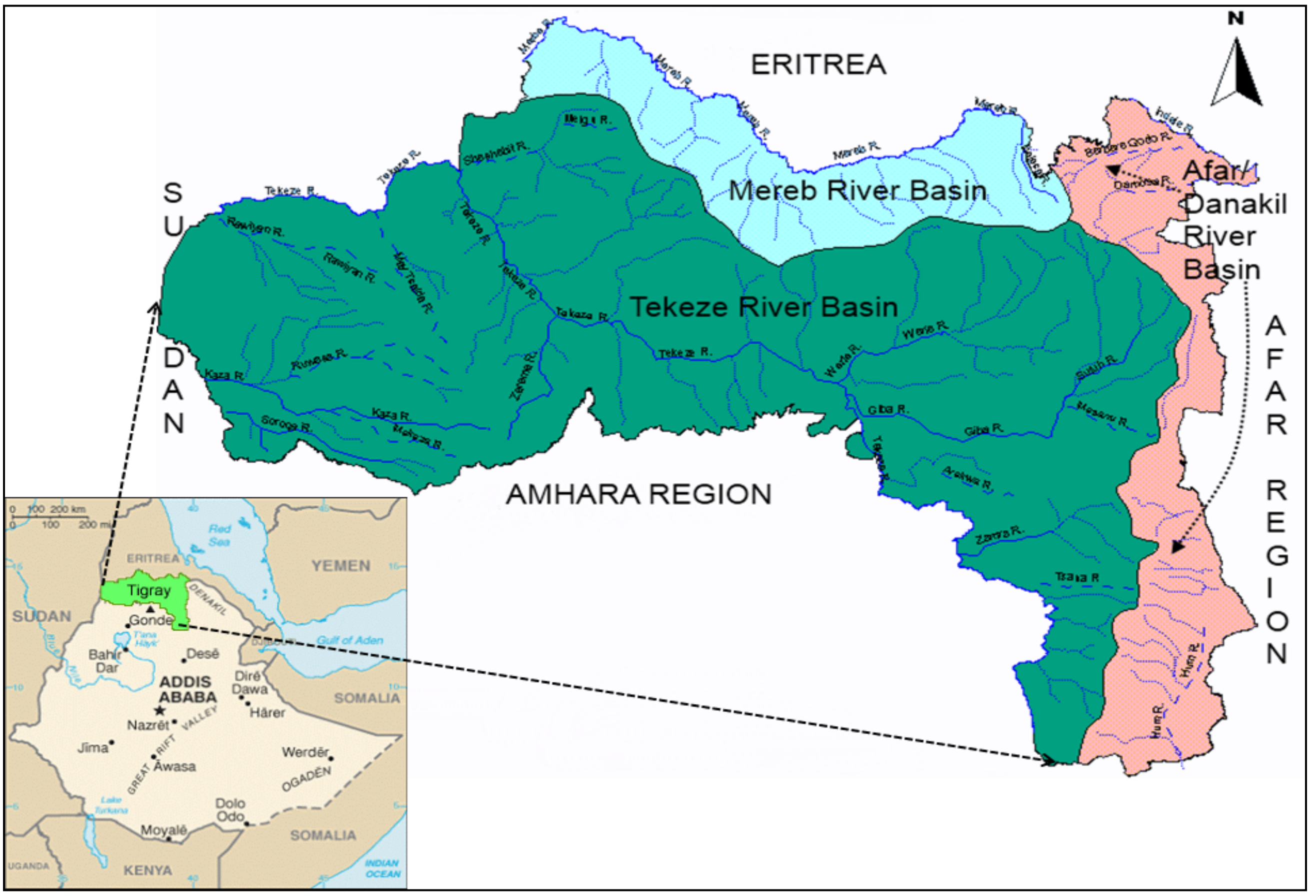


Figure 2.1. Location map of the study area (left bottom: Ethiopia and right top: Tigray) (modified after BoFED, 2002).

The main aim of this chapter is to review and evaluate the current situation of all 92 MDRs in Tigray in terms of their geotechnical/engineering problems focusing on leakage and their livelihood impacts, bringing together the geological and geo-hydrological information of all MDRs for the first time.

METHODS

The situation analysis covers 92 MDRs found in Tigray (northern region of Ethiopia) based on secondary data, direct field observations, personal communications with local farmers, and with key informants including members of the Tigray Water Resource Development Bureau (TWRDB), Tigray Bureau of Agriculture and Rural Development (TBoARD), the Woreda (=*district*) Water Bureaus and Agriculture Bureaus.

During the dam inventory, which was conducted in 2011, 2012 and 2013, emphasis was given to the following livelihood impacts, geo-hydrological and engineering geological conditions of the dams: 1) qualitative observation on socio-economic and livelihood impacts, 2) leakage problems, 3) geotechnical problems on dam body, 4) failures and erosion of spillway, 5) siltation/sedimentation, 6) filling of reservoir (run-off) and 7) water management problems.
The direct field observation was mainly focused to understand the geological set up, individual problems of the MDRs including siltation, leakage, in-flow problem and damages on components of the schemes, while the salient features of MDRs were compiled from TWRDB archives/reports and other published papers (e.g. Haregeweyn *et al*., 2006; Asmelash *et al*., 2007 and references therein).

All 92 MDRs found in Tigray were inventoried and results analysed quantitatively and qualitatively.

RESULTS AND DISCUSSION

Socio-economic, environmental and livelihood impacts

The basic purpose of constructing the dams was to conserve every drop of water available from floods or run-off to improve socio-economic condition and livelihood of farmers by shifting the rainfall dependent agricultural practices into modern irrigation system. During field inventory observations, from personal communications (interviews and discussions) with elder farmers, the following qualitative results were obtained in relation to socio-economic, environmental and livelihood improvements: 1) increased farmers household income (2 to 3 fold increase from that of rainfed agriculture), 2) water availability for different uses increased (Fig. 2.2a), 3) traditional low value cropping pattern shifted to market oriented high-value or cash crops (e.g. from wheat and maize to vegetables, Fig. 2.2b); 4) availability of fodder increased, 5) diversity of birds species, fishery and beekeeping (Fig. 2.2c) around MDRs increased, 6) rise in groundwater level behind dam-reservoirs (Fig. 2.2d) and emerging of new springs and those which were dried up, due to groundwater recharge from the reservoir, which is a chance to develop new shallow hand dug wells for irrigation and domestic uses, 7) microclimate regulation and buffer against extreme weather events and some aesthetic values.

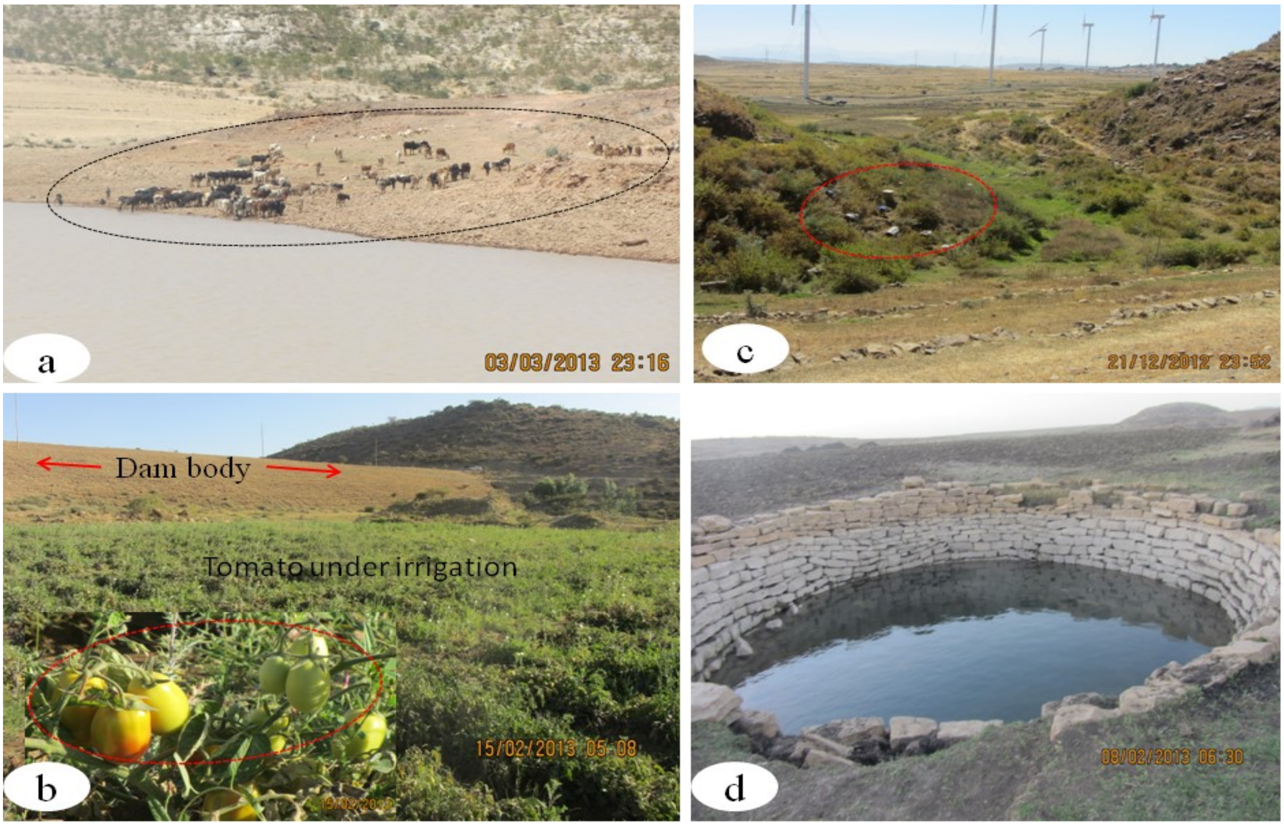


Figure 2.2. Some selected benefits of MDRs in Tigray: a) Watering livestock (Meskebet), b) food security or income generation through dry tomato irrigation (Gerebshegal), c) Beekeeping introduced as a result of MDR construction (Adiamhary) and d) Shallow subsurface water enhanced downstream of MDR, an opportunity for various uses (Arato).

Different researchers obtained generally similar results from different parts of Ethiopia (e.g. Benin, 2006; Sisay *et al*., 2011; Bantero *et al*., 2010; Teshalle, 2001; Behailu, 2002; Pender and Berhanu, 2002; Bacha *et al*., 2011; Nedaw and Walraevens, 2009; Woldearegay, 2001) and from other different countries (e.g. Bhutta, 1999; Murray-Rust *et al*., 1999; Saleh and Mondal, 2001; Hussain *et al*., 2003; Hussain and Hanjra, 2003, 2004; Ashraf *et al*., 2007; Munawar *et al*., 2004; Owusu *et al*., 2011; Pavlov *et al*., 2006; Bhattarai and Narayanamoorthy, 2003; Chen and Ravallion, 2003; Wajid *et al*., 2013). The results of almost all studies show that investment in agricultural water (like small water harvesting schemes, dams, etc.) is a positive and significant determinant of income and consumption, and a negative determinant of poverty (Hanjra *et al*., 2009).

Geology and hydrogeology

Dams vary greatly in their design and construction. Their effectiveness and safety also depend critically on their foundation and all sites differ in their geology. The need for adequate engineering geological investigations in the design and construction of dams can hardly be over-emphasized, for geology, to a large extent, determines the location and type of dams that are built.

Geological considerations are required in dam engineering in at least three main areas (Malomo and Olawole, 1984 and references therein):

(i) the safety of the dam on its foundations,
(ii) the water tightness of the foundation and reservoir area created by the impoundment and
(iii) the availability of construction materials and economic considerations.

The building of the dams in the study area involved geological, engineering geological and geo-hydrological investigation of the dam sites to a variable extent. It is only after establishment of CoSAERT that some geological investigations were performed when constructing a MDR. Hence, complete geological and engineering geological data for all MDRs are not available and they are fragmented and found with individuals. This situation made it difficult to establish inventories, make performance assessment and conduct investigations on leakage problems, and was calling for new information. This was acquainted during field visits (foundation and abutment geology collected). Hence, this MDRs survey is the first of its kind in Tigray and in Ethiopia, which encompasses geological and geo-hydrological information. Moreover, it is a base for other researches related to the MDRs.

Figures 2.3 and 2.4 illustrate the statistical distribution of MDRs in relation to distribution of rock types at their foundation and catchment area. The foundation of a dam is the natural material on which the dam structure is placed, while catchment is the area where all surface water drains to the reservoir created by the dam. Generally, most of the MDRs, 63% out of 92, are founded on Palaeozoic and Mesozoic sedimentary rocks (predominantly sandstone, limestone and shale);

while MDRs located on metamorphic and igneous rocks constitute 18.5% and 12% respectively (Fig. 2.4). The foundations of nearly 6.5% of the MDRs are on two rock groups, igneous (dolerite) intrusion and sedimentary rock groups.

The geology of the catchment area of the MDRs is dominantly covered with sedimentary rocks. About 75% (69 out of 92, Fig. 2.3) of the catchment area of the MDRs are at least partly covered with sedimentary rocks. The rest of the MDRs are located dominantly on metamorphic (13%) and igneous rocks (6.5%), while 5.4% are on both metamorphic and igneous rock groups.

In general, the Palaeozoic and Mesozoic sediments of North Ethiopia can be divided into six stratigraphic units namely Enticho Sandstones, Edaga Arbi Glacial deposits, Adigrat Sandstone, Antalo Limestone, Agula Shale and Upper Sandstone (Amba Aradam formation) (Enquire, 2010) with variable thickness. All these rocks have primary as well as secondary porosity that is responsible for the movement of groundwater and leakage from surface reservoirs. Vertical tectonic joints and horizontal bedding planes characterize the sedimentary rocks in Tigray. These geologic features are favourable for circulation of water. Field observations show that many of the MDRs sited on sedimentary rocks are suffering from excessive leakage problems and are performing less than foreseen.

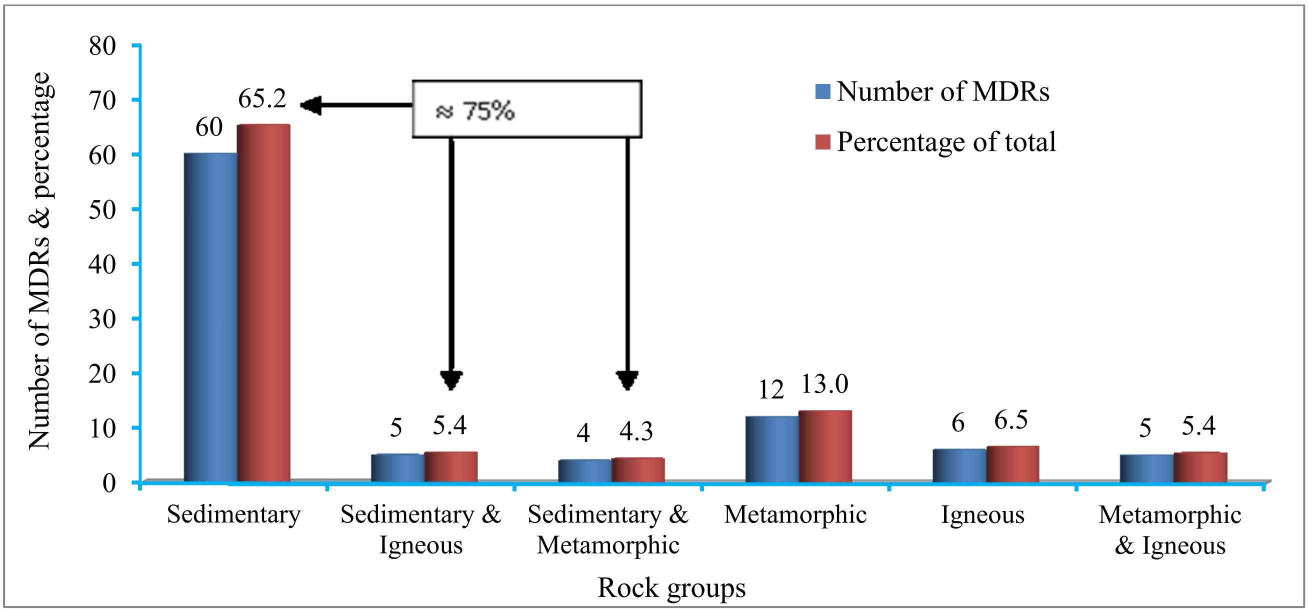


Figure 2.3. Simplified statistical distribution of the catchment geology of MDRs in Tigray.

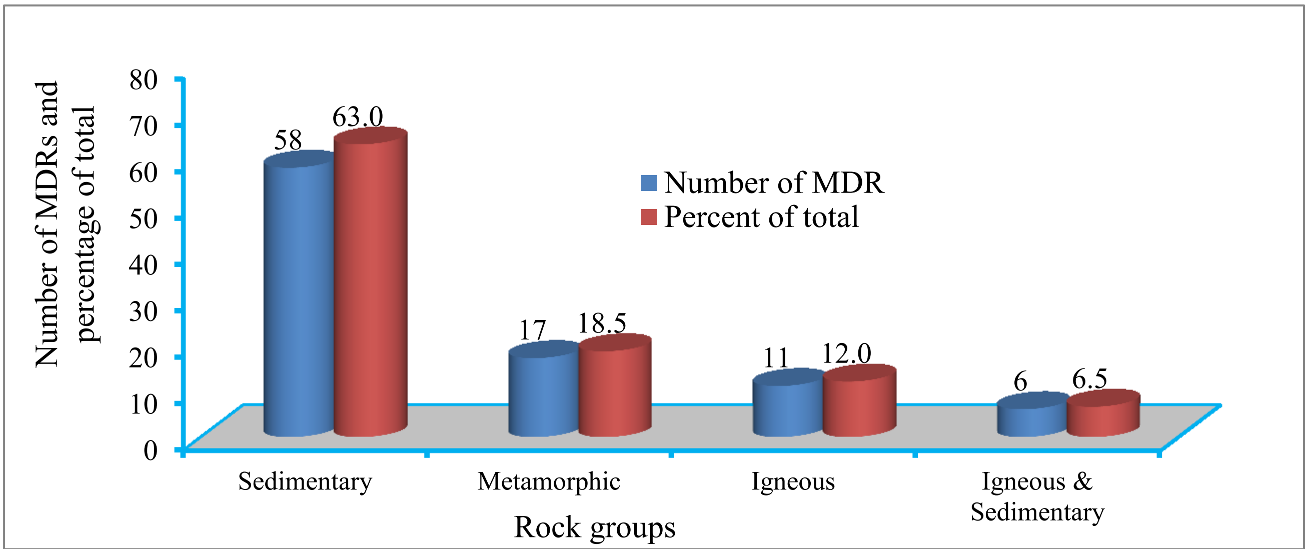


Figure 2.4. Distribution of the MDRs foundation in different geological rock units.

In northern Ethiopia, the metamorphic basement is characterized by low grade metamorphic rocks, mainly meta-volcanics and meta-sediments devoid of primary water bearing structures (Alemayhu, 2006). Their hydraulic conductivity, generally low, is mainly controlled by weathering and fractures. The Precambrian low-grade metamorphic rocks (slates, phyllites, chloritic and sericitic schists) form a regional aquiclude, but marble and meta-limestone with fracture permeability have high productive aquifers. MDRs located at sites free of deep weathering and fractures are found to be safe in terms of leakage problem (e.g. Meskebet) and those located in meta-carbonates are found to show high leakage (e.g. Rubagered).

Groundwater circulation and storage in the volcanic rocks depend on the type of porosity and permeability formed during and after the rock formation. Generally, the volcanics can be divided into Trap Series volcanics (Early Cenozoic) dominantly localized in the highlands, and Mio-Pliocene volcanics (Rift Series) mostly confined within the rift floor (Ayenew *et al.*, 2008). In Tigray, mainly in the central, eastern and western part, the Trap Volcanics are common. Their geo-hydrological character is a function of various factors, among others the effective porosity formed during and after the rock formation is important. Hence, MDR site selection has to consider primary structures formed contemporaneous to the rock formation, and secondary structures developed after the formation of the rocks due to tectonic stress and weathering effects. Furthermore, field observation shows that MDRs founded on igneous rocks that are slightly weathered to fresh, with widely spaced or rare fractures or joints and tight aperture are performing well in terms of leakage problems (e.g. Mainigus).

With respect to risk factors in the MDR construction, particular attention must be paid to ensure the water tightness of the reservoir. An appropriate project concept prior to construction can significantly reduce the risks of geotechnical problems like water losses, or at least minimize them to acceptable levels.

A regional engineering geological and hydrogeological mapping is desirable in areas of rapid dam construction programs, which is non-existent currently. Maps produced from such surveys would depict the geological environment in terms of the suitability for dam construction (chapter 7, Berhane and Walraevens, 2012). The maps would be used in the planning and development of future dams.

General physical and engineering characteristics of dams in Tigray

Historical development of the Micro-Dam Reservoirs (MDR)

Development of MDRs in Ethiopia started in the late seventies (Tiruneh, 2005) to curb the recurrent drought in the country, mainly following the 1974/75 chronic drought (NBCBN-RE, 2005). During 1978 to 1982 five MDRs were constructed throughout Ethiopia in a centralized system in collaboration with donors and technical support from different countries. One of these micro-dam reservoirs (Chichat) is located in the Tigray region within the Tekeze Basin, while the others are in Awash and Wabishebelle Basins (Tiruneh, 2005; NBCBN-RE, 2005).

Since 1992, implementation of MDRs has been decentralized from the Federal Government to Regional Governments. To this effect, the Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSAERT) was established and later in 2002 merged into Tigray Water Resources Development Bureau (TWRDB). Establishment of CoSAERT introduced modern irrigation systems in the region by constructing MDRs. CoSAERT and later other governmental and non-governmental organizations implemented 92 MDRs. Figure 2.5 presents a general overview of year of construction of the MDRs in the northern part of Ethiopia (Tigray Regional State). The peak of MDR construction is dated in the CoSAERT period (1992 to 2001), when its policy and goal was aiming at expanding irrigated lands for the production of food and cash crop. These impressive actions have resulted in a great increase in irrigated lands, even though there are technical and operational problems.

About 57 % of the MDRs were constructed in seven years' period. After the merger of CoSAERT with other organizations, construction was almost stopped for about four years (2002 to 2005), except two MDRs constructed by Relief Society of Tigray (REST), and again resumed in 2006/2007 (Fig. 2.5). Currently two MDRs are under construction and seven are in study and design phases. Table 2.1 presents the general salient features of the MDRs constructed so far in Tigray.

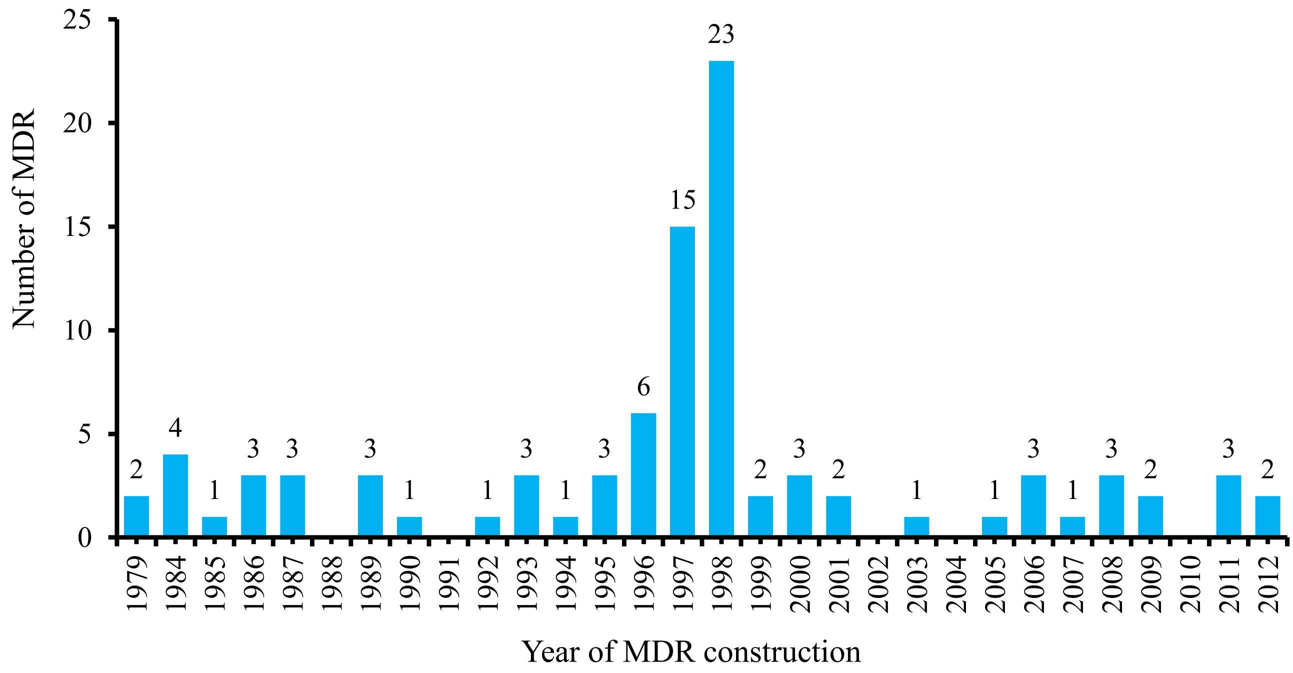


Figure 2.5. Construction of MDRs per year in Tigray. No MDR construction reported between 1980 to 1983.

Distribution of MDRs in Tigray

Initially implementation of MDRs was started in areas where water is a scarce resource for irrigation, livestock and other uses. In Tigray, the Eastern and Southern zones are areas that experience frequent drought, and most of the MDRs were constructed in these parts of the region, with few of them scattered in the Central Zone (Fig. 2.6). All the MDRs except five fall within the Tekeze River Basin and the others fall in Mereb and Danakil/Afar River Basins (Fig. 2.1).

Table 2.1. Basic characteristics of MDRs in Tigray.

Salient features	Dam height (m)	Catchment area (km^2)	Crest length (m)	Max. Reservoir (storage volume) capacity (Mm^3)	Designed command area (ha)
Average	16	9.3	372.8	1.5	121
Maximum	30	43	765	12	3000
Minimum	9	0.36	128	0.1	5

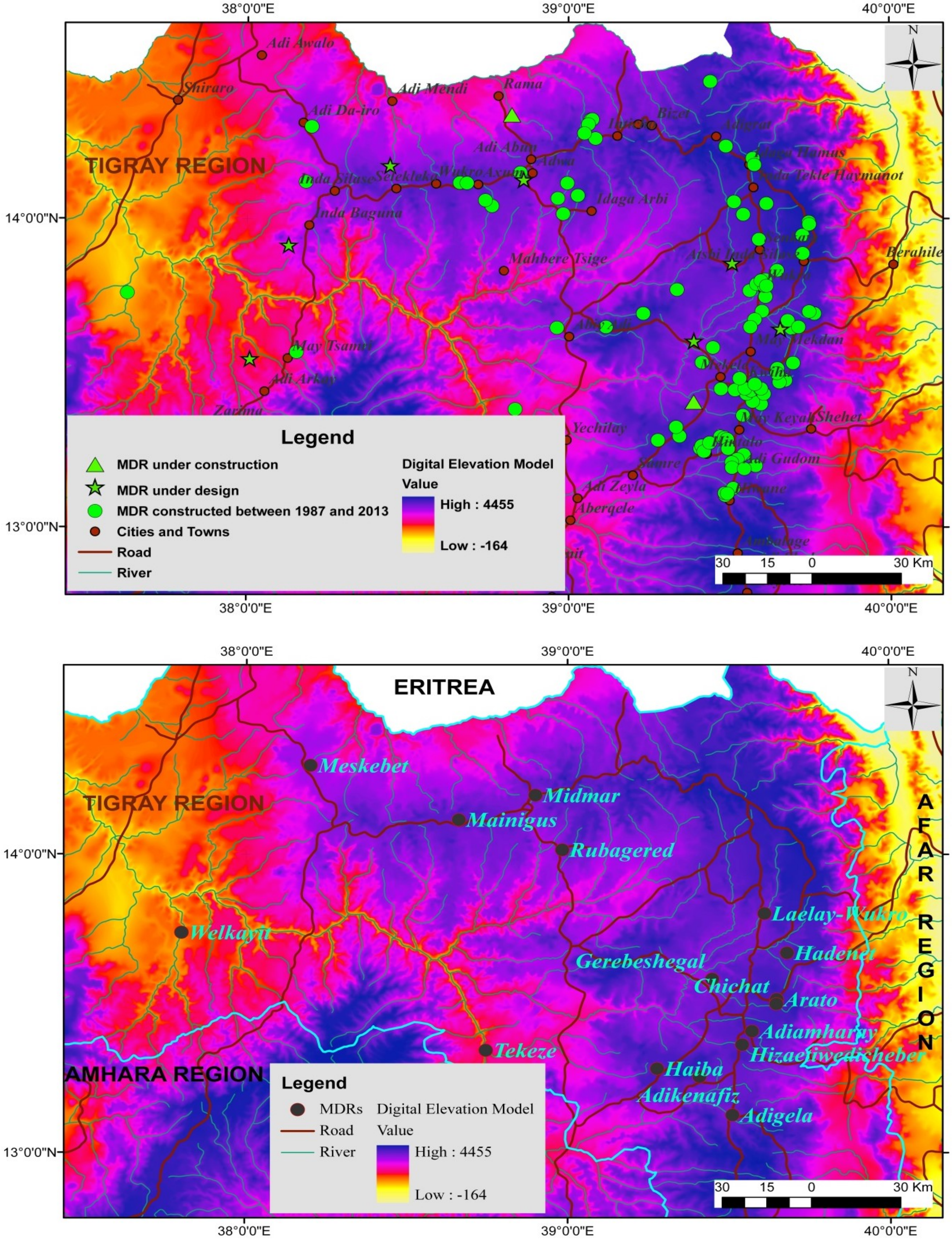


Figure 2.6. Distribution of MDRs in Tigray Region (Northern part of Ethiopia) (top) and location and names of MDRs mentioned in the text (bottom). (DEM data source from ETHIO-GIS data sets/SRTM/.http://dds.cr.usgs.gov/ srtm/version2_1/SRTM3/Africa/)

Height and crest length of the MDRs

Height of dam is the vertical measurement expressed in meters as measured from the downstream toe of the dam at its lowest point to the elevation of the top of the dam, while dam crest length is length of the top of the dam.

Height of the MDRs is important from site investigation, design, construction and operation perspectives. Dams with large height require detailed study and design activities. The height of the MDRs ranges from 9 m to 30 m with an average of 15.7 m. For comparison the height of Tekeze hydropower arch type dam is 185 m and that of Welkait/May-Day dam, which is a sugar cane cultivation project, is about 142 m (WIC, 2013); both are found in the region and they are implemented by the Federal Government.

Dams which are greater than 15 m in their maximum height, measured from the lowest point to the maximum crest level, or dams between 10 to 15 m in height with capacity of more than 1×10^6 m^3 or maximum flood discharge dealt with by the dam is greater than 2000 m^3 per second or the dam is of unusual design are classified as large dams, according to the International Commission on Large Dams (ICOLD, 1974). Following this classification, about 69% of the MDRs are large dams. Therefore, currently there are 66 large dams in Tigray, including Tekeze, Welkayit/May-day and Midmar projects. Large dams require detailed and multidisciplinary investigations. Using the above classification, worldwide there are about 40,000 large dams and an estimated 800,000 small dams (ICOLD,1998). Almost 90 per cent of of the large dams were built after 1950.

The available data for dam crest length are very limited. Many of the MDRs constructed before the establishment of CoSAERT did not have recorded data. From the available data, the dam crest length of the MDRs varies from a minimum of 128 m to a maximum of 765 m with an average of 377 m. Many of the MDRs in Tigray have a side channel spillway located on either sides of the abutment, but few of them have a spillway located on the periphery of the reservoir on a saddle topography.

Catchment area and reservoir capacity

The size, land use and general characteristics of a catchment have important impact on the sustainability of the reservoirs. Large parts of the natural forest in Tigray have been removed and few scattered trees are common along inaccessible slopes and churches. The Northern part of Ethiopia is highly degraded due to a number of factors including agricultural expansion to steep slopes, population pressure, overgrazing, drought, etc. Hence, the problem of soil erosion is straightforward as many researchers pointed out (Haregeweyn *et al*., 2006; Nyssen *et al*., 2004, 2006, 2007, 2008a; Tamene, 2005; Wolka, 2012 and others). Tamene (2005) investigated siltation problems of MDRs in Tigray and showed that the area specific sediment yield of the reservoirs ranges between 345 and 4935 t km^{-2} $year^{-1}$ with a mean of 1900 t km^{-2} $year^{-1}$, which is higher than the Global and African averages, about 1500 and 1000 t km^{-2} $year^{-1}$ respectively (Wolka, 2012). It was concluded that most of the reservoirs will be silted up in less than 50% of their planned lifetime.

The catchment area of the MDRs in Tigray varies from a minimum of 0.36 km^2 to 43 km^2 with an average of 9.3 km^2. About 75% (69 out of 92, Fig. 2.3) of the catchment area of the MDRs falls dominantly or at least partly on sedimentary rocks of less erosion resistant and weak types (e.g. weak shale, friable sandstone and fractured sandstone being the dominant types) with minor part of the catchment covered with other rock groups. The rest of the MDRs are located dominantly on metamorphic (13%) and igneous rocks (6.5%), while 5.4% are on both metamorphic and igneous rock groups (Fig. 2.3). The highlands of Tigray have a mountainous to hilly topography, interspersed with flat to rolling plateaux and plains. The highlands are cut into a number of blocks by deeply incised gorges of the main rivers and tributaries. Generally, rainfall intensity is very high in the highlands of Tigray (Nyssen *et al.,* 2004); combined with less erosion resistant rocks on most catchments this results in high sediment yield in most of the reservoirs downstream. This situation was confirmed during direct field observation, in that a considerable number of MDRs are silted up to the extent that their irrigation outlet (intake pipe) is clogged with sediments (e.g. Maiseraket, Adigela) and others are completely filled in with sediment (e.g. Adikenafiz) (Figs. 2.6 and 2.7). Similar results were obtained by Tamene *et al*. (2011), who concluded that catchments with a high proportion of erodible rocks exhibited higher siltation risk than those dominantly covered with less erodible rocks. Moreover, influence of topography or terrain on sediment yield is found to be opposite and areas of steep slope generate a low sediment yield compared to less steep areas due to geological factors. Gentle slopes dominantly covered with erodible rocks (e.g. shale) generate high sediment yield; on the other hand steep slopes covered with erosion resistant rocks generate less sediment yield (e.g. metamorphic rocks like slate).

The designed capacity of the MDRs varies from a minimum of 0.1×10^6 m^3 to a maximum of 12×10^6 m^3 with an average of 1.5×10^6 m^3. MDRs constructed before the establishment of CoSAERT do not have pertinent archives on their design features and only field observations were used to establish their geological background and problems.

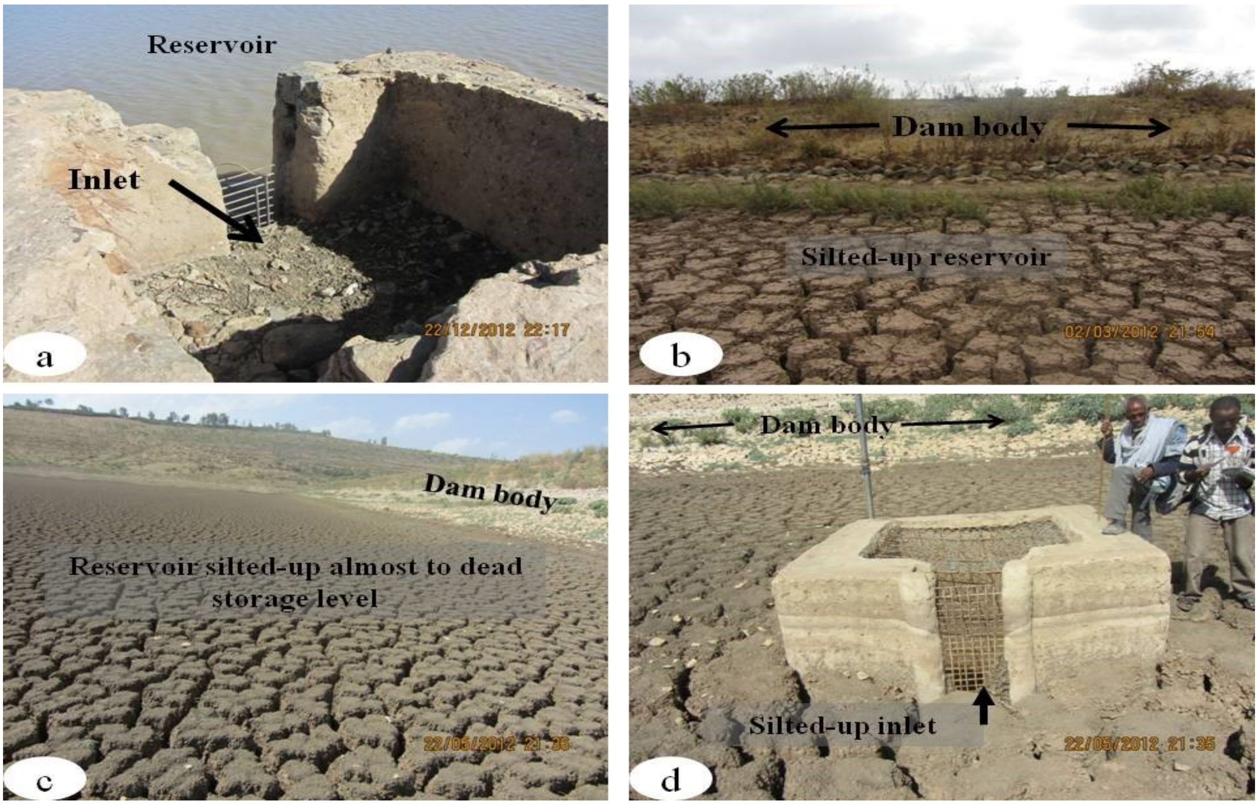


Figure 2.7. Current situation of sedimentation problem in the MDRs in Tigray: a) Intake/inlet clogging in Maiseraket, b) Reservoir completely silted up at Adikenafiz and c & d) Intake/inlet approaching complete silted up at Adigela. For locations see Fig. 2.6.

Purpose of the MDRs

Dams vary greatly in their design and purpose. Current observations and TWRDB archives show that about 77% of the MDRs in Tigray were designed and constructed with the main purpose of water storage for irrigation, but about 47% of them are being functional at a lower performance than expected targets. The remaining 23% of the MDRs were basically implemented for livestock drinking and few of them for supplementary irrigation. Even though it is for very short period of time (shortly following the rainfall season) almost all of the latter group are used for the intended use, i.e. watering livestock. Providing water to livestock in countries like Ethiopia (Tigray) is important, as livestock contributes a lot to the GDP and is a mainstay in the livelihoods of many Ethiopians. In Tigray, livestock provides power, manure, etc. to cultivate the land and meat, milk, etc.

There are two other large dams in the region implemented by the Federal Government for hydroelectric power generation (Tekeze dam) and for water supply (Midmar dam, located in Adwa, Fig. 2.6). Both of them are performing as per their design. Yet, sedimentation problems will affect these dams, unless proper watershed management and protection is planned and implemented in the near future. A third one, Welkayit/May-Day dam, is currently under construction and its main purpose is sugar cane irrigation (Fig. 2.6).

In addition to the main purposes mentioned, the MDRs in Tigray are serving many uses including drinking, recreation, washing, fishing, bee keeping, etc.

Currently observed problems

The present survey of MDRs was focused on geotechnical/engineering geological and engineering problems/aspects. Leakage, reservoir siltation, lack of sufficient inflow, structural damages on dam body and damages on spillway route are among the commonly observed problems at present. Problems pertinent to siltation and inflow/hydrology of the MDRs are well addressed by different researchers (e.g. Abdulkadir, 2009, Haregeweyn *et al*., 2005; Tamene *et al*., 2006; Teka *et al*., 2013; Yazew, 2005 and others). Abdulkadir (2009) also outlined problems associated with poor irrigation management and water application, agricultural extension services, lack of design and construction guidelines, institutional issues, market and infrastructure and socio-environmental issues, and concluded that the problems are wider in scope and need immediate attention by the responsible institutions.

Globally earth dams are one of the most widespread hydraulic structures because of their low cost and comparative simplicity in construction. For example, in the US, it has been estimated around 3,604 earth dams (73% of the total number of dams; Singh 1996). Von Thun (1996) indicated that in the western sector of the USA 60% of earth dams higher than 15 m (in height) have failed due to the process of piping/leakage. Lou (1981, in Singh, 1996) in his compilation of several reports, carried out in different parts of the world, estimates that piping/leakage processes have contributed to the failure of 37% of earth dams. About 73% of the total numbers of dams in USA are earth dams.

Looking into some leakage related problems from around the globe, after 12 years of dam operation, the McMilan Reservoir which was constructed in 1893 dried up (Pearson, 1999). Ambikaipahan (2011) reported 250 dams in Norway (15 m or more in height) and 172 (69%) of them are earth dams. The designing and construction of the earth dams were started in 1924. According to the historic records none of the Norwegian embankment dams higher than 15 m have failed up to 2011, but at the same time several small dams have failed because of inadequate dam engineering works involved. Therefore a careful attention and regular inspection should be focused on small earth fill dams to prevent possibilities of failure.

In UK for embankment dams constructed between 1984-1960 about 30% show incidents mainly due to leakage and leakage related internal erosion which is higher than the incidents by other causes (e.g. 24% inadequate spillway and 18% settlement). On the other hand Tedd *et al*. (2000) reported in UK nearly 173 reservoirs have been discontinued or abandoned attributed to various types of failures. Charles (2000) also reported no dam failure which have caused loss of life since 1930, although there have been a number of failures involving breaching of embankment and many serious incidents. From Africa Akanmu et al. (2011) reported about 200 dams in Nigeria and their associated problems, among others, are seepage/leakage through foundation and lack of hydrological information.

Zhang *et al*. (2007) compiled 900 dam failure cases (66% of which are earth dams) throughout the world (from over fifty countries including US (70%), India (4.2%) and UK (3.6%)) excluding China into a database. Out of the 900 dam failures 593 failure cases on earth dams were used to draw the following statistics based conclusions related to earth dams: of the failed dams more than half are less than 15 m high; most of the failed earth dams were constructed in two periods (1890-1939 and 1950-1979) suffered the higher rate of failure; a dam is most likely to fail within its first five-year service, especially during the first year after construction; most of the cases were caused by either overtopping or quality problems (leakage and piping), both contribute for about 80% of the failures. Table 2.2 presents summary of different types of dams and their associated leakage rate and main rock types.

Table 2.2. Leakage of dams and reservoirs from different countries collected from various sources/literature.

Dam name	**Country**	**Built (year)**	**Height (m)**	**Capacity (m^3)**	**Leakage**	**Location of leakage**	**Geology (main rock types)**	**Source**
Foum-El-Gherza	Algeria	1952			1.6-20.7×10^6 m^3 per year	Both abutments	fissured karstic limestone	Hocini and Moulla (2005)
Hengshan	China	2007	41.55	31.62×$10^6 m^3$	0.540 m^3/s	Right abutment and reservoir	Basalt	Xiao *et al*. (2014)
Da Ye	China	1958 (1974, 1984 and 1989 grouted)			Significant	Beneath dam	Diorite and limestone	Di and Wang (2010)
Ballowal Sounkhri	India	1983-1984	8.5	123.5×$10^3 m^3$	85% of its capacity	Reservoir bed	Clayey soil	Sur *et al. (*1999)
Takarla	India	1983-1984	8.0	15.1×$10^3 m^3$	86%	Reservoir bed	Clayey soil	,,
Karoran	India	1983-1984	1.0	46.6×$10^3 m^3$	61%	Reservoir bed	Clayey soil	,,
Kafrein	Jordan	1968	75.5	4.5×10^6 m^3	0.4-0.7 m^3/s,	Reservoir (1 km far from the dam	Alluvial, faulted limestone and marl	Malkawi and Al-Sheriadeh (2000)
Bayer	Jordan	2006/2007	6	1×10^6 m^3	100%	Reservoir floor	Limestone/marl	Al-Omosh *et. al*. (2008)
Xin–Shan	Taiwan	1980	90	10×10^6 m^3	8 m^3 /day	shell	Sandstone/shale	Peng and Wang (2008)
La Loteta	Spain	1998-2009	34	105×10^6 m^3	>0.046 m^3/s	abutments	Clay, marl, gypsum,	Gutiérrez *et al*. (2015)
San Juan[1F]	Spain	1999		850,000 m^3	excess	Foundation & abutment	Gypsiferous Alluvial, shale	Gutiérrez *et al*. (2003)
Ataturk	Turkey	1990	169	26.7×10^9 m^3	*14 m^3/s	foundation	Marl, limestone	Fell *et al*. (2015)
Unmun Dam	Korea	1992/94	55	1.35×10^6 m^3	0.024-0.058 m^3/s	b/n spillway & dam, dam	Alluvial,andesitic, granite rocks	Lee *et al*. (2005)
Hales Bar	USA	1913/46			54 m^3/s		Carboniferous limestone and shale	Erguvanli (1979)

Keban	Turkey	1974	163	$30.6\times10^{12}m^3$	26-30 m^3/s	Reservoir (cavity at 320 m below crest)	Palaeozoic limestone/marble	Erguvanli (1979); Ertunc (1999)
Lar	Iran	1974/80	110	960×10^6 m^3	16 m^3/s	Foundation & abutments (cavity 210 m below river bed)	Mesozoic limestone, volcanics, lake deposits	Fell *et al*. (2015); Uromeihy (2000)
Attaturk	Turkey	1990	179	48.7×10^9 m^3	>10 m^3/s	Foundation and abutments (below grout)	Palaeozoic limestones, folded and faulted	Unal *et al*. (2007); Ertunc (1999)
Great Falls	USA	1925/44			13 m^3/s		Limestone	,,
Camarasa	Spain	1920			12 m^3/s		Jurassic dolomitic limestone	Erguvanli (1979)
Dokan	Iraq	1959/60			4 to 5 m^3/s		Cretaceous dolomitic limestone	Erguvanli (1979)
Fodda	Morroco	1928/33			3 to 5 m^3/s		Jurassic limestone	,,
Civitella Liciana	Italy				Never stored		Cretaceous limestone	Erguvanli (1979)
Kopili	India	1970/1975			Never stored		Eocene limestone	,,
May	Turkey	1959			Never stored		Mesozoic and Cenozoic limestone	Erguvanli (1979)
Montejagne	Spain	1920			Never stored		Mesozoic and Cenozoic limestone	Erguvanli (1979)
Perdikas[1]	Greece	1962	96	785×10^6 m^3	Never stored		Miocene limestone	Erguvanli (1979)
Shahid Abbaspour[2]	Iran	1976	200	Regulate Karun River	11 m^3/s	Reservoir/right abutment	karstic limestone, marl, shale and gypsum	Ghobadi *et al*. (2005)
Hales Bar	USA				50 m^3/s		Karstified rock	Milanovic (2015)
Taoqupo	China				27.8 m^3/s		Karstified rock	,,

Vrtac	Montenegro				25 m^3/s		Karstified rock	,,
Iliki	Greece				13 m^3/s			,,
Camarsaa	Spain	1927/31.	92		11.2 m^3/s		karstified dolomites & limestone	Milanovic (2015)
Marum[4]	Iran		170		9.5 m^3/s	foundation	Karstified rock	,,
Great Falls[3]	USA	1917	28	60×10^6 m^3	9.5-12.7 m^3/s		Karstified rock	,,
Fodda	Morocco				3-5 m^3/s		Karstified rock	,,
Mosul[1]	Iraq	1981/84	110	11.1×10^9 m^3	1.4 m^3/s	Foundation (60-70 m deep)	Clayey and marly rocks, gypsum,limestone	Milanovic (2011)
Huoshipo[1]	china		23	4.7×10^6 m^3	0.237 m^3/s	Foundation	Gypsum bearing dolomite	Milanovic (2011)
Kamskaya	Russia	1954	21		excess	foundation	Argillite, sandstone, gypsum, limestone	Milanovic (2011)
Armagan[1]	Turkey	1997	57.5	51.59×10^6 m^3	0.049-0.8 m^3/s	foundation	Metalimestones & chalk schists, fault	Unal *et al.* (2008)
Wadi Arab[1]	Jordan	1987	82.5	20×10^6 m^3.	0.02-0.072 m^3/s	Foundation, abutment	Limestone, chert, chalky marl, faults	A1-Homoud *et al*. (1995)
King Talal	Jordan	1978	108	86×10^9 m^3	0.512 m^3/s	Foundation, left abutment	Limestones, shales, marls, sandstone, faults	A1-Homoud *et al*. (1995)
Arato[1]	Ethiopia	1997	20	2.59×10^6 m^3	**0.016-0.053 m^3/s	Foundation & reservoir	Limestone/marl/shale	this study (chapter 5)
Gumselassa[1]	Ethiopia	1995	11.5	1.9×10^6 m^3	$^+$0.0395 m^3/s	Foundation & abutment	Dolerite/shale/ limestone	Abdulkadir (2009).
Haiba[1]	Ethiopia	1998	16	3.1×10^6 m^3	$^+$0.0666 m^3/s	Foundation	Dolerite	,,
Laelay-Wukro[1]	Ethiopia	1998	14.3	0.85×10^6 m^3	≈0.0 m^3/s	-	Sandstone/siltstone/ shale	,,

[1] Earth Dam, [2]Concrete Arch Dam, [3]concrete gravity, [4]Rock fill, [F]Failed, *grout depth from 180 m to 300 m, **it was designed for 9965 m^3 (annual) as allowable seepage, $^+$during maximum reservoir level.

The present inventory and direct field observations (in Tigray, Ethiopia) show that the MDRs are facing many problems. About 61% are facing siltation problems, 53% leakage, 22% inflow problems, 25% structural damages on dam body and 21% damages on spillway route (a structure over or through which surplus flood flows are discharged) mainly due to erosion (Fig. 2.8). Haregeweyn et al. (2006) reported for 60% of MDRs serious leakage, for 61% insufficient inflow and for 35% sedimentation problems, based on a survey of 54 MDRs mainly founded on or their catchment falling on sedimentary rocks. The discrepancy here might be attributed to temporal variations (siltation problem in a given MDR increases with time compared to leakage) and the number of surveyed MDRs. It is important to note at this point that many of the MDRs are suffering from more than one problem. Teka *et al.* (2013), after evaluating the performance of two MDRs in Tigray (Haiba and Laelay Wukro), pointed out that a combination of evaporation and seepage losses are the main reasons for the lower availability of irrigation water than initially foreseen, even though the mechanisms and causes of seepage/leakage were not addressed in their paper. Sur *et al.* (1999), after investigating three earthen dam reservoirs in northern India, outlined that seepage/leakage is found to be the major mode of water losses which accounts for 61 to 86% of the total water losses from the reservoirs. Moreover about 1.18% of their storage capacity is lost per year by a siltation rate of about 38 t/ha.

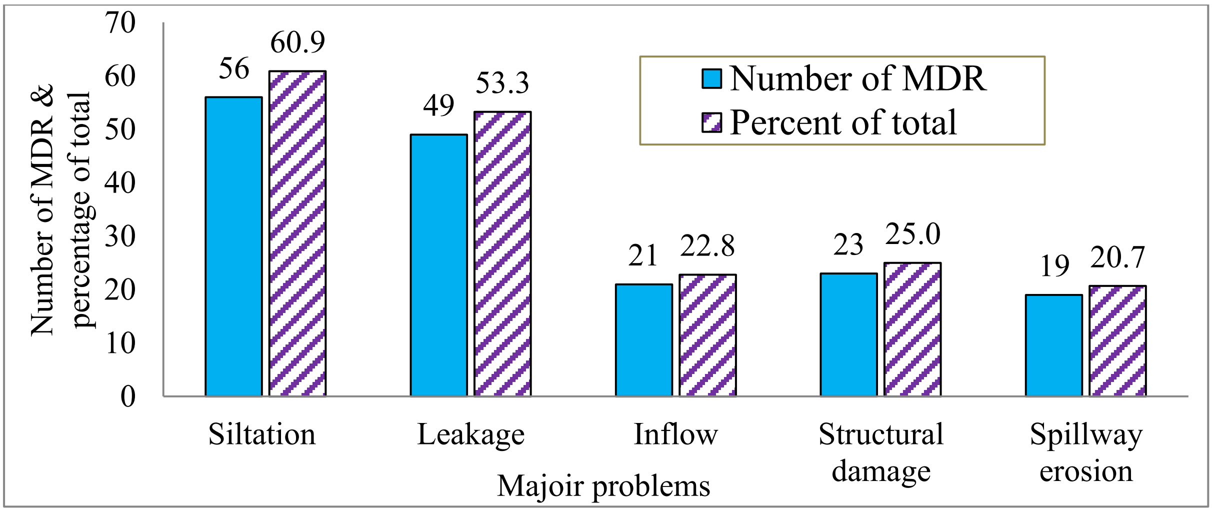


Figure 2.8. Statistical distribution of different problems with MDRs in northern Ethiopia (Tigray).

Table 2.4 presents a survey of the main problems, foundation and catchment geology of individual MDRs with their respective location. The main problems include reservoir siltation, leakage from reservoir and problem of inflow (no sufficient yield from the catchment to fill the reservoir). In addition, geotechnical problems associated to the dam body and spillway route were observed. This includes dam and spillway crack, erosion, subsidence or settlement of dam and slope instability. This survey further showed that more than 75% of MDRs in Tigray are founded on or their catchments fall at least partly on sedimentary rocks (Tables 2.3 and Fig. 2.9), while almost all of the MDRs located in sedimentary terrain have one or more problems. Sedimentary rocks like shale and sandstone, which are common in the sedimentary terrain in Tigray, are highly erodible due their inherent weakness, steep slopes of catchments and high intensity of rainfall in the area. This situation illustrates the significance and magnitude of the problems. Moreover, Fig. 2.9 clearly portrays that the proportions of the problems (siltation and leakage) are significant in MDRs founded completely or at least partly on sedimentary rocks, followed by metamorphic and finally igneous rocks. Out of 58 MDRs founded on sedimentary rocks, 36 have a leakage problem (62%), 15 structural damage (26%) and 12 spillway erosion (21%). Out of 17 MDRs founded on metamorphic rocks (metavolcanics, slate, phyllite), 6 have leakage problem (35%), 4 structural damage (24%) and 4 spillway erosion (24%), and out of the 11 MDRs on igneous (dolerite, basalt) rocks, 2 have leakage problem (18%), 4 structural damage (36%) and 2 spillway erosion (18%). Similarly, out of 6 MDRs founded on a combination of igneous and sedimentary rocks, 5 have leakage problems (83%) and one has spillway erosion (20%) while no structural damage was observed. Siltation problem and leakage are more pronounced in sedimentary rocks or sedimentary related geological terrain, while the other problems like structural damages on dam body and spillway route, more or less are equally distributed in all rock types. It was observed that siltation is more important on catchments where shale is dominant, while leakage is more pronounced in foundations where fractured and bedded limestone is dominant (Berhane and Walraevens, 2012 and chpater 3).

Catchment geology contributes more to siltation and inflow problems than foundation geology, hence catchment geology is considered in the evaluation of siltation and inflow problems. Out of the 60 MDRs with their catchment area falling on sedimentary rocks, 45 (75%) and 17 (28%) of them have siltation and inflow problems respectively. Similarly, out of 5 MDRs on a combination of sedimentary and igneous rocks, 4 (80%) and 1 (40%) of them have siltation and inflow problems. Out of the 4 MDRs on a combination of sedimentary and metamorphic rocks, 1 (25%) has siltation problem, but no inflow problem; out of the 12 MDRs on metamorphic rocks, 4 (33%) and 2 (17%) of them have siltation and inflow problems respectively; out of the 6 MDRs on igneous rocks, 2 (33%) of them have siltation problem but no inflow problem, and out of the 5 MDRs whose catchments fall on a combination of metamorphic and igneous rocks, 1 (20%) has inflow problem and no siltation problem was observed.

In general, during the time of the field survey (2012/13), out of the 92 MDRs, 56 have siltation problem, 49 leakage, 23 structural dam body damage, 21 inflow problem and 19 have spillway route erosion.

Some examples of the geo-hydrological and geotechnical problems are shown in Fig. 2.10, like failure of spillway by erosion (Fig. 2.10a), excessive leakage (Fig. 2.10b) and sediment filled up reservoir (Fig. 2.10c). It can be concluded that construction of MDRs in this cyclically alternating sedimentary succession in Tigray is very challenging and requires an in-depth three dimensional understanding of the geotechnical and geo-hydrological conditions.

Table 2.3. Summary of list of MDRs, observed problems and respective site geology (more inventory data are included in Appendix C2 on CD). dol=dolerite, sedi=sedimentary, ign=igneous, meta=metamorphic.

S. No.	Name of MDR	GPS location		Observed problems					Geology	
		X	Y	siltation	leakage	inflow-problem	structural damage	spillway route erosion	foundation	catchment
1	Adikenafiz	544282	1465485	yes	no	no	no	yes	sedimentary	sedimentary
2	Mai-egam	544774	1466420	yes	yes	no	no	no	sedimentary	sedimentary
3	Flegleg	545500	1464438	yes	yes	no	yes	no	sedimentary	sedimentary
4	Gumselasa	558892	1463259	yes	yes	no	no	no	ign+sed	sedimentary
5	Hizaetiwedicheber	558645	1477362	yes	yes	no	no	no	sedimentary	sedimentary
6	Gerebmihiz	551047	1469762	yes	yes	no	no	no	sedimentary	sedimentary
7	MaiGassa-2	552471	1469368	yes	yes	no	no	no	sedimentary	sedimentary
8	MiaGassa-1	553271	1468830	yes	yes	no	no		sedimentary	sedimentary
9	Maidele	556716	1461628	yes	yes	no	no	no	sedimentary	sedimentary
10	Grashito	554851	1460492	yes	yes	no	no	no	sedimentary	sedimentary
11	Mejae	554941	1458662	no	yes	yes	no	no	sedimenatry	sedimenatry
12	Adigela	555375	1451253	yes	yes	yes	no	no	sedimentary	sedimentary
13	Shilant-4	552725	1448642	yes	yes	yes	no	no	sedimentary	sedimentary
14	Shilant-3 (small)	552516	1449497	no	yes	yes	no	no	sedimentary	sedimentary
15	Shilant-I	553379	1449351	no	yes	yes	no	no	sedimentary	sedimentary
16	Korir	566212	1519876	yes	yes	no	yes	no	sedimentary	sedimentary
17	Laelay-Wukro	566096	1525982	yes	no	no	no	no	sedimentary	sedimentary
18	Aynalem/Lather Factory	560909	1522043	yes	yes	no	no	no	sedimentary	sedimenatry
19	Adishuhu	574937	1508567	yes	yes	no	yes	no	sedimentary	sedimenatry
20	Hadenet (Maimogeo)	573680	1511354	yes	no	no	no	yes	sedimenatry	sedimenatry
21	Ruba-Feleg	578606	1541930	no	yes	no	yes	yes	metamorphic	metamorphic
22	Teghane	578712	1535400	no	yes	yes	yes	no	metamorphic	metamorphic
23	Gindae	536462	1522393	yes	yes	yes	yes	no	sedimentary	sedimentary
24	Hizaeti-Afras	563207	1524387	yes	yes	no	yes	yes	sedimentary	sedimentary
25	Gorongoh (Laelay Agulae)	565055	1514649	no	no	yes	yes	yes	sedimentary	sedimentary
26	Haiba	530048	1468434	yes	no	no	no	no	ign/dolerite	ign/dol+sedi
27	Meila	537268	1469877	yes	yes	no	yes	yes	sedimentary	sedimentary
28	Betquae	536130	1473132	no	yes	no	no	no	sedimentary	sedimentary
29	Embagedo	564710	1481393	yes	yes	no	yes	no	sedimentary	sedimentary
30	Adiamharay	561894	1482314	yes	yes	no	no	no	ign/dol+sedi	sedimentary
31	Maiserakit	575495	1496133	yes	yes	no	no	yes	sedimentary	sedimentary
32	Hashenge	572850	1489900	yes	yes	no	no	no	dol+sedi	dol+sedi
33	Adiazaboey/Endazoey	570879	1489260	yes	yes	yes	no	no	sedimentary	sedimentary
34	Arato	570198	1494180	yes	yes	yes	no	no	ign/dole+sedi	ign/dole+sedi
35	Duranbessa	547394	1467513	yes	yes	no	yes	no	sedimentary	sedimentary
36	Gerbsegen	553619	1465412	no	yes	yes	no	no	dol+sedi	sedimentary
37	Gerebawso	559827	1485048	yes	yes	no	no	no	sedimentary	sedimentary
38	Adihilo	561327	1486172	yes	yes	yes	no	no	sedimentary	sedimentary
39	Earquhila	564560	1486767	yes	yes	no	no	no	sedimentary	sedimentary
40	Maitewaru	562913	1459283	no	yes	yes	no	no	sedimentary	sedimentary
41	Gerebeshegal	548533	1501661	yes	yes	yes	no	no	sedimentary	sedimentary
42	Sewhimeda	544878	1496321	yes	yes	no	no	no	sedimentary	sedimentary
43	Dibdibo	509077	1576560	no	no	no	no	yes	igneous	igneous
44	Meskebet	413720	1580890	no	no	no	no	no	metamorphic	meta+sedi
45	Mai-nigus	463493	1560733	no	no	no	no	no	igneous	igneous
46	Mai-gundi	474241	1552390	no	no	no	no	no	metamorphic	meta+sedi

47	Mai-Leba	525110	1513860	yes	yes	no	no	no	sedimentary	sedimentary
48	Mai-Haydi	559073	1458213	no	no	no	no	no	sedimentary	sedimentary
49	Adiakor	565680	1485068	yes	no	no	no	no	sedimentary	sedimentary
50	Gereb-Baeti	551259	1486829	no	no	no	no	no	sedimentary	dol+sedi
51	Rubagered	498203	1549567	no	yes	no	no	no	metamorphic	metamorphic
52	Adiazabe-Agulae	562588	1511721	no	no	yes	no	no	sedimentary	sedimentary
53	Kihen	561115	1509031	yes	no	no	no	yes	sedimentary	sedimentary
54	Mai-siye	472055	1554423	no	yes	no	no	no	metamorphic	meta+igneous
55	Maisessela	503134	1556129	yes	no	no	no	no	metamorphic	metamorphic
56	Filaga	580773	1546642	no	no	no	no	no	metamorphic	metamorphic
57	Era	582615	1513850	no	no	yes	no	no	sedimentary	sedimentary
58	Beles	507548	1583338	no	yes	no	no	no	igneous	meta+igneous
59	Mehimas	507998	1583385	no	no	no	yes	no	igneous	meta+igneous
60	Endagewergis	506704	1581668	no	no	no	yes	no	igneous	meta+igneous
61	Mokadu	505368	1578433	no	no	yes	yes	no	igneous	meta+igneous
62	Maikoko	547617	1597004	yes	no	no	no	no	metamorphic	meta+sedi
63	Adiabagie	563995	1540435	no	no	no	no	no	metamorphic	metamorphic
64	Tsinkanet	558718	1549382	yes	no	no	no	no	sedimentary	sedimentary
65	Mai-Demu	411770	1561110	no	no	no	yes	yes	metamorphic	meta+sedi
66	Serenta	408500	1500100	no	no	no	no	no	igneous	igneous
67	Sesa	499617	1560577	no	no	no	no	no	metamorphic	metamorphic
68	Aqushela	482025	1479551	no	no	yes	no	no	metamorphic	metamorphic
69	Chichat	570103	1492448	yes	no	yes	yes	no	sedimentary	sedimentary
70	Hangoda	555612	1553871	no	no	no	no	no	sedimentary	sedimentary
71	Kalema	360985	1518949	no	no	no	no	no	igneous	igneous
72	Adi-Asmae	496075	1508724	yes	no	no	no	no	metamorphic	metamorphic
73	Bokoro	561894	1569466	yes	no	no	no	no	sedimentary	sedimentary
74	Dibla	552876	1573827	yes	yes	no	no	no	sedimentary	sedimentary
75	Enda-Gabriel	562433	1567194	no	yes	yes	no	no	sedimentary	sedimentary
76	Wukro college	565839	1523756	yes	no	no	yes	yes	sedimentary	sedimentary
77	Adiseleste	555938	1486430	no	yes	no	no	yes	sedimentary	sedimentary
78	Mai-Delaeta	591673	1564307	no	no	no	yes	yes	metamorphic	metamorphic
79	Godew	559318	1486921	yes	no	no	yes	yes	sedimentary	sedimentary
80	Haresaw	580888	1545882	yes	no	no	no	no	sedimentary	sedimentary
81	Kelsha-Emni	577293	1509031	no	no	no	yes	no	sedimentary	sedimentary
82	Mai-Abakat	465848	1560622	yes	no	no	yes	yes	igneous	igneous
83	Mai-Tsaeda	566508	1553252	yes	yes	no	no	no	sedimentary	sedimentary
84	Metseko	570103	1529299	yes	yes	no	no	yes	metamorphic	metamorphic
85	Mai-Korbet	557520	1490606	yes	no	no	no	yes	dol+sedi	dole+sedi
86	Chini	512583	1509031	yes	yes	no	no	no	igneous	igneous
87	Mai-Mungude	496405	1555094	yes	yes	no	no	no	metamorphic	metamorphic
88	Wukro North	564710	1525614	yes	no	no	yes	yes	sedimentary	sedimentary
89	Shuwela/Anguleita	580888	1514559	yes	yes	yes	no	no	sedimentary	sedimentary
90	Gereb-Maizbie	566508	1523771	yes	no	no	yes	yes	sedimentary	sedimentary
91	Adi-Era/Aba-Gabr	564710	1486921	no	no	no	no	no	sedimentary	sedimentary
92	Mokoro	562616	1488528	yes	no	no	no	no	sedimentary	sedimentary

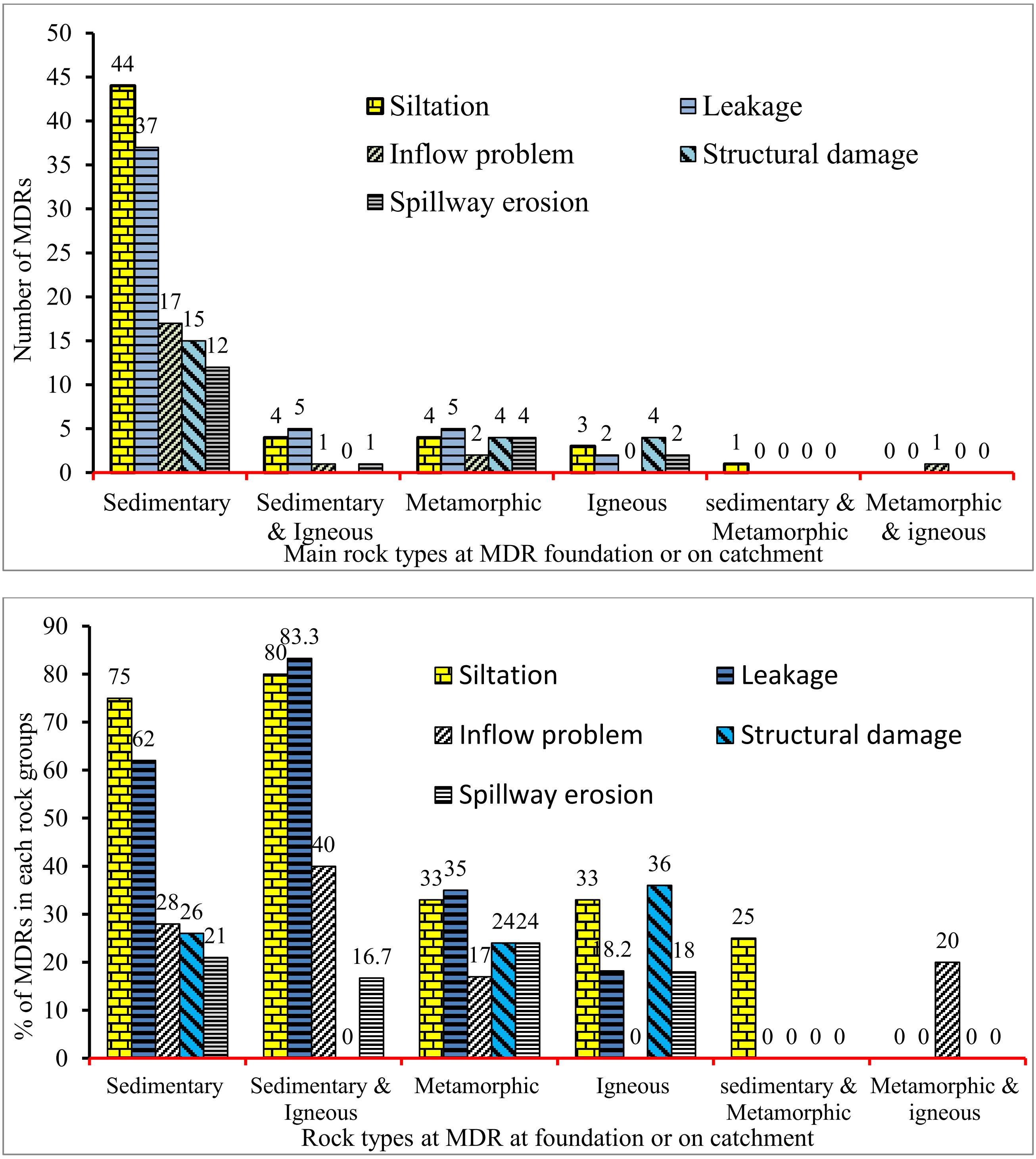


Figure 2.9. Statistical distribution of the major geo-hydrological and geotechnical problems in relation to major rock types at dam foundation (top) and percentage of MDRs with problems in each rock group (bottom). For siltation and inflow problems, catchment geology was considered and for the other problems, foundation geology was considered.

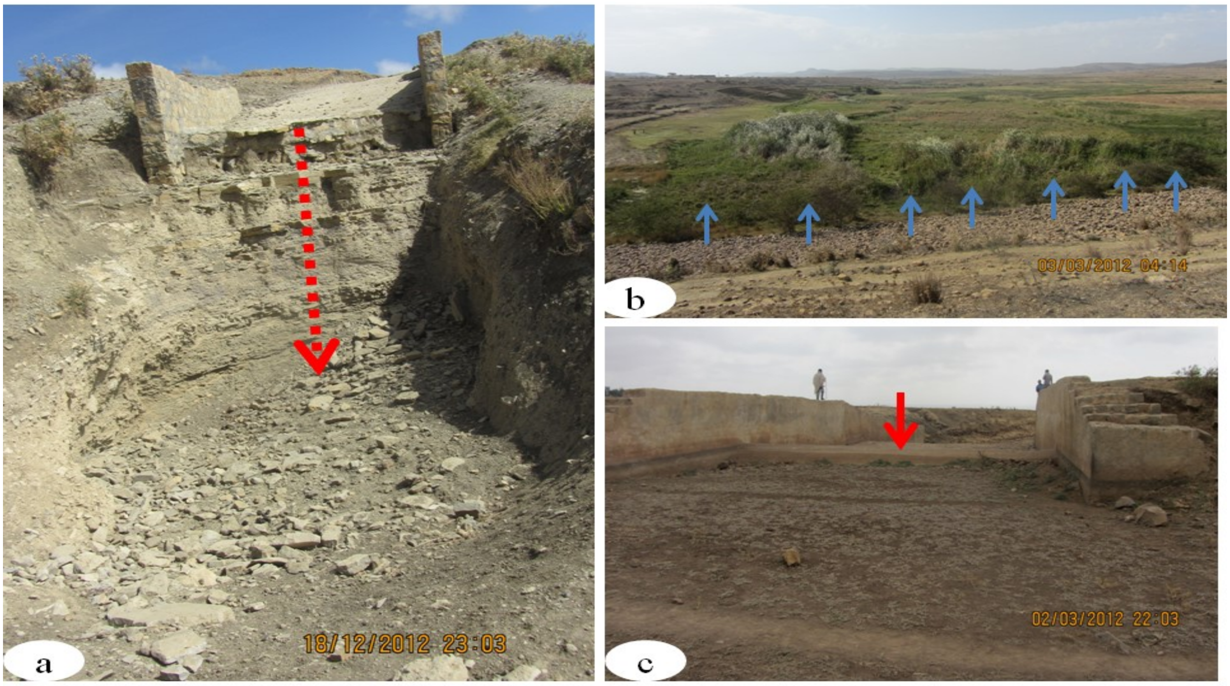


Figure 2.10. Selected engineering geological and geo-hydrological problems: a) severe erosion removed the stilling basin of the spillway (Hadent), b) leakage problems through foundation bed rock (Hizaetiwedicheber), c) reservoir silted-up already to the crest level of the spillway (Adikenafiz). For locations see Fig. 2.6.

CONCLUSIONS AND RECOMMENDATION

An inventory of the 92 MDRs in Tigray with their respective problems and geology was conducted. With respect to risk factors in MDR and other water harvesting scheme construction projects in complex geological settings, particular attention must be paid to ensure the water tightness of the reservoir and foundation. An appropriate project concept prior to planning followed by in-depth geotechnical and geo-hydrological studies can significantly reduce the risks or at least minimize water losses or leakage, siltation and other problems to acceptable levels. The decision to construct a MDR should not be based on poor geological understanding and without respect of or adaptation to the findings of geological conditions.

The main problems highlighted, siltation and leakage, are found to be highly linked to geological conditions. These problems are found to be very high in MDRs located in sedimentary rocks. Siltation is found to be more significant in areas where shale is the dominant rock type; on the other hand leakage is more common in areas where limestone predominates. It is well known among workers and researchers of reservoir related problems in the study area that the high rate of seepage is the main problem, but its sources, mechanisms and causes were not understood. This study clearly demonstrates the crucial role of geology related to the MDR problems. In-depth geological investigation of an area targeted for MDR construction, is an indispensable condition for reducing the problems with MDRs in the future.

ACKNOWLEDGEMENTS

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Contribution of authors

Name of author	**Role of the author in this chapter**
Gebremedhin Berhane	*Was responsible for all the aspects of the study, data collection, inventory, interpretation and writing the article/chapter*
Tesfamichael Gebreyohannes	*Contributed during fieldwork*
Kristine Martens	*Share ideas on interpretation*
Kristine Walraevens	*Was the supervisor in the study, and critically reviewed the article*

A close view of Hashenge MDR (part of the right abutment/flank, limestone-shale-marl intercalation unit, and the dam body) ©2010 Gebremedhin Berhane

CHAPTER 3

Water leakage investigation of micro-dam reservoirs in Mesozoic Sedimentary sequences (Northern Ethiopia)

This chapter is based on Gebremedhin Berhane, Kristine Martens, Nawal Al Farrah, Kristine Walraevens. (2013). Water leakage investigation of micro-dam reservoirs in Mesozoic sedimentary sequences in Northern Ethiopia. J. African Earth Sci 79: 98–110. DOI:10.1016/j.jafrearsci.2012.10.004.

ABSTRACT

Billions of people throughout the world depend on dam reservoirs for domestic water supply, irrigation, electricity and flood protection. In the last two decades, a number of micro-dam reservoirs (MDRs) have been constructed in northern Ethiopia to fight the recurrent drought and improve agricultural productivity through irrigation. However, about 53% of these MDRs are suffering from excessive leakage. Comprehensive studies have been carried out on two micro-dams to assess and pinpoint the causes of leakage. Arato and Hashenge micro-dams located in Northern Ethiopia have 20 m and 19 m height and 2.59 Mm^3 and 2.23 Mm^3 reservoir capacities respectively. Observational geological description, shallow hand dug test pits, vertical electrical sounding and drilling of geotechnical holes were used to understand the overall geological, engineering geological and geo-hydrological set-up of the area. The different methods applied, such as discontinuity analysis, geophysical surveys, drilling information and packer test delivered results that were found to be in close agreement and led to the identification of the leakage zone. The geological units found in both sites are limestone-shale-marl intercalation, dolerite and recent soil deposits. The research results revealed that the limestone-shale-marl intercalation unit is heterogeneous and shows alternating sequences. Analysis of the different data shows that the limestone-shale-marl intercalation is a pervious unit (hydraulic conductivity in the range of 10^{-4} to 10^{+2}cm/s) and was found to be responsible for the excessive leakage of the micro-dams. It is hoped that the observations, data and insights gathered from these case studies will enable to plan technically and economically viable anti-leakage measures for these schemes and help for future new site selection and design activities in the region and other regions with a similar geological environment.

INTRODUCTION

Billions of people throughout the world depend on dams and reservoirs for domestic water supply, irrigation, electricity and flood protection. Dams require significant investments for investigation, design, building and maintenance, and yet their usefulness and integrity are constantly threatened by leakage and sedimentation. Leakage and preferential flow paths are often controlled by the geology of the site. Therefore, any leakage study should always include obtaining detailed geological and hydrogeological information as the first step.

The variability of rainfall coupled with extended duration of droughts is threatening food and water security in sub-Saharan Africa in general (De Hamer, 2008) and in East Africa, in particular. Construction of micro-dams in Ethiopia started in the late seventies to combat the recurrent drought in the country (Tiruneh, 2005). The construction of micro-dam reservoirs (MDRs) in arid and semi-arid areas like in Northern Ethiopia, where the main socio-economic activity is rain fed agriculture directly linked to the erratic and variable rainfall in time and space (Yazew, 2005), is quite important. The northern part of the country, particularly the area around Mekelle Outlier, is characterized by intermittent rivers, which are dry 8 to 9 months of the year (Nedaw and Walraevens, 2009). From the perspectives of food security and poverty reduction, the construction of MDRs, to ensure dry season water availability, is crucial. In the last two decades, about 92 MDRs have been constructed in Ethiopia for irrigation and domestic purposes.

Since 1992, the Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSAERT), responsible for constructing MDRs, has been established. However, due to technical and operational problems, most of the MDRs (chapter 2) are not serving as planned objectives (Abdulkadir, 2009; Berhane, 2010a; Desta, 2005; Gonzalez-Quijano, 2006; Haregeweyn *et al*., 2005; Nedaw and Walraevens, 2009) (Table 3.1).

According to Haregeweyn *et al*. (2006), out of the 54 constructed micro-dam reservoirs in Tigray, nearly 60% of them have serious leakage problems, 61% have problems of insufficient inflow or hydrological problems and 35% have sedimentation problems, attributed to inadequate planning and lack of experiences. Moreover, a survey made on 40 micro-dam reservoirs in 2007 by Abdulkadir (2009) indicated that there are a number of problems which are affecting their performance. The assessment was made based on the United States Federal Emergency Management Agency (FEMA) dam-safety guidelines. The observed problems were insufficient inflow, leakage, sedimentation and dam instability. The seepage quantity estimated by CoSAERT based on records made in successive months in 2001 varied significantly among reservoirs with the lowest being 0.27 l/s and the highest 81 l/s. Moreover, in many micro dam reservoirs the rivers are perennial in the downstream, while ephemeral or intermittent in the upstream part. This situation indicates that a continuous leakage from the reservoir is recharging shallow aquifers and leads to emerging of new springs and increased discharge of existing ones (Gebreyohannes, 2009; Gonzalez-Quijano, 2006).

Desta (2005) pointed out that, due to the ambitious plan of constructing a large number of micro-dams in the shortest time possible, adequate studies related to proper site selection and other pertinent investigations were not conducted. Due to this fact, water leakage has become a major problem in many of the MDRs (Abdulkadir, 2009; Haregeweyn *et al*., 2006). The leakage may be through the base, while in other cases it is through the sides and through the strata in which the reservoir was constructed.

Engineering geological investigation and mapping mainly focus towards understanding the interrelationships between the geological environment and the hydraulic structure, the nature and relationships between the geological components, the active geodynamic processes and the prognosis of processes likely to result from the changes being made (UNESCO, 1976). Even though a number of studies have been carried out related to runoff or inflow, sediment yield, ecology and health related issues of the reservoirs in Tigray (e.g. Abdulkadir, 2009; Awulachew *et al*., 2005; Desta, 2005; Dejenie *et al*., 2008, 2009; Girmay *et al.*, 2009; Gonzalez-Quijano, 2006; Haregeweyn *et al*., 2005, 2006, 2008a, b, 2011, 2013; Tamene, 2005; Tamene *et al*., 2011; Teka *et al*., 2013; Teshome, 2003; Yazew, 2005 and others), leakage and associated engineering geological and geo-hydrological aspects, which are critical in terms of water harvesting perspectives for existing and future reservoirs and related development plans, have not yet been touched. This chapter is aiming at assessing and evaluating the engineering geological and geo-hydrological conditions of the two MDRs (Arato and Hashenge) and at identifying the main causes of leakage. The author hope that the representative examples of these MDRs in the Mekelle Outlier presented in this chapter may help dam planners and decision makers in conceiving their future water harvesting and management strategies, and may call for further research on the problem.

SELECTION OF STUDY AREAS AND STATEMENT OF THE PROBLEM

Two MDRs were selected namly Hashenge and Arato, which are located in the central part of the Mekelle Outlier, about 35 km east of Mekelle on the extension of the central highlands of Ethiopia (Fig. 3.1). The altitude of the study area ranges between 2200 m and 2660 m above mean sea level. The area is bounded by rolling mountain ranges in the east, south and north, and flat land to west. The catchment or drainage area of Hashenge and Arato MDRs is 19.3 and 20.8 km^2 respectively. Other salient features of the two MDRs are presented in Table 3.1.

The two MDRs were selected by taking into account the following factors and criteria: (1) representative geological set-up of Mekelle Outlier (geology of the selected MDRs is similar with the geology of Mekelle Outlier where many MDRs are located); (2) low sedimentation problem from field observation and limited inventory by CoSAERT; (3) reservoirs which have sufficient inflow; (4) availability of catchment/drainage area; (5) evidence of new springs, wetlands and increase in discharge of streams after construction; (6) availability of suitable land for irrigation and (7) possibility of rehabilitation to get benefit from the already constructed reservoirs.

Table 3.1. Salient features of few MDRs located in the sedimentary basin of Mekelle Outlier.

Name	*Year of construction*	*UTM (zone 37) locations*			*Reservoir capacity (Mm^3)*	*Dam height (m)*	*Command Area (ha)*	
		E (m)	N (m)	Elevation (m)			Designed	Actual
Adi-Kenafiz	1997/1998	544009	1465486	2161	0.75	15.50	60	<20
Arato [a]	**1997**	**570103**	**1461125**	**2424**	**2.59**	**20.00**	**120**	**<10**
Dur-Anbessa	2000/2001	547394	1467513	2133	0.13	18.00	61	<25
Gereb-Shegalu	1998	548533	1501661	1921	1.00	15.33	50	<20
Gereb-Mihiz	1997/1998	550630	1469662	2123	1.35	17.50	80	38
Hashenge [a]	**1996**	**572850**	**1489900**	**2400**	**2.23**	**19.00**	**120**	**11**
Korir	1995/1996	566088	1519994	2022	2.00	15.00	100	60
Mai-Leba	1997/1998	524955	1513791	2290	0.96	19.00	50	none
Era Quihila	1996/1997	564560	1486767	2321	1.18	n.a.	87	25
Sewhi-Meda	1998	544938	1496133	1995	0.36	14.50	70	none

[a]selected micro-dams for detailed study, n.a.= data not avaialable.

Serious leakage problems were experienced since their construction and they are considered to be geologically representative of the Mesozoic sedimentary series in the Mekelle Outlier. Since the construction of these micro-dam reservoirs, following the rain season it is common to see farmers divert the leakage water, 500–900 m downstream of the reservoirs by constructing temporary traditional weirs, to their farm plots to supplement their rain fed crops. The yield of springs, size of new wetlands and stream discharge found downstream of the dams have been increased since their construction. Such serious leakage played its part in the discrepancy between the planned or designed and actual irrigated area as illustrated in Table 3.1.

All dams produce seepage in different orders of magnitude and quantities. Seepage is not necessarily problematic, provided the objectives and the stability of the dam are not affected. Certain degree of leakage or seepage is accepted as long as it does not compromise the safety or objective of the dam and surrounding facilities. However, problems may occur when seepage rates increase unexpectedly or become uncontrolled to the extent that the planned objective is not met. The rate at which water moves through the embankment, foundation and flanks depends on the type of soil/rock in the embankment, how well it is compacted, the foundation and flank preparation, and the number and size of cracks and voids within the embankment and natural flanks. Upon first filling of the reservoirs, numerous leakage areas developed in the left flank on the downstream side of Hashenge dam and on the southern side of the central foundation of Arato dam. Hence, the micro-dam reservoirs fail to store water and the land proposed for irrigation could not yet be put under cultivation. This chpater tries to pinpoint the main reasons to the water harvest failure that further help as a baseline to propose and implement anti-leakage solutions to the micro-dams under consideration and other developments in a similar geological setup.

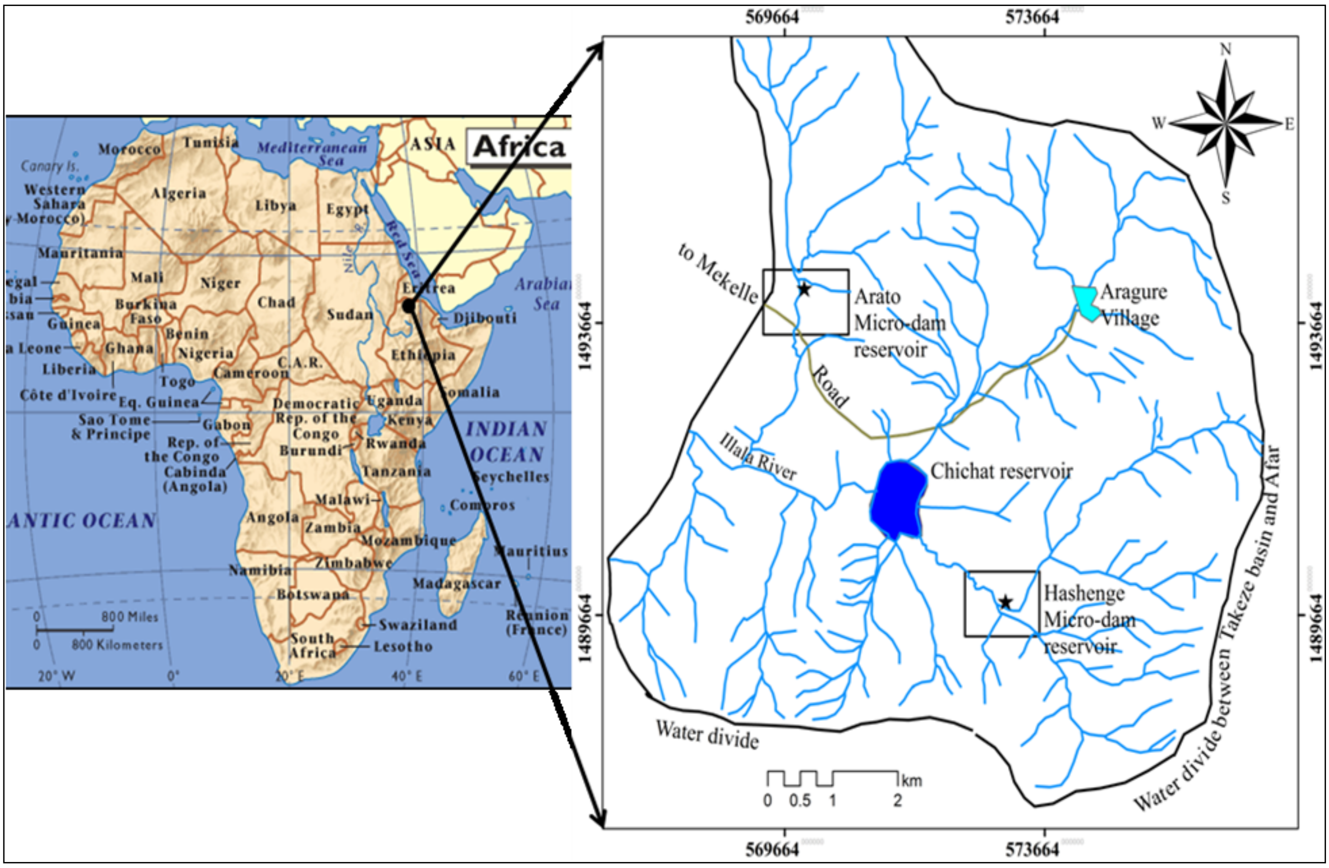

Figure 3.1. Location map, inset squares are target areas of detailed study (MDRs).

MATERIALS AND METHODS

The research work involved several field campaigns carried out in the period 2007-2012. A number of field discontinuity measurements (470 and 214 discontinuities from Hashenge and Arato MDRs, respectively) and observations were conducted to characterize the engineering behaviour and geo-hydrological parameters (e.g. hydraulic conductivity) of rocks and soils of the area. Most of the measurements were collected from abutments of the MDRs, as the central foundation is covered with alluvial soil at both MDRs. Detailed geological mapping (1:1000) of each MDR were undertaken by using a grid system where profile (observation) lines were laid out at 100 m interval and observations were taken at 20 m interval (where every there are changes in geology) on each profile line. At Arato profile lines were set down in E-W direction making the baseline in N-S direction while at Hashenge it was the reverse.

Rock and soil descriptions were done according to the methods suggested by the International Society for Rock Mechanics (ISRM, 1978, 1981a, b). Excavation of test pits/trenches for in-situ observations, exposure description and discontinuity measurements using slope face and scanline mapping methods (at abutments) were conducted during the course of all fieldworks. Moreover, drilling of three boreholes (11.7 m to 25 m deep) as well as a geophysical survey (six vertical electrical soundings, VES) were carried out at Hashenge micro-dam. The VES survey, were executed using Terrameter SAS (signal averaging system) 1000 manufactured by ABEM, Sweden. The VES were performed with Schlumberger array (detail procedures are given in chapter 4). In this array, electrodes (two potential electrodes and two current electrodes) are aligned along a line, centered at the location of sounding. Both electrodes are at equal distances from the point of sounding (MN/2 and AB/2), but MN/2 was kept much less than AB/2. Half current electrode spacings (AB/2) ranging from 1.5 m to 150 m were used. Details on the methods and analysis techniques are also provided in Hassanein *et al*. (2007), Panthulu *et al*. (2001) and others. VES data was interpreted using IPI2Win software developed (at Moscow State University) by Bobachev (2002).

The subsurface investigation was designed to determine the types and distribution, hydraulic conductivity, and sequences of the earth materials. The geotechnical drilling at Hashenge microdam was specifically performed to:

- Secure samples of soil and rock for visual examination and for laboratory testing.
- Characterize the subsurface soil and rock conditions from water tightness perspectives.
- Obtain information on groundwater level condition.
- Conduct a packer test and understand the role of joints, bedding planes and other geologic features to hydraulic conductivity of the rock mass and to predict the leakage line or path.

Lugeon test (also called packer or water pressure test) is the most commonly in-situ test used to estimate hydraulic conductivity of rock masses (Quinones-Rozo, 2010). The test, which derives its name from Maurice Lugeon (1933), is a constant head type test that takes place in an isolated portion of a borehole. Water at constant pressure is injected into the rock mass through a slotted pipe bounded by pneumatic packers (Fig 3.2). A pneumatic packer is an inflatable rubber sleeve that expands radially to seal the annulus space between the drill rods and the boring walls by gas (Nitrogen). Prior to the beginning of the test a maximum test pressure (P_{MAX}) is defined. P_{MAX} is chosen such that it does not exceed the confinement stress (σ_3) expected at the depth where the test is being conducted, thus avoiding the development of hydraulic fracturing or hydraulic jacking. As a rule of thumb, P_{MAX} is usually established using P_{MAX}=D×(0.22 bar/meter), where D is equal to the minimum ground coverage–depth in the case of a vertical boring in a flat site or minimum lateral coverage in the case of a test conducted in a hillside.

The test was conducted in five stages (Table 3.2), with a particular water pressure magnitude associated with each stage. A single stage consists of keeping a constant water pressure at the test interval for 10 minutes by pumping as much water as required. The first stage is held at a low water pressure, increasing the pressure in each subsequent stage until reaching P_{MAX}. Once P_{MAX} is reached, pressures are decreased again as shown in Table 3.2.

Table 3.2. Pressure magnitudes typically used for each test stage (Quinones-Rozo, 2010).

Test Stage	Description	Pressure Step
1st	Low	$0.50 \cdot P_{MAX}$
2nd	Medium	$0.75 \cdot P_{MAX}$
3rd	Maximum (peak)	P_{MAX}
4th	Medium	0.75 P_{MAX}
5th	Low	0.50 P_{MAX}

During the execution of each stage, both water pressure (P) and flow rate (q) values are recorded every minute. Subsequently, average values for P and q are then used to compute the hydraulic conductivity for each stage using equation 3.1. The hydraulic conductivity is expressed in terms of the Lugeon value (LU), which is empirically defined as the hydraulic conductivity required to achieve a flow rate of 1 liter/minute per meter of test interval under a reference water pressure equal to 1 MPa.

$$\mathrm{LU} = \frac{\mathrm{q}}{\mathrm{L}} \times \frac{1\mathrm{MPa}}{\mathrm{P}} \tag{3.1}$$

where LU is Lugeon value, q is flow rate or intake (liters/minute), L is test section (m) and P is test pressure (MPa). Under ideal conditions (homogenous and isotropic medium) Lugeon is equivalent to 1.3×10^{-5}cm/s (Fell *et al*., 2005; Houlsby, 1976) or equal to 1×10^{-5}cm/s (Allaby, 2013).

Drilling operation was carried out for the purpose of this study in the weathered near surface part using augering, while in bedrock, diamond rotary coring was performed. After completion of the fieldwork, final interpretation was made by integrating all field observations and subsurface information.

The method proposed by Kiraly (1969) and Wyllie and Mah (2004 and references therein) was used, in addition to packer test result, to estimate the hydraulic conductivity (K) of the different rock units:

$$\mathrm{K} = \frac{\mathrm{g}\mathrm{e}^3}{12\mu\mathrm{S}} \tag{3.2}$$

where g is the gravitational acceleration (981 cm/sec^2), e the average aperture of discontinuity (cm), μ the kinematic viscosity of water (0.0101 cm^2/sec for water at 20 °C) and S is the average spacing of discontinuities (cm).

Discontinuities are assumed to be smooth and parallel. This assumption was verified by observational field data: the discontinuities in the limestone-shale-marl intercalation are smooth, while the discontinuities in dolerite are slightly rough but dominantly smooth.

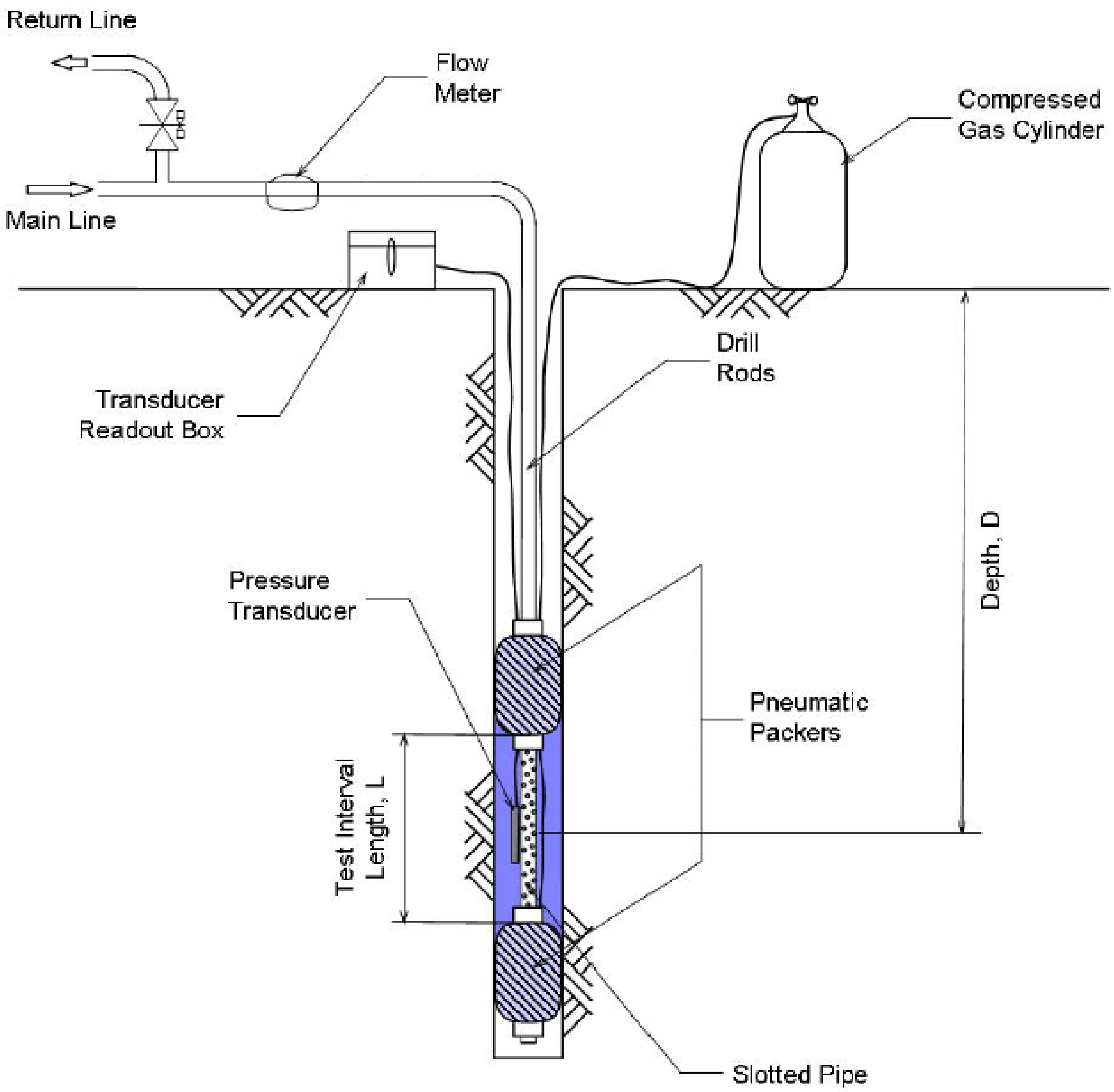

Figure 3.2. Sechmatic configuration of Lugeon test (Quinones-Rozo, 2010).

RESULTS AND INTERPRETATION

Site geology

The major lithologic units of the present study area include: Quaternary deposits, dolerite and limestone-shale-marl intercalations (Figs. 3.3 and 3.4). Brief description of these units is presented below.

Quaternary deposits cover the valleys of tributaries, depressions and flat lands along the reservoir floor, but are partly removed as construction material. Their thickness is generally variable, but thicker near the river course and thinner toward the steep sides of the abutments and reservoir periphery.

The dolerite in the area is manifested as swarms of sills and dykes. It is slightly to completely weathered, in the form of exfoliation weathering. It is greenish grey, medium to coarse grained, massive rock. Weathering degree decreases with depth for this unit, as observed in natural outcrops on the right flank. The dolerite outcrops mostly following weak beds and fault zones and displays both concordant and discordant relationships with the country rocks.

The sedimentary limestone-shale-marl intercalation unit covers a large portion of the area. Its color varies from place to place and with depth (white, yellowish, brown, etc.). The beds are mostly horizontal, but inclined or tilted in the fault zone and near dolerite intrusions (Fig. 3.4). All grades of weathering are observed in these rock units. Near contacts to the dolerite, the limestone-shale-marl intercalations are highly disintegrated due to the baking effect of the dolerite intrusion. Layers of shale within this intercalation are fissile, weak, highly to completely weathered, while the marl and limestone are relatively hard, thickly bedded and moderately weathered.

The main geological structures observed in the study area are faults, fractures/joints and bedding planes. The major fault in the area is the Mekelle Fault. It strikes in the direction of NW–SE and it crosses the Hashenge micro-dam site. Joints are the dominant structures in the area, which are generally variable in strike direction. The WNW–ESE and NE–SW striking joints are the dominant ones (Figs. 3.5 and 3.6). Next to vertical joints, horizontal joints can also be observed at the surface. Bedding joints are very common in the sedimentary rock units.

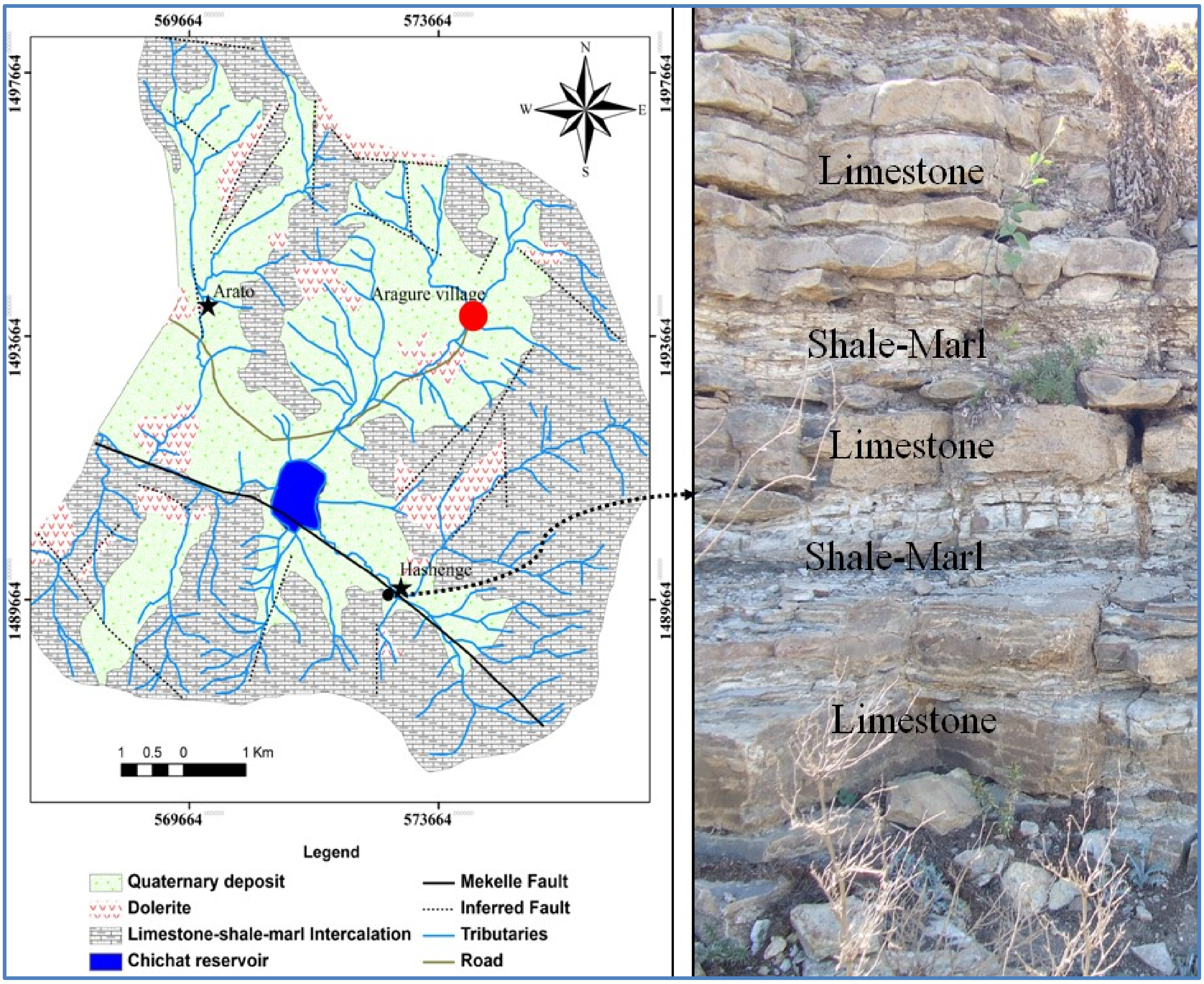

Figure 3.3. Geological map of the two MDRs and field photo illustrating the nature of the rock units.

Engineering characteristics: a geological approach

Alluvial/Quaternary deposit

The central foundation and parts of the reservoirs of both micro-dams are covered by alluvial soil deposits (Figs. 3.4 and 3.6). Maximum thicknesses of 3.8 m and 1.5 m for Arato and Hashenge respectively were observed in test pits. Alluvial deposits become very thin toward the rim of the reservoirs. Dominant soil type is dark-brown, stiff and heterogeneous silty clay and silty sand. On Arato central foundation, leakage was observed below the alluvial deposits from the limestone-shale-marl intercalation unit at a depth of 5 m. The alluvial deposits have no influence or role in the leakage mechanisms at both sites.

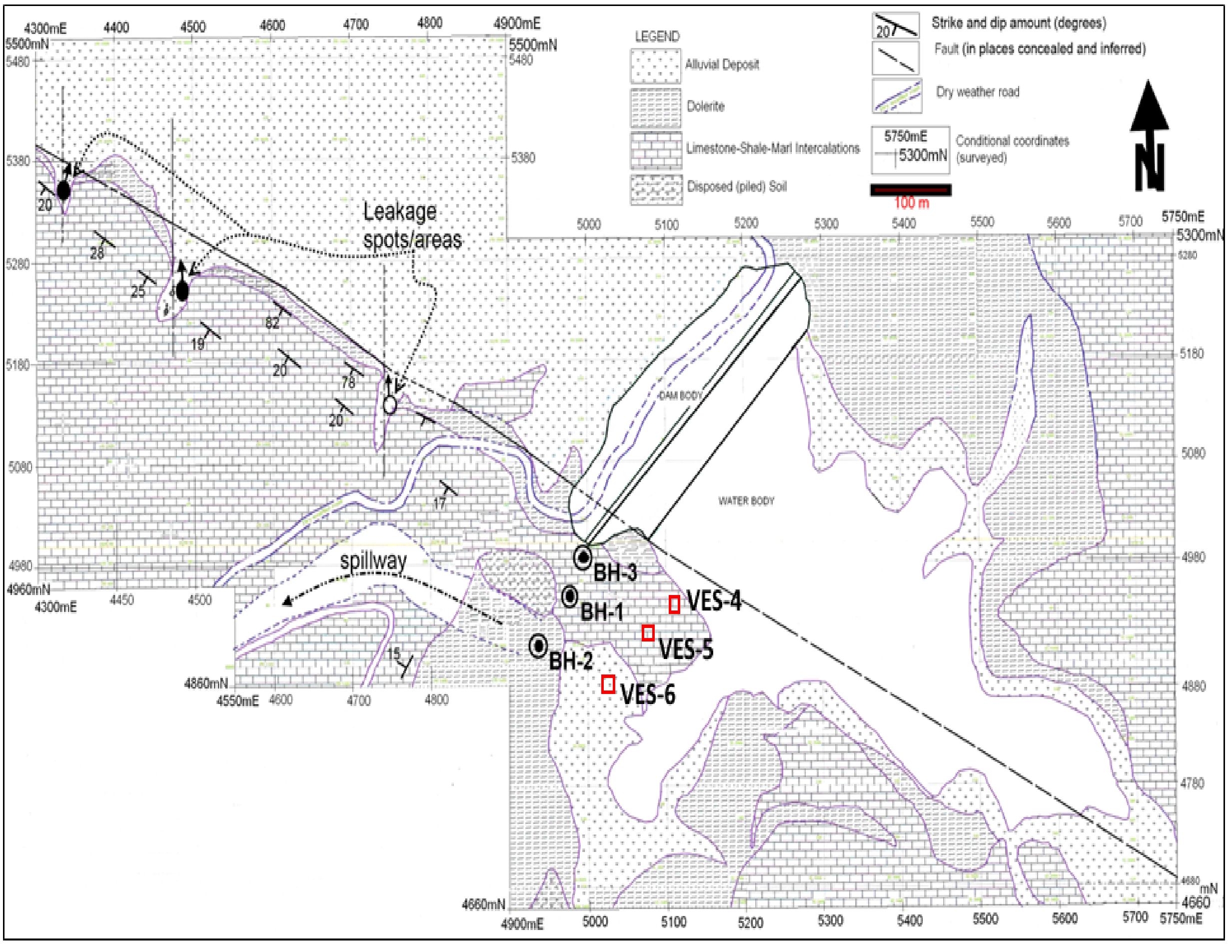

Figure 3.4. Geological map of Hashenge micro-dam site and its reservoir area and location of vertical electrical sounding (VES) points and boreholes at Hashenge. Boreholes BH-1, BH-2 and BH-3 coincide with VES-1, VES-2 and VES-3, respectively. Log and coordiantes of the boreholes are included in Appendix C3 on CD).

Limestone-shale-marl intercalations

This unit covers the left flank and part of the reservoir area at both sites as well as the central foundation at Arato micro-dam, underlying the alluvial deposits (Figs. 3.4 and 3.6). This unit shows an alternating sequence of limestone, shale and marl beds (Figs. 3.3, 3.4 and 3.7), that was also revealed from drilling and VES results (Figs. 3.8 and 3.9). The beds are horizontal in the case of Arato and locally inclined at different angles at Hashenge. The dominant strike and dip of the inclined beds at Hashenge is N60°W/20°SW (Fig. 3.4), but local deviations are common. The strike of the inclined beds is nearly parallel to the Mekelle normal fault belt. The strike orientation of beds at Hashenge coincides with the leakage points observed at creeks to the west of the dam (Fig. 3.4). The inclination of these beds at Hashenge is attributed to faulting and dolerite intrusion. Bed thickness is variable from thin laminations in shale up to about 3 m in limestone beds.

One of the leakage points at Hashenge was located from information obtained from local people and occurred only during the first filling of the reservoir, while the other two leakage locations were observed during the fieldwork. Leakage points at Arato were observed along tributaries and depressions on the southern side of the dam (Fig. 3.6). Locations of leakage points emerging on surface as springs and diffuse flow are presented in Figs. 3.4, 3.6. Weathering condition of the unit varies with depth and in space. All grades of weathering have been observed in the field (fresh to completely weathered) and there is no systematic decrease of weathering intensity with depth (Fig. 3.7). The unit is highly affected by discontinuities of different types, like bedding joints, contact and tectonic joints. The NW–SE and NE–SW trending discontinuities are the dominant sets, and these discontinuity sets intersect the dam axis at different angles in both sites (Figs. 3.5 and 3.6). In addition to the two major sets of discontinuities, there are some discontinuities with a variable or random orientation. Discontinuities are closely spaced and open (Table 3.3) and their surfaces are smooth and damp to wet in shallow test pits, but dry in surface exposures. The above observations lead to the conclusion that this unit is generally permeable (hydraulic conductivity greater than 10^{-4} cm/s), as confirmed by packer testing (see below).

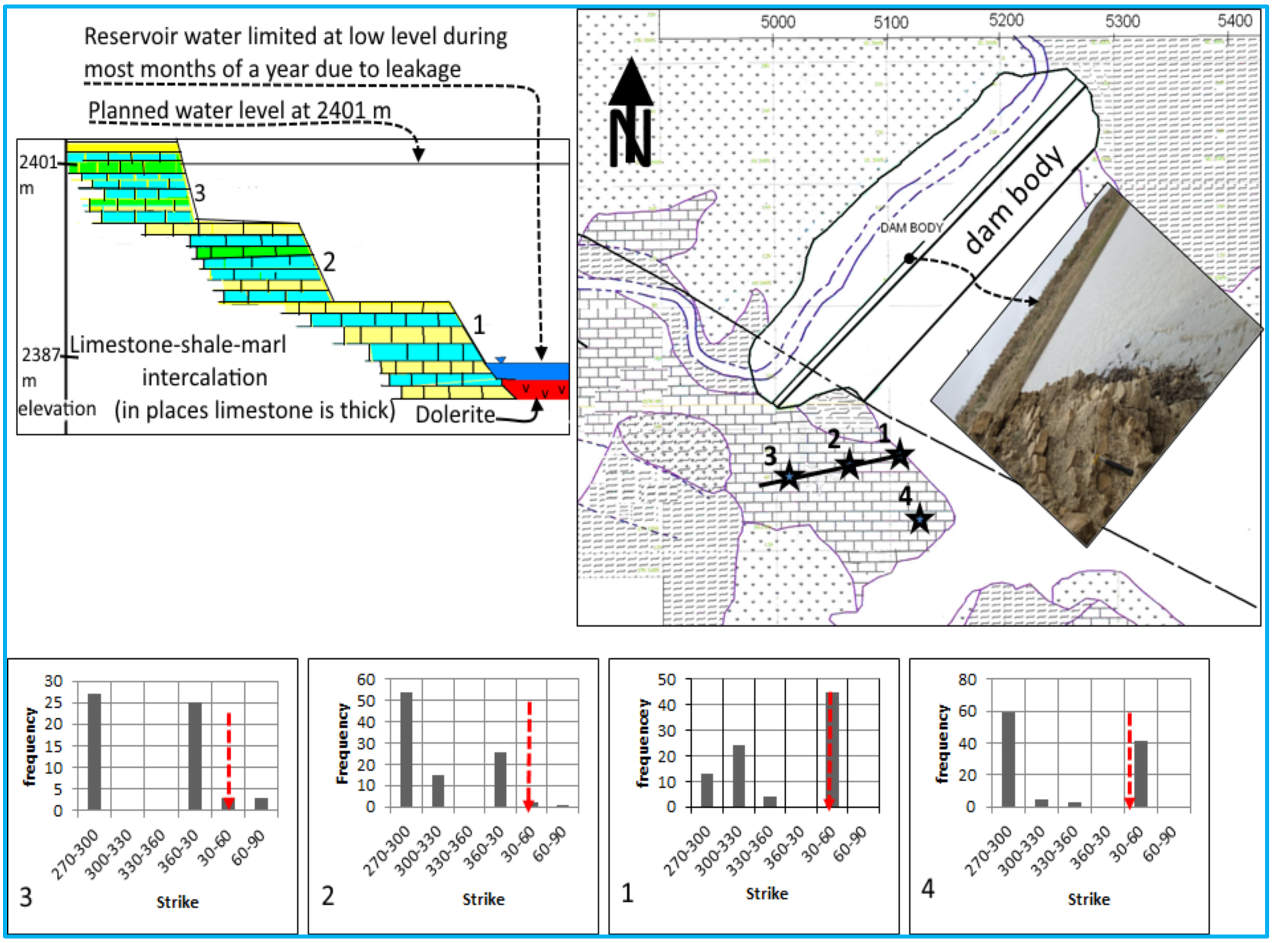

Figure 3.5. Location of measurement points and respective histogram for discontinuities (Hashenge). The limestone-shale-marl intercalation unit is slightly tilted way from the reservoir (Fig. 3.4).

Dolerite

The right flank and central foundation of Hashenge micro-dam are on dolerite (Fig. 3.4), while in the case of Arato micro-dam, it is only the right flank that is on dolerite (left flank and central foundation is underlain by limestone-shale-marl intercalation). The cut-off trench on dolerite was extended to less weathered material during construction of the micro-dams (CoSAERT, 1999). Generally, the emplacement mode or nature of intrusive igneous rocks has engineering significance. Unlike sills and dykes in the left flank of Hashenge, massive intrusive bodies such as stocks and batholiths tend to have relatively homogeneous compositions and textures in three-dimensions. The weathering grade is variable, fresh to completely weathered, but weathering intensity decreases with depth (Fig. 3.6), unlike for the limestone-shale-marl intercalation, in which no defined pattern is observed (Fig. 3.7). Discontinuities are widely spaced and tight and the surfaces of the joints are slightly rough, but dominantly smooth and they were found to be dry.

All the above geological features indicate that this unit is relatively impermeable, i.e. due to the homogeneity of the dolerite and wide spacing and tightness of discontinuities (Fig. 3.6). The upper part of the unit is affected by weathering and hence pervious.

Discontinuity data

It is often the nature of the discontinuities (joints, fractures, bedding planes, faults, and other breaks in the continuity of the rock) and not of the intact rock that governs the mechanical and geo-hydrological behaviour of the rock mass (Maerz and Zhou, 1999). Leakage of water through rock masses usually takes place via the discontinuities (Vandecasteele *et al*., 2011). The characterization of discontinuous rock requires measuring and description of the discontinuities. Discontinuities in outcrops of the flank slope and central foundations (from upstream and downstream side) were studied. Figures 3.5 and 3.6 show the location of some of the measuring stations for both sites, and histograms for Hashenge and rose diagrams for Arato. A considerable volume of data (470 from limestone-shale-marl and 214 from dolerite unit) was collected from both sites. Measurements were taken systematically and particular attention was given to discontinuity spacing and aperture (Hudson and Priest, 1983; Hoek and Bray, 1981) from leakage perspective during measurements in the field with respect to alignment of the dam axis and reservoir configuration. Favourable discontinuities to leakage are those which intersect the dam axis and strike and dip in a direction downstream or toward lower gradient/elevation areas away from the reservoir area. Discontinuity sets were identified visually, as well as from collected orientation data and the joint parameters measured in the field include joint spacing, opening/aperture, strike and dip, infill material type and thickness, and number of joints at the station or extent of exposure. Statistical analysis of combined observations for both dam sites (Table 3.3) shows that the dolerite unit is found to be better in terms of water tightness due to widely spaced and tight discontinuities. The higher equivalent hydraulic conductivity in the sedimentary unit is attributed to the presence of frequent tectonic and bedding discontinuities, while for the dolerite discontinuities are less frequent and have a smaller aperture or are tight.

Table 3.3. Summary of discontinuity analysis for the two rock units, based on data from both dam sites, for hydraulic conductivity estimation using Equation (3.2). Observation stations at dam abutments and partly toward reservoir and downstream sides.

Rock unit	Limestone-shale-marl Intercalation unit (470 joints)	Dolerite unit (214 joints)
Average spacing (cm)	14.7	171.12
Maximum spacing (cm)	35	300
Minimum spacing (cm)	3	50
Geometric mean of spacing (cm)	11.32	158.37
Average aperture (cm)	0.21	0.0045
Maximum aperture (cm)	1	0.01
Minimum aperture (cm)	0.01	0.001
Average hydraulic conductivity (cm/s)	$4.00\times10^{+1}$	2.27×10^{-5}
Maximum hydraulic conductivity (cm/s)	$5.3\times10^{+2}$	1.62×10^{-4}
Minimum hydraulic conductivity (cm/s)	5.40×10^{-4}	4.05×10^{-8}
Hydraulic conductivity using geometric mean (cm/s)	4.19×10^{-1}	2.06×10^{-6}

The joints are generally continuous laterally and in depth as confirmed in the field and drilling data. Surface of joints (wall surface) is smooth with minor calcite precipitation and the opening/apertures varies from place to place (very tight for dolerite to moderately open for limestone–shale–marl intercalation). Hydraulic conductivity of jointed rocks depends on the number and dimensions of the joints: the closer the spacing and the wider the opening, the higher the hydraulic conductivity is. Joints and bedding planes or contacts between individual beds cause planes of weakness in the rocks and form leakage channels. Intersection of two or more sets of discontinuities form a wider opening that facilitates leakage (Fig. 3.7) and the orientation of this line of intersection strikes away from the reservoir which is found to be favourable to leakage in both dam sites. As portrayed in the histograms in Fig. 3.5 and rose diagrams in Fig. 3.6, most of the discontinuities traverse or strike away from the reservoir and intersect the orientation of the dam axis at both sites nearly perpendicular.

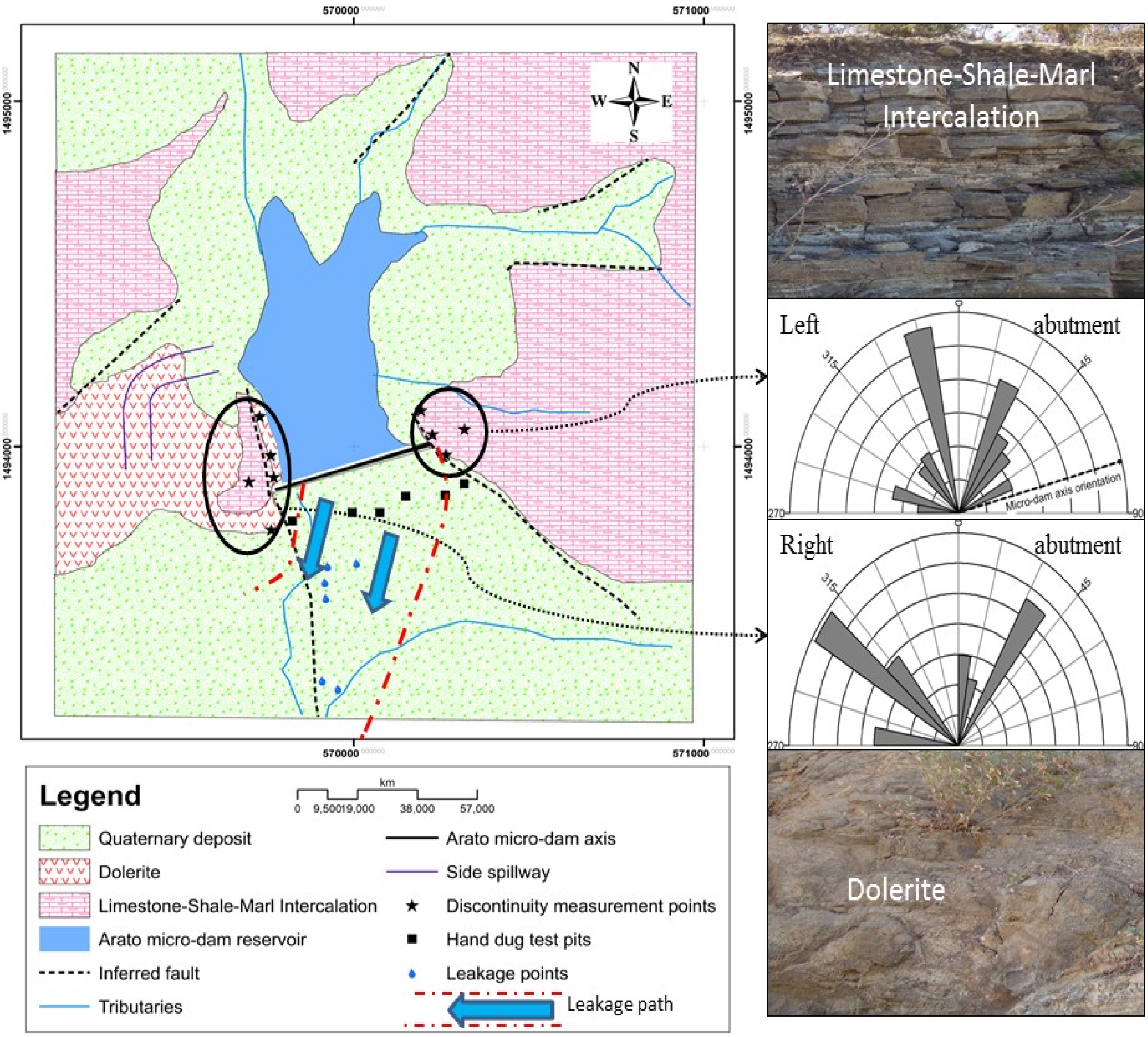

Figure 3.6. Location of measurement points, respective histogram for discontinuities and leakage path (Arato). Leakage points observed during rain season are indicated in the south side of the dam.

Figure 3.7. Field photograph showing bedding and tectonic joints and intersection of different sets of discontinuities in limestone-shale-marl intercalation.

Geotechnical drilling results from Hashenge

Based on the existing information from hand dug test pits, surface geology, geophysical survey and topography, three drilling sites were selected exactly at the locations of VES-1, 2 and 3, two of which (BH-1 and BH-3) are on the left flank and one (BH-2) at the spillway (Fig. 3.4).

Figure 3.8 shows the logs and cross-section of the three boreholes. A close inspection of the core samples indicates variation in lithology, weathering grade, discontinuities and thickness of beds with depth and space. The drilling operation and samples recovered further confirmed the presence of highly permeable layers, perhaps are cavities. During drilling operations, water recovery was low, generally below 40%, but almost complete drilling fluid (water) loss occurred at different depths (Fig. 3.8; at BH-1: depths between 11–14.5 and 20–23.1 m; at BH-2: 7–9.5 m and 10.2–11.1 m and at BH-3: 6–7.5 m; 8.1–9.6 m and 10.2–11.4 m), suggesting the presence of highly permeable sections or open voids/discontinuities.

The three boreholes show almost similar geological units with a variation in degree of discontinuity and weathering. The main units include limestone, shale and marl, but at BH-2 and 3 dolerite is also encountered. The unit thicknesses are variable and generally, the units occur in a cyclic fashion or sequence. At BH-2, dolerite extends to a depth of 7.4 m; below this depth, a sedimentary sequence of limestone and shale are the dominant rock types. Similarly, at BH-3 traces of dolerite sill start at a depth of 12.1 m and continue at depths of 12.8 m, 13.6 m and 14.7 m. The drilling data revealed that fractured limestone-shale-marl intercalation is the dominant rock unit and controls the overall geo-hydrologic characteristics of the rock mass in the left flank of Hashenge dam site.

In addition to the log and joint description of the drill holes, a packer/pressure test was also conducted at BH-1 at a depth interval of 12.4 m to 13.4 m, to obtain information on the hydraulic conductivity and to validate the drilling information and resistivity data.

The test was conducted in five stages at different pressures. The Lugeon value obtained was very high, ranging from 210 to 440 (equation 3.1) and according to Quinones-Rozo (2010) and Gurocak and Alemdag (2011), such values, indicate a very highly permeable rock mass ascribed to open, closely spaced, discontinuities or voids. One Lugeon is a flow of l liter per minute per meter of borehole under a pressure of 1 MPa. Calculation of the hydraulic conductivity of the rock mass, considering average Lugeon value gives a value of 3.25×10^{-3} cm/s (2.73×10^{-3} to 5.72×10^{-3} cm/s), which shows deviation or variation from the results obtained from discontinuity measurements of average spacing and aperture (Table 3.3). This value is lower, but within the range of minimum and maximum values obtained from Equation (3.2). This may be due to depth or stress variation as the discontinuity data were collected from surface exposures, expected to have wider apertures compared to joints at depth with some overburden pressure. In other words, the data collected from surface exposures may not be representative of the rock mass at the depth where the packer test is conducted, owing to weathering agents, like stress relief causing closer joint spacing and an increase in aperture. So, this might be the reason for the variation of the hydraulic conductivity values reported in Table 3.3. In spite of this variation, both results indicate that this rock mass is responsible for the excessive leakage observed from the micro-dams.

Vertical electrical sounding (VES) results from Hashenge

Core drilling was conducted (BH-1, 2 and 3, Fig. 3.4) at three VES points (VES-1, 2 and 3, Fig. 3.4 exactly concides with locations of BH-1, 2 & 3) and the VES data were interpreted based on the information from the drilling and geology of the area (Figs. 3.9 and 3.10, Appendix C3). Discontinuities and other weak zones produce low resistivity anomalies either by serving as leakage zones (Vandecasteele *et al*., 2011) or because of the presence of weathered horizons. The resistivity values show an interesting variation with depth (Figs. 3.9 and 3.10). The variation in depth shows a difference in lithology, degree of weathering and discontinuities as confirmed by drilling information and natural exposures.

In Figs. 3.9 and 3.10, VES-2 and VES-1 show low resistivity values (67.9 and 77.8 Ω m respectively) in the top part attributed to weathered soil material consisting of clay particles as confirmed by drilling at BH-1 and highly weathered dolerite at BH-2 (Fig. 3.9).

On the other hand at VES-3, relatively higher values of resistivity (879 Ω m) were obtained in the top part attributed to a lower degree of weathering and partly due to drier conditions related to very low water level in the reservoir and correlated to dry and fresh limestone-shale-marl intercalation.

With depth, the resistivity values vary in a cyclic fashion with higher values for relatively massive thick limestone and low values for thin and fractured limestone alternating with shale.

Variation in degree of weathering leads also to contrasting resistivity values. A good example is VES-2 (BH-2), where the same dolerite unit shows a contrasting resistivity value: 67.9 Ω m for highly weathered dolerite and 262 Ω m for slightly to moderately weathered dolerite. The bottom part of this dolerite again shows lower resistivity values (Fig. 3.9, BH-2) attributed to high weathering near the contact, which can be considered as a weak zone. This condition was confirmed by drilling information in which almost complete drilling fluid loss occurred within this section.

The second important observation from the correlation of drilling logs and VES data is that weak zones, like contact zones between rock layers, are masked by the adjacent rock resistivity (e.g. BH-2 contact at a depth of 7.4 m; BH-1 contact at 14.5 m and 18.5 m and BH-3 contact at a depth of 2.4 m and 5.8 m). Similarly, thin rock layers are also masked by neighbouring rock resistivity (the suppression effect), e.g. at BH-1 thin rock layer between depth interval of 18.5–20.0 m and at BH-3 between depth interval of 5.8–7.2 m and 8.5–10.3 m. In this particular case, thin fractured layers or few but very wide open discontinuities might lead to the drilling water loss at these sections (Figs. 3.8 and 3.9, BH-3).

A third interesting deduction is that variation in the extent of fracturing can be seen from the correlation of VES and drilling logs, not only in the vertical direction, but also the spatial variation in the same rock type. The resistivity value for the same limestone bed varies from the lowest value of 33.3 Ω m at VES-3 to a maximum value of 2779 Ω m at VES-1. This extremely wide variation might be attributed to variable intensity of discontinuities and moisture content. The lower values (33.3–92.9 Ω m, VES-3) are correlated to very close to close spacing in jointed limestone, considered as a pervious layer, while the intermediate resistivity values (300–800 Ω m, VES-1) are correlated to moderate spacing in jointed limestone, considered to be semi-pervious. The higher resistivity values (1500–2779 Ω m, VES-1 and 3) are correlated to wide to very wide spacing in jointed or massive limestone, considered to be impervious.

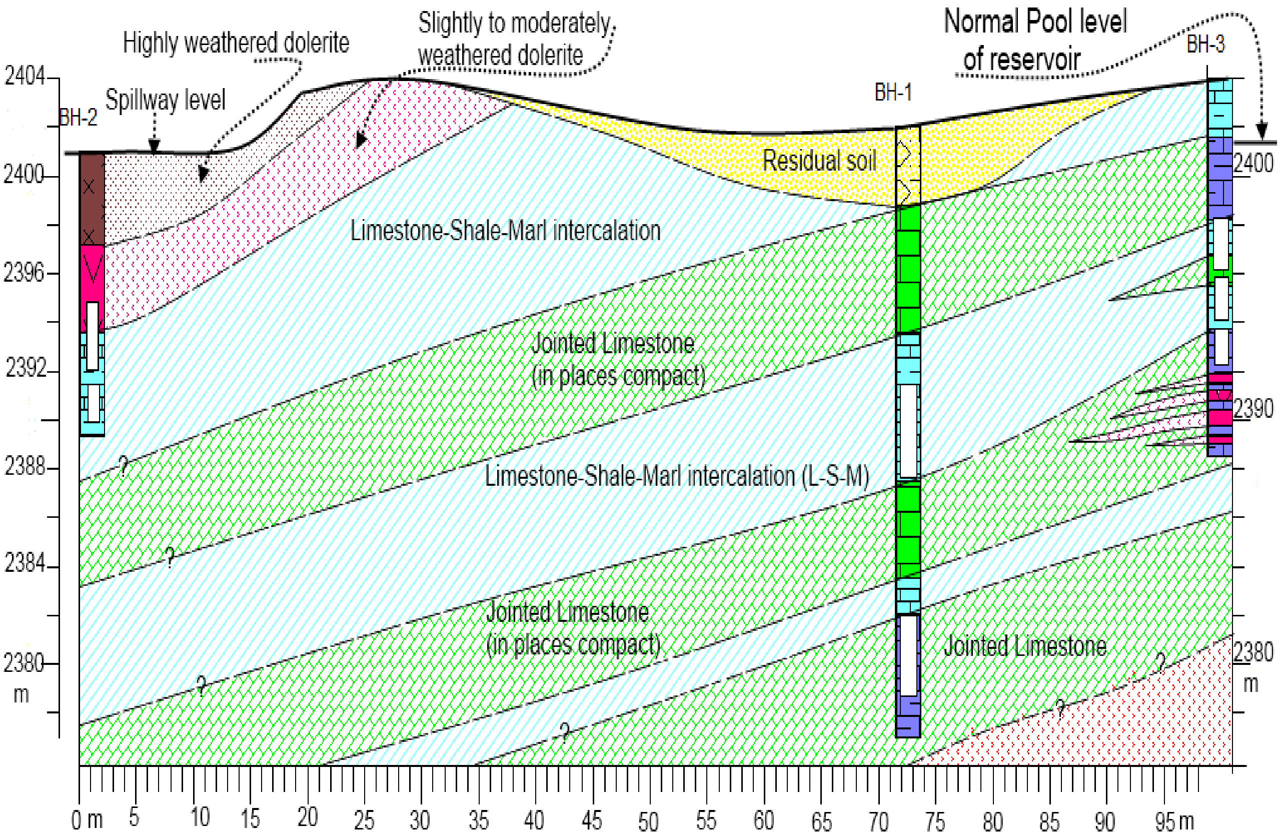

Figure 3.8. Simplified geological cross-section along BH-2, BH-1 and BH-3 (left abutment of Hashenge, Fig. 3.4, borehole locations coincide with VES-2, 1 and 3 respectively). Vertical axis represents elevation in m above mean sea level (GPS reading). Horizontal axis represents horizontal distance in meters. Line of cross-section is almost perpendicular to strike. Planned water level of reservoir is at 2401 m, but actually limited at about 2387 m during most months of a year due to leakage. White boxes inside the column logs indicate complete water loss and extremely low drilling water recovery sections. Legend of of borehole log concides with the rock units described in the cross-section (see Appendix C3 on CD))

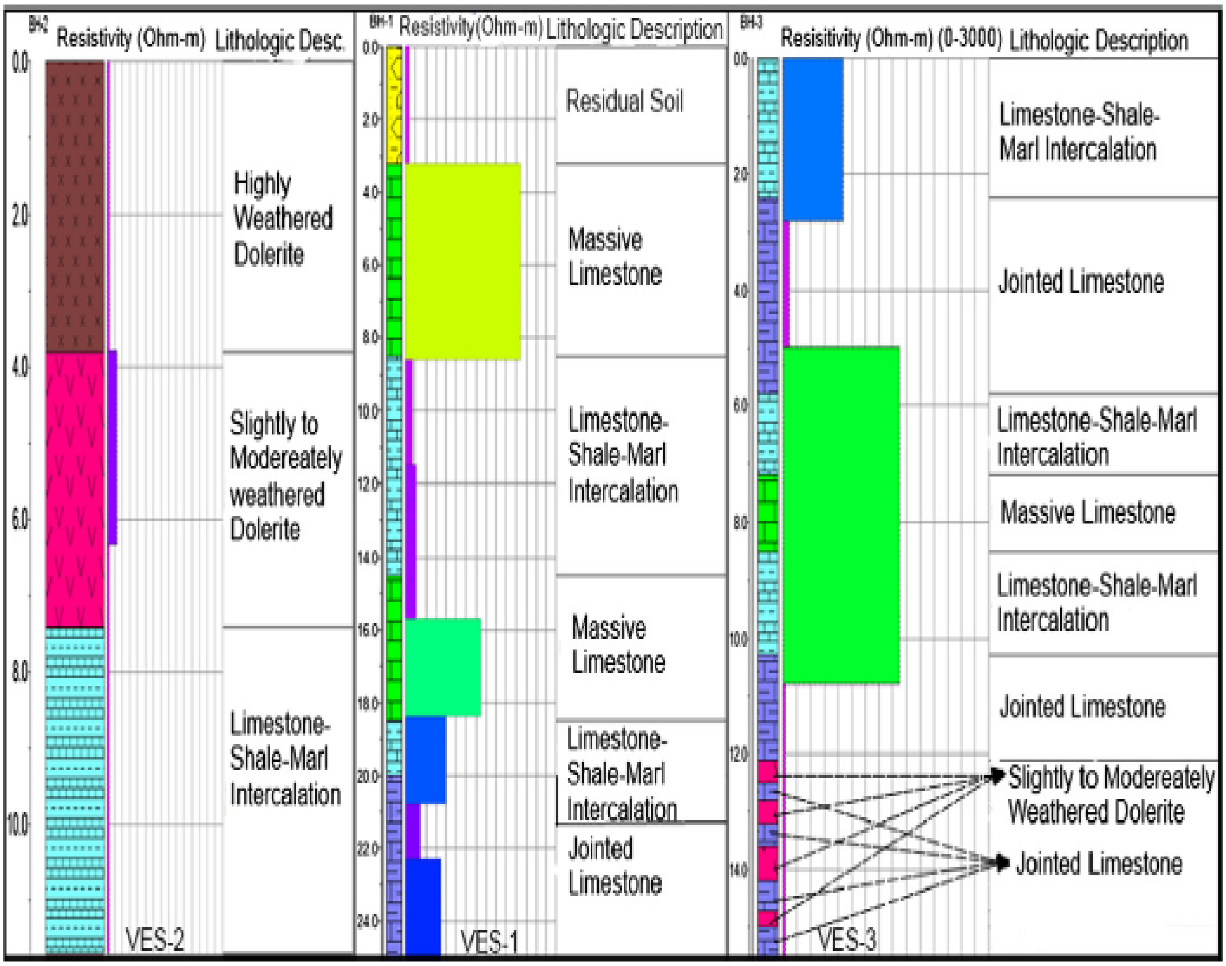

Figure 3.9. Vertical electrical sounding (VES) curves after forward modeling interpretation using IPI2Win program and correlated with borehole data. Lithology descriptions are from drilling information. Location of VES-1, 2 and 3 exactly coincides with location of BH-1, 2 and 3 respectively. Actual reservoir water level during most of the year nearby BH-3/VES-3 is about 16–17 m below the surface. Solid colors indicate variations in resistivity.

After the correlation of the first three VES surveys with actual drilling information, the remaining three VES (4–6) surveys were interpreted, based on resistivity values and the location of the VES points in relation to the local geology. The interpreted units against the plot of resistivity values with depth are shown in Figs. 3.10 and 3.11. At this point, it is important to emphasize the need of local geological knowledge and direct subsurface data to validate the indirect geophysical survey (VES) for specific engineering purposes in complex and cyclic sedimentary terrain intruded with intrusive bodies.

DISCUSSION ON LEAKAGE PATH AND MECHANISMS

The reservoir leakage has been surveyed and observed on-site. Understanding the surface and subsurface geology of a site is of paramount importance in predicting leakage zones and paths. The geology of the two sites under investigation shows that a number of discontinuities traverse the foundation and flank rocks of the dam. In case of rocks, the hydraulic conductivity is highly affected by discontinuities of syngenetic (developed contemporaneously with the rock) and epigenetic (developed after the formation of the rock) forms. Both types of discontinuities intensively affect the limestone-shale-marl intercalation unit at both sites. These geological and structural conditions make this unit permeable. Observational data shows that the dolerite unit is less affected by discontinuities. Field observational approach was confirmed by analyzing the data of drilling and geophysical prospecting that the cyclic limestone-shale-marl intercalation is found to be pervious.

The leakage path at Arato is from the central and left reservoir bank and directs in a slight curved shape toward the leakage points creating stream along the tributaries on the downstream (Fig. 3.6).

The leakage path at Hashenge is from the reservoir left flank/bank and directs almost linearly toward the three leakage points/springs located on the downstream (Fig. 3.12). The different methods (geological, discontinuity data, drilling, VES) were used to analyze and diagnose the leakage path and mechanism of Hashenge reservoir. All show that the leakage of the reservoir passes through the rock discontinuities (bedding planes and joints).

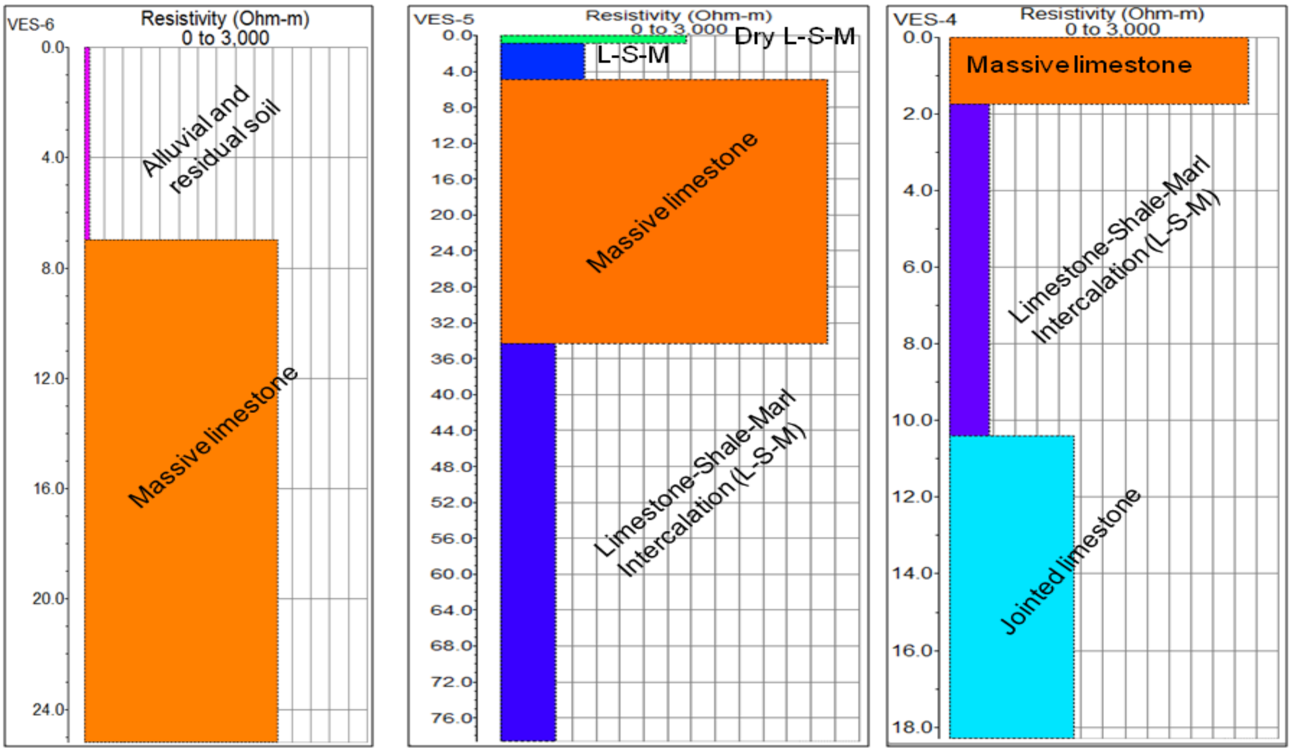

Figure 3.10. Vertical electrical sounding (VES) curves after forward modeling interpretation using IPI2Win program. Colors indicate variations in resistivity.

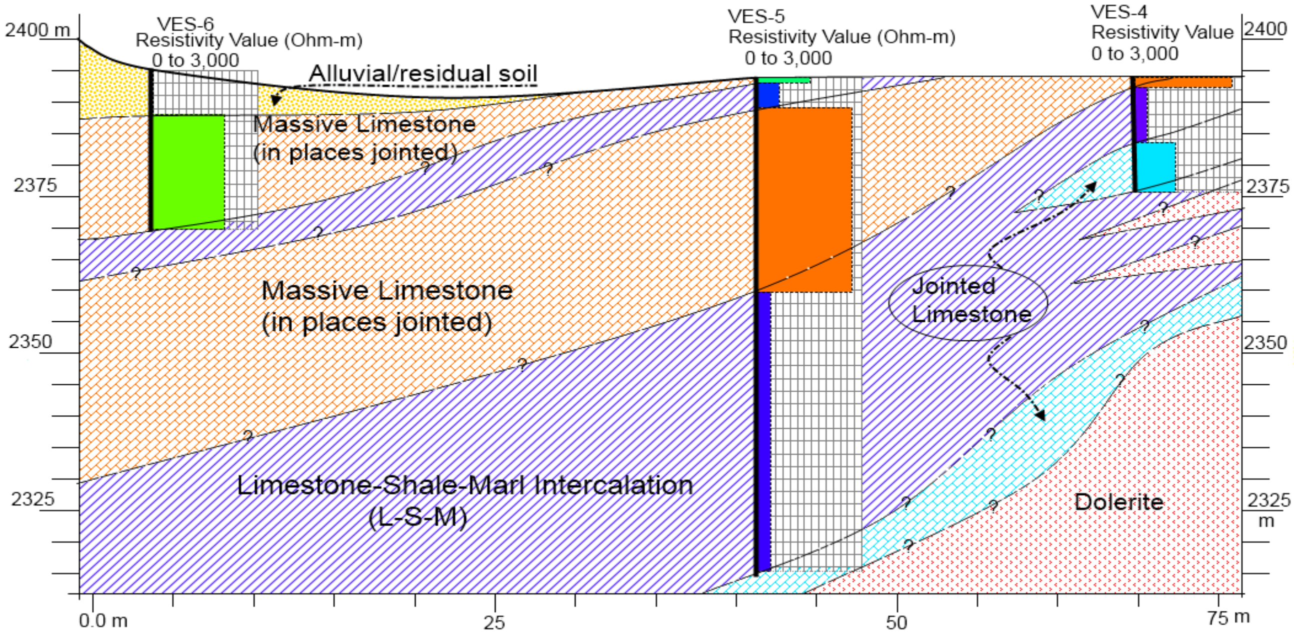

Figure 3.11. Interpreted geological cross-section along VES-6, 5 and 4. Vertical axis represents elevation in m above mean sea level (GPS reading) and horizontal axis represents horizontal distance in m. Solid color indicate variations resitstivity.

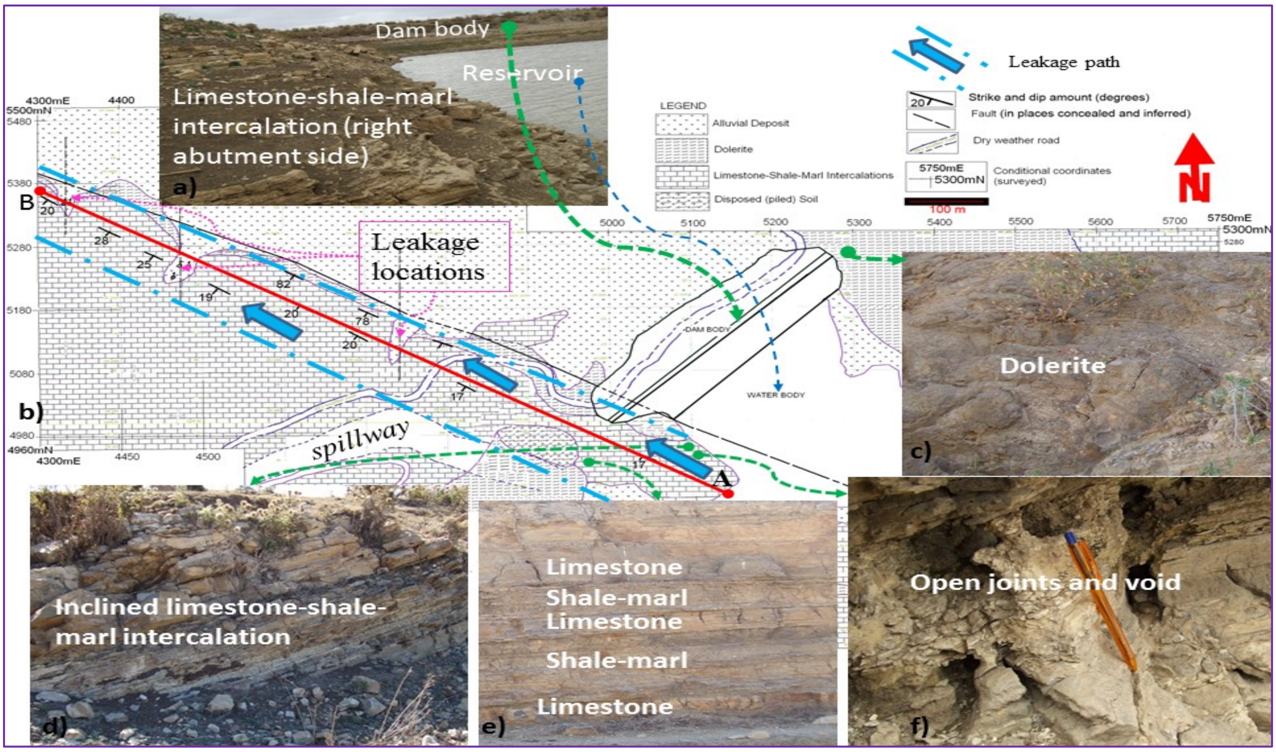

Figure 3.12. Detailed geological map of Hashenge micro-dam and typical features of the rocks. AB is the line of cross section in Fig. 3.13.

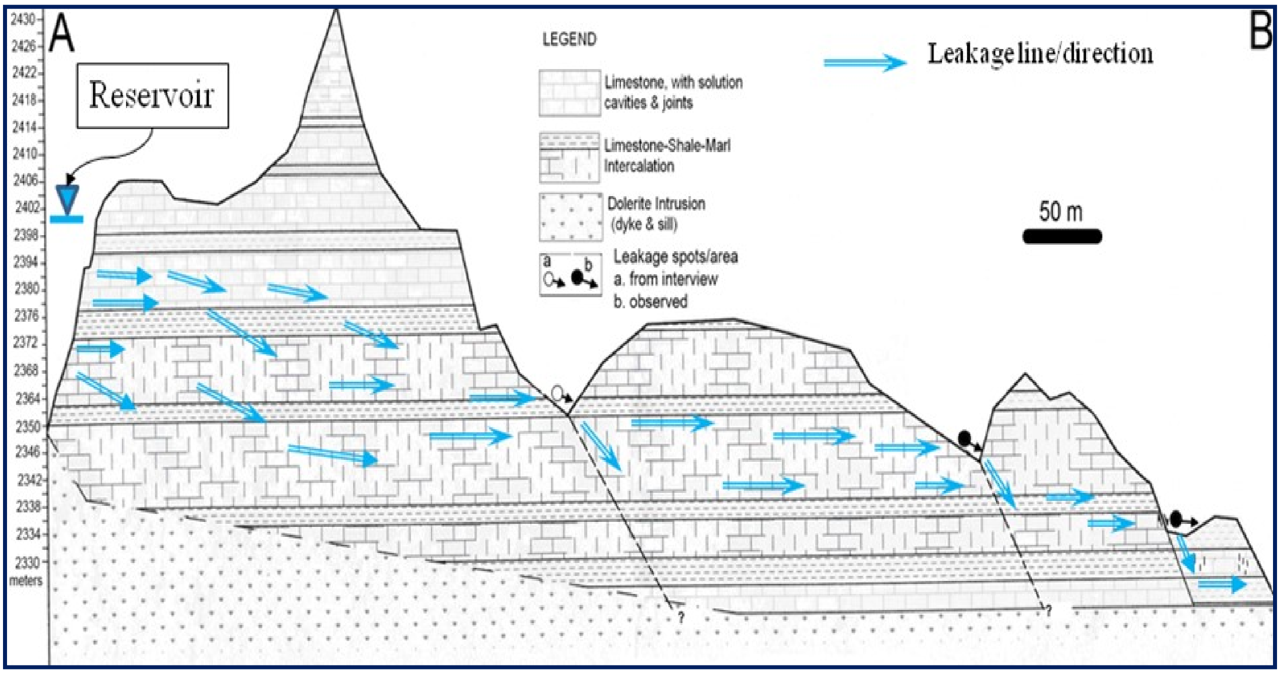

Figure 3.13. Engineering geological cross-section/model of Hashenge. Upstream (A) to downstream (B) side along the left abutment. For localization of line A–B see Fig. 3.12. Arrows show flow direction/leakage. Line of cross-section is more or less parallel to strike line. Maximum pool level of reservoir is at 2401 m. Dominant discontinuity strike is parallel to the cross-section.

A1-Homoud *et al*. (1995) reported on problems of dams constructed in sedimentary terrain (mainly chalky limestone, marl, shale, chert, sandstone) in Jordan (Jordan rift valley). Inspite of many grouting treamtents leakage problem persists and addtional intensive grouting was required for most of the dams (e.g. Wadi Arab and King Talal Dams). Chemical grouting at King Talal dam proved very effective, reducing the permeability of the sandstones at the dam site by 95% (A1-Homoud *et al*., 1995). Synthesis of all surface and subsurface information collected during the course of this research leads to the development of a comprehensive geological cross-section or model (Fig. 3.13) along the leakage path (line AB localization in Fig. 3.12) for Hashenge micro-dam, but more subsurface data are required for Arato. The conceptual model is validated by observational field data that series of new springs emerge at morphologic break or depression along the leakage path after the construction of the dam. In addition, as the water level in the reservoir is lowered, almost below dead storage, the springs also dried out. The model helps in understanding the leakage phenomena and can be used as baseline information in proposing and implementing anti-leakage mitigation measures. This initial information assists in drawing up a consequent strategy leading to the implementation of remedial measures.

CONCLUSIONS AND RECOMMENDATIONS

The research has shown that the sedimentary sequence found on the left flank of both the Arato and Hashenge micro-dams and below the central foundation in Arato micro-dam are pervious units and hence leakage zones. On the other hand, the dolerite that underlies the right flank of the two micro-dams and the central foundation of Hashenge micro-dam is found to be semi-pervious to impervious. Any mitigation strategies should take the geo-hydrological and engineering geological conditions of the MDRs into account.

It is also shown that the discontinuity data from slope face mapping and measurements, vertical electrical sounding results, drilling information and observational geological description were in close agreement and could be used to identify the leakage paths. The discontinuity spacing and aperture were found to be important factors, affecting the hydraulic conductivity of the rock mass.

The packer test results and analysis of discontinuity data also showed that the limestone-shale-marl intercalation unit is pervious. The hydraulic conductivity from packer testing falls within the range of minimum and maximum values obtained from the discontinuity data analysis for the limestone-shale-marl unit.

The authors believe that these results are considered very important for future new site selection in the region and other regions with a similar geological environment, as well as to design and implement anti-leakage measures. Monitoring of the leakage rate and reservoir water level as a function of time is recommended by manual or automatic sensors. In addition, a geophysical survey is recommended at the Arato micro-dam to better understand the subsurface conditions and develop a model.

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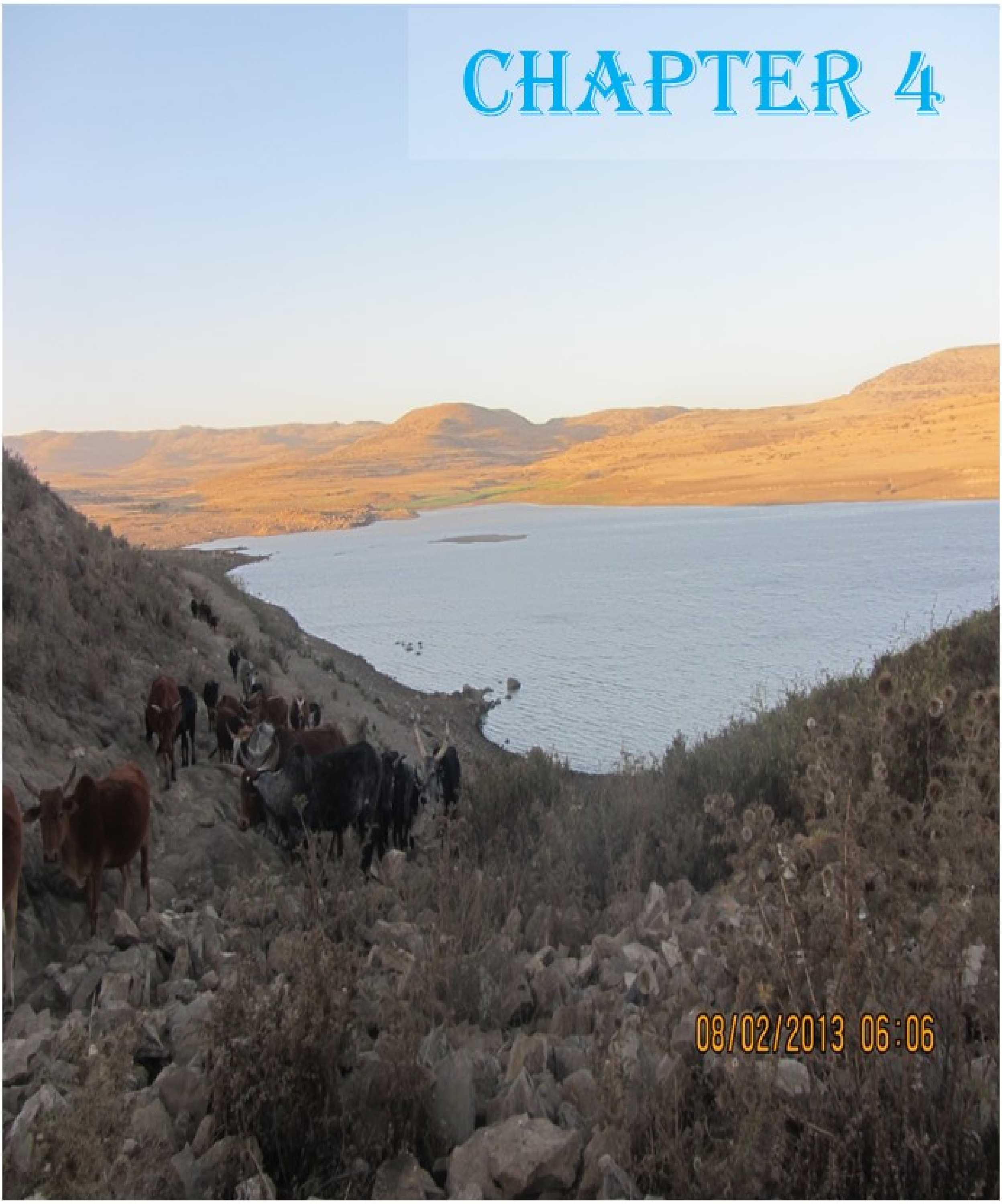
Contribution of authors

Name of author	Role of the author in this chapter
Gebremedhin Berhane	*Was responsible for all the aspects of the study, data collection, VES and BH location selection, interpretation and writing the article/chapter*
Kristine Martens	*Contributed and shared ideas on VES data interpretation*
Nawal Al Farrah	*Share ideas on interpretation*
Kristine Walraevens	*Was the supervisor in the study, and critically reviewed the article*



Panoramic view of Arato MDR from SW to NE direction, catchment area in the background and reservoir water level below dead storage level ©2013 Gebremedhin Berhane.

CHAPTER 4

An integrated approach for detection and delineation of leakage path from Micro-Dam Reservoir (MDR): A case study from Arato MDR, Northern Ethiopia

This chapter is based on Gebremedhin Berhane, Samuel Kebede, Tesfamichael Gebreyohannes, Kristine Martens, Marc Van Camp, Kristine Walraevens. (2016). An integrated approach for detection and delineation of leakage path from Micro-Dam Reservoir (MDR): a case study from Arato MDR, Northern Ethiopia. Bull Eng Geol Environ 75:193–210. DOI:10.1007/s10064-015-0750-9.

ABSTRACT

Water is at the center of all efforts to address food security, poverty reduction, economic growth, energy production and human health. In arid and semi-arid regions, groundwater and water harvesting structures (such as Micro-Dam Reservoirs, MDRs) plays a significant role for irrigation and maintaining the sustainability of water resources. Fighting poverty and drought using construction of MDRs is becoming a common practice in Tigray (northern Ethiopia), but their implementation is not without challenges. Reservoir leakage, *inter alia*, is one of the main problems facing MDRs in the region. This paper presents geological, geophysical, hydrogeological and hydrochemical study results in MDR to better understand and delineate leakage zones and mechanisms. Conventional geological mapping, geo-electrical methods (VES and ERP), hydrogeological and geochemical methods were used to understand the geological and geo-hydrological situation of the MDR. Integrated interpretation and synthesis of the data enable to delineate the leakage zone and path. The limestone-shale-marl intercalation unit that makes up the foundation and reservoir area is found to be the leaky unit due to syngenetic and epigenetic discontinuities, while the dolerite unit is relatively impervious. Installation of a cut-off wall at the upstream toe of the dam could be a possible solution to minimize the leakage problem underneath the dam foundation and left abutment/flank. As an alternative, proper utilization of the water from shallow wells from the leakage zone downstream of the MDR may be also conceived as a target without incurring additional costs of maintenance.

INTRODUCTION

Water is the most valuable and regularly used natural resource and is critical for the survival of life (Wood, 2002) and providing a wide variety of ecological and social services (Döll, 2009; Houben and Weihe, 2010; Laio *et al*., 2009). As stated on GWP (2010), water is at the center of all efforts to address food security, poverty reduction, economic growth, energy production and human health. In arid and semi-arid regions, groundwater and water harvesting structures (such as Micro-Dam Reservoirs, MDRs) play a significant role for irrigation and maintaining the sustainability of water resources (Garrido *et al*., 2006; Scanlon *et al*., 2006). Shortage of water in Ethiopia is a serious issue and the problem is more severe in arid and semi-arid areas like northern, northeastern and eastern Ethiopia. Population growth and erratic and torrential nature of the rainfall exacerbates the problem and increases drought frequency in the region. Using groundwater and MDRs for irrigation and other purposes in these regions of Ethiopia has recently been put in place to fight poverty and secure food sufficiency.

An intensive water resource development can have a crucial role in the economic and social development of the country and in alleviating drought. In order to alleviate the problem of recurrent drought and household food security, the government of Ethiopia has taken household level water harvesting ponds, MDRs and shallow hand dug wells development as one strategy, among others, to improve the country's irrigation development (Tesfay, 2007).

In northern Ethiopia, in addition to groundwater use to address the problems of recurrent drought, famine and food insecurity, efforts are being made to harvest surface water runoff in micro-dams for use both in households and small-scale irrigation schemes. Over the last two decades, a number of MDRs were constructed in Tigray (chapter 2). As a result, substantial improvements were registered in the livelihood of the rural community (Behailu and Haile, 2003) and availability of water for various uses has increased. Micro-dams are usually made of earth and stones, often with inlet-outlet pipes to irrigate from few up to hundreds of hectares, although some of them are suffering from problems like siltation, water leakage and insufficient inflow (yield) and water logging of agricultural land on their downstream (Evans *et al*., 2012, Abdulkadir, 2009; Haregeweyn *et al*., 2006). Due to these technical and operational problems, most of the MDRs are not functioning or operating as per intended objectives (Abdulkadir, 2009; Berhane, 2010; Desta, 2005; Gonzalez-Quijano, 2006; Haregeweyn *et al*., 2005, 2006; Nedaw and Walraevens, 2009).

As in most part of northern Ethiopia, in the study site of Arato the amont of rainfall is variable and is drained by intermittent streams which area dry for eight to nine months of the year (Nedaw and Walraevens, 2009). About 75 to 80% of the rainfall comes during the months of July and August. The hydro-meteorological condition/pattern is a clear and straightforward reason for the need of surface water harvesting structures (e.g. ponds, MDRs, medium and large dams, etc.) to ensure availability of water during the long dry months of the year. Indeed, implementation of Water Harvesting Structures (WHS) like micro-dam reservoirs is relevant in the semi-arid regions of the African tropics, characterized by large inter-annual changes in precipitation and river discharges, and where increasing population pressure makes areas more sensitive to the fluctuations of water resources. In response to the drought and erratic rainfall patterns that have affected this area, the Federal and regional governments have undertaken the goal to rectify these defects by implementing WHS of different types.

Earth and rock dams are designed to operate under steady state seepage. Anomalous seepage may be a threat to the integrity of the structure. In spite of advances made in the fields of engineering geology, it is not possible to have 100% leak-proof structure (Panthulu *et al*., 2001). Any excessive and unplanned seepage may lead to the structural and water storage failures of the dam.

Research on reservoir leakage is an important subject in water resources, irrigation and hydropower projects (chapter 3). Understanding the performance and leakage mechanisms of the MDRs in the country is made difficult by the paucity of available data. A lack of appropriate leakage investigation and monitoring can result in repairs that are unsuccessful in controlling or reducing leakage.

This chapter is aiming at assessing and evaluating the leakage paths and mechanisms using engineering geological and geo-hydrological investigations of the MDR and at identifying the main causes of the leakage. The main goal was to investigate the hydraulic connection between the impounded reservoir and the downstream seepage/leakage discharge zone, and to provide a plausible explanation and solution to the problem.

DESCRIPTION OF THE STUDY SITE

Arato MDR, the MDR studied in this chapter, is located at about 35 km east of Mekelle City. It was designed with a dam height of 20 m and gross reservoir capacity of 2.59×10^{6} m^{3}. The purpose was to harvest runoff from a catchment area of 20.7 km^{2} and use the water for irrigation purposes during dry seasons (Hagos, 1995). Arato MDR is a typical example of an almost abandoned irrigation scheme as a result of reservoir leakage. Figure 4.1 shows simplified location of Arato MDR and its surrounding. The topographic elevation of the Arato study area varies from 2400 m to 2560 m (a. s. l). Arato River is the biggest river in the catchment and it flows southwards of the study area until it joins the Illala River further downstream of Arato MDR. It used to be seasonal, but nowadays, after Arato MDR was constructed, it became perennial. Seasonal tributary streams originating from the highlands are flowing towards the Arato reservoir.

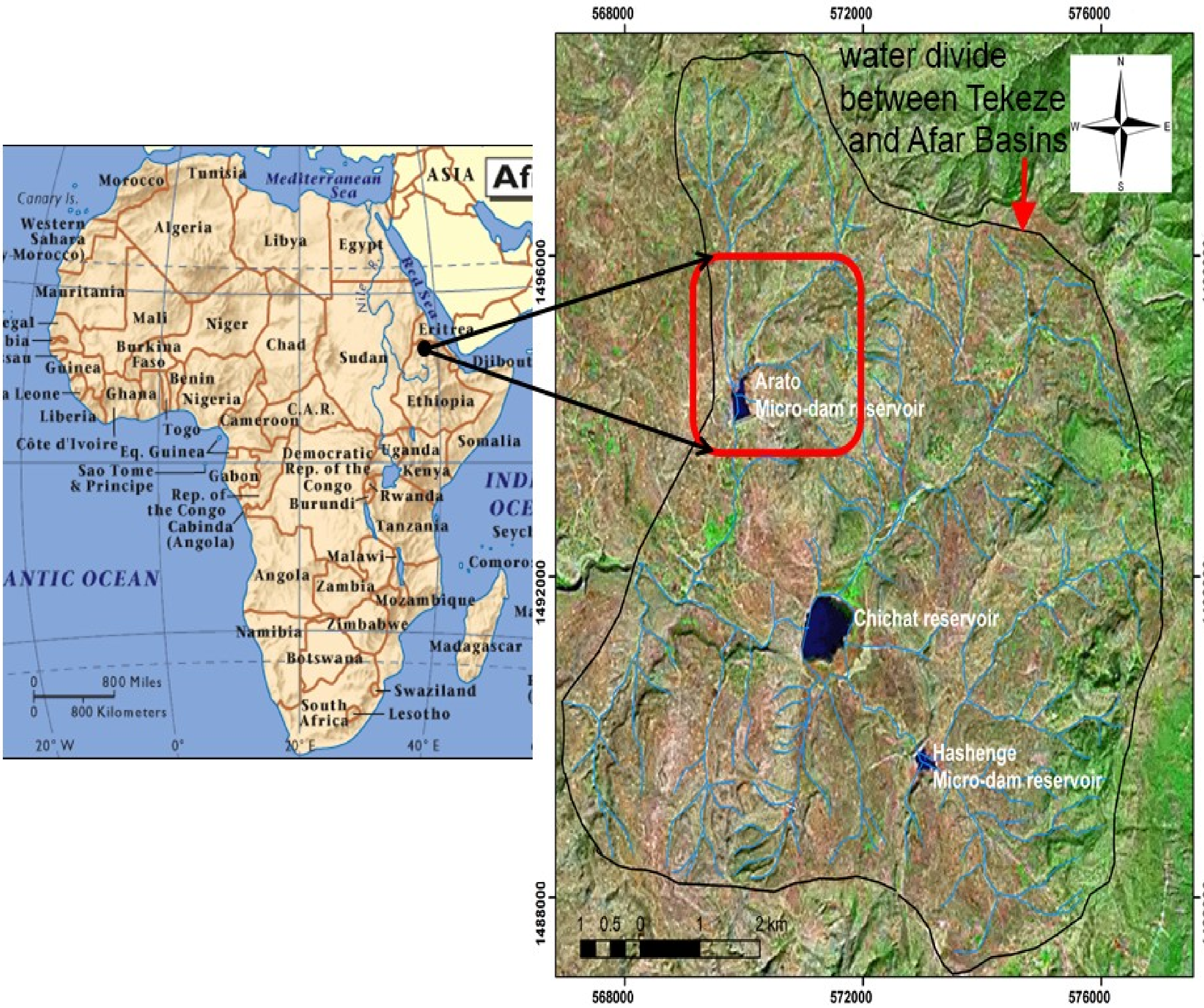
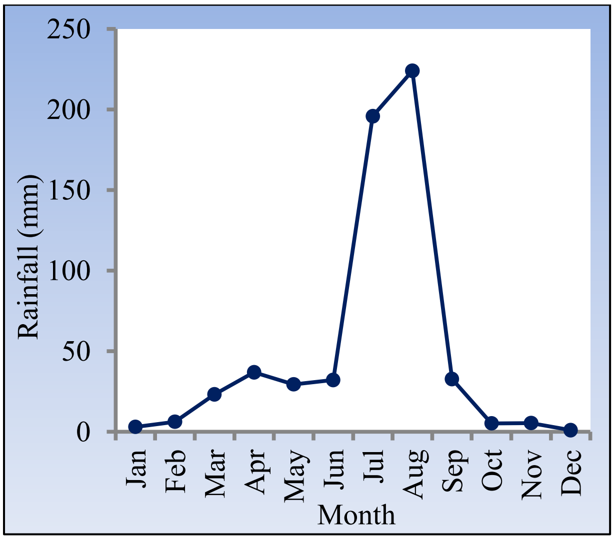


Figure 4.1. Simplified location map of Arato MDR and its environs showing other MDRs in the area (colour satellite image in the background). UTM Zone 37N coordinates (satellite image data source from ETHIO-GIS data sets).

In many MDRs (e.g. Tsinkanet MDR), the rivers are seasonal in the upstream, whereas perennial in the downstream, due to continuous leakage from the reservoir that recharges shallow aquifers and leads to emerging new springs and increases the discharge of existing ones (Gonzalez-Quijano, 2006). This situation is also true at Arato MDR as confirmed by direct field observation. The Arato Reservoir, which entered into service in 1998, has suffered from severe leakage from the outset, preventing it from performing the water management functions originally foreseen for it (e.g. irrigation of about 100 ha of land). However, MDRs contribute to or enhance distributed water availability feeding shallow aquifers and streams through diffuse seepage and/or concentrated leakage. Present hydrogeophysical studies have made it possible to determine the response of the underlying Quaternary deposit and weathered bed rock aquifer into which the reservoir water is draining.

The mean annual rainfall of the region is about 762 mm (Nyssen *et al*., 2010) with the maximum amount recorded during July and August (Fig. 4.2). Generally, more than 80% of precipitation on yearly basis is falling in the "Kiremt" (summer) season, June to September (Nyssen *et al*., 2005). According to Baert (2011), the seasonal temperature variation shows a cool (15-18°C) winter from October to March followed by warm (> 20°C) spring from April to June. However, the temperature drops again in summer season.



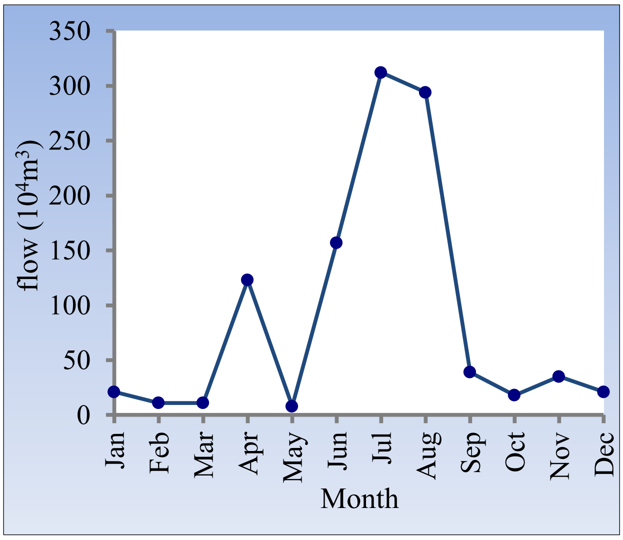


Figure 4.2. Long term mean monthly rainfall (1960-2000) (left) and hydrograph of Illala River (1980–1986) (right). Location of the meteorological and Illala River gauging stations are about 15 km downstream of Arato MDR.

MATERIALS AND METHODS

Conventional geological approach, geo-electrical prospection and hydrogeological/hydro-geochemical methods were used in the present study to characterize the site and to detect and delineate the leakage path from Arato MDR.

Geology and hydrogeology

Conventional geological fieldwork with the help of topographic map, GPS and pre-planned traverses were used to characterize local geology of the site. Description of natural outcrops, borehole logs (14) and large diameter shallow test pits (9) excavated for water extraction for local scale irrigation purposes were used to better understand the nature of weathering, thickness of soil profile and subsurface flow of water. A piezometric map was produced to better understand the groundwater flow system of the area. Groundwater level records were obtained from archives for 14 boreholes many of which were drilled in 2009 and field measurements in 9 shallow hand dug wells on the 21st of November, 2014. To produce the groundwater contour map initially ArcGIS (version 9.3) software was used but later manually modified to fit with the geology and drainage system of the area.

Geophysics

Subsurface information gathered by drilling test holes are time consuming, expensive, data represents a single location, and lateral changes must be estimated or interpolated between distant points (Massoud et al., 2009). Surface geophysical methods, on the other hand, used in combination with strategic test drilling, provide more complete areal coverage than test drilling alone. Of all surface geophysical methods, the electrical resistivity method has been applied most commonly for groundwater investigations (Coker, 2012; Sharma and Baranwal, 2005; Telford *et al*., 1990) and identify zones of anomalous seepage or leakage (Bedrosian *et al*., 2012 and references therein; Panthulu *et al*., 2001; Rønning *et al*., 2014; Srinivasamoorthy *et al*, 2014).

By inducing an electrical current into the ground, the earth resistivity can be measured (Telford *et al.*, 1990). Direct current is passing into the ground through a pair of current electrodes (A and B) and the resulting potential measurement over a pair of potential electrodes (M and N) is recorded. The resistivity of the subsurface formation observed is a function of the magnitude of the current, the recorded potential difference and the geometry of the electrode array that was used. Using SAS Terrameter (signal averaging system) 2000 produced by the Swedish company ABEM, for each electrode configuration the resistance was measured for a volume of earth material within the electrical space. Thus, it is possible to determine the apparent resistivity (ρ_a) using Equations 4.1 and 4.2 (Lowrie, 2007; Sharma and Baranwal, 2005 and Telford *et al.*, 1990).

$$\rho_a = \frac{k\,\Delta V}{I} \qquad (4.1)$$

in which

$$k = 2\pi\left[\left(\frac{1}{AM} - \frac{1}{BM}\right) - \left(\frac{1}{AN} - \frac{1}{BN}\right)\right]^{-1} \qquad (4.2)$$

k is the geometric factor for AMNB collinear four electrodes (Fig. 4.3), that depends on the electrode configuration:

$$k = \pi\left[\frac{L^2 - l^2}{4l}\right] \quad \text{(for Schlumberger array)} \qquad (4.3)$$

$$k = 2\pi a \quad \text{(for Wenner array)} \qquad (4.4)$$

where L is separation between current electrodes and l is separation between potential electrodes (Schlumberger), a is separation between each pair of successive electrodes, which is equal for Wenner array; I is amount of electric current injected into the ground through the current electrodes A and B, and ΔV is the electric potential difference between electrodes M and N.

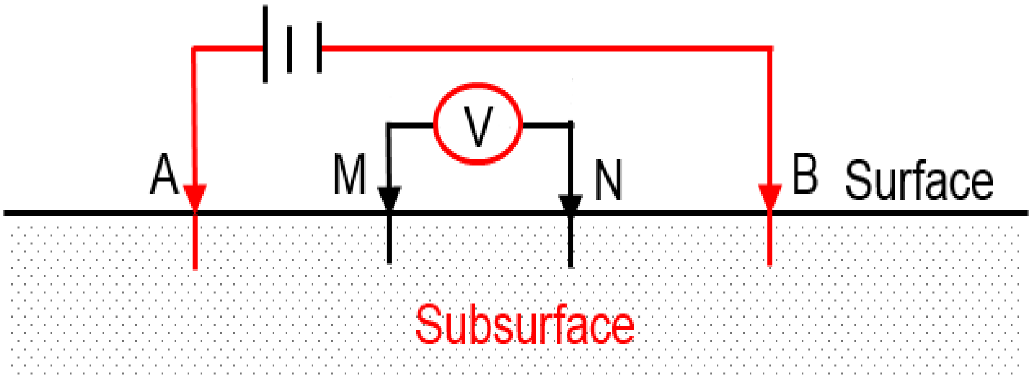


Figure 4.3. Collinear four-electrode array used in resistivity surveying (A and B are current or injection electrodes and M and N are potential/measuring electrodes).

The sounding measurements with Schlumberger array were started with an electrode spacing of 3 m (AB/2 1.5 m) and increased systematically up to 660 m (AB/2 of 330 m), with fixed measuring centre. For electrical profiling with Wenner array, fixed electrode spacings of 20 m or 40 m were used, moving the measuring centre at each measurement with an interval of 10 m.

A total of 8 vertical electrical sounding (VES) using Schlumberger array were conducted, and 6 electrical resistivity profilings (ERP) using Wenner array with a=20 m and a=40 m for profile lines AP1, AP2, AP3 and AP4, while a=40 m only for AP5 and AP6. The ERP measurements were taken at an interval of 10 m (X=10 m). Modelling of VES results was done using the IPI2win IP software developed by Bobachev (2002), utilizing the inversion modeling procedure. It gives the formation resistivity and thicknesses of the subsurface electrical layers beneath the sounding point or station.

Hydro-geochemistry

Three water samples collected (using a 0.5 liter plastic bottles) on the 23rd of January, 2012, from the reservoir (Reservoir), a nearby downstream shallow hand dug well (ASHDW) and the stream (Stream) (Fig. 4.4) were analyzed for major cations and anions at the Laboratory for Applied Geology and Hydrogeology of Ghent University, Belgium. Major cations (Ca^{2+}, Mg^{2+}, Na^{+} and

K^{+}) were determined by a Flame Technique in a High Resolution Continuum Source AAS and anions (Cl^{-}, SO_4^{2-} and NO_3^{-}) were determined by using Ion Chromatography, while HCO_3^{-} was determined using titration. In addition two hydro-geochemical analysis results from boreholes (SHW37 and BH80, Fig. 4.4) in the surrounding of Arato MDR were collected from archives of Tigray Water Resources Development Bureau (TWRDB) to compare with unaffected groundwater. The reliability of the chemical analyses was verified by using an ionic balance error equation (Appelo and Postma, 2005). The values were within ±5 %; hence, suitable for geochemical interpretations.

RESULTS AND DISCUSSION

Geology and geohydrology

To understand site specific features of geology and geohydrology a series of field campaigns were conducted in the area. A simplified geological map of the area is shown in Figs. 4.4 and 4.5. The foundation and reservoir are covering with three main lithological units: Quaternary deposits, Dolerite and Agula Shale (limestone-shale-marl intercalation). The Quaternary deposit within the reservoir was partly removed as construction material for the dam. This construction activity resulted in exposure of the dolerite and limestone-shale-marl intercalation units.

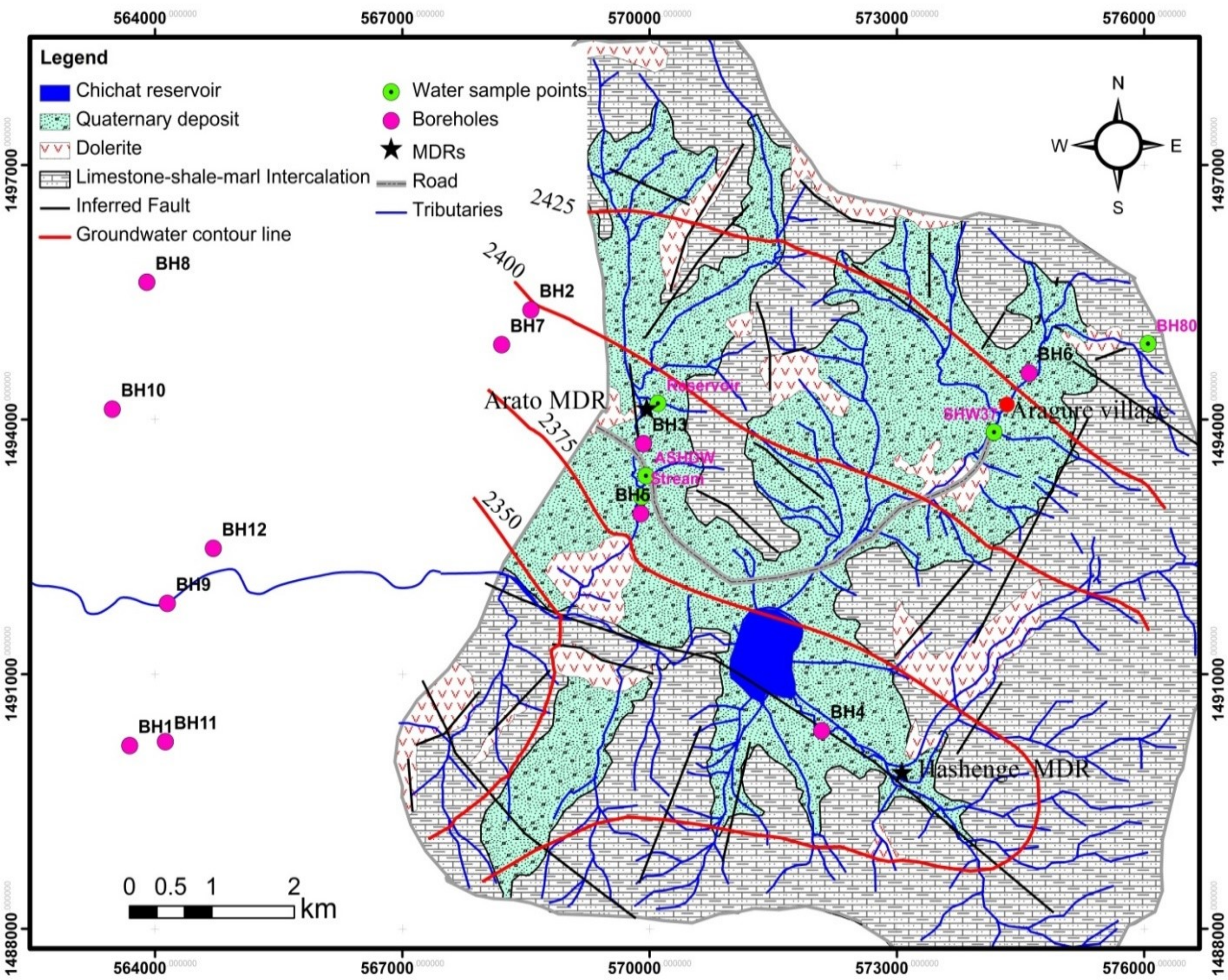


Figure 4.4. Geological map of Arato MDR and its environs (chapter 3). Groundwater contour lines are indicated and labeled in m. a. s. l.

Geological features such as lithology and structure control the ease with which water will flow through the ground. Based on well log data from the surrounding of the site (Kassa, 2011), the main aquifers in the area are fractured or jointed and karstified limestone, and weathered and fractured dolerite and limestone-shale-marl intercalation. Except for the Quaternary deposits, the aquifer system in the area is generally due to secondary porosity and permeability. The dominant aquifer is the limestone-shale-marl intercalation unit, whereby weathered, fractured and karstified limestone forms the main water-bearing zones in the area. The water level measurements obtained from different wells with pumping test data and logs in the area suggest confined and unconfined aquifers (Kassa, 2011). This is explained by the interlayering of shale in between the productive layers which acts as an aquitard.

Quaternary deposits

Quaternary deposits are exposed at flat slopes both upstream and downstream of the Arato MDR derived from nearby dolerite and limestone-shale-marl intercalation. The thickness varies from place to place from half a meter up to 5 m. The grain size of this lithological unit ranges from clay to coarse sand with minor inclusions of gravel (chapter 3). The central foundation of the MDR is covered by this superficial materials underlying by limestone-shale-marl intercalation.

These deposits cover the central part of the reservoir and downstream of Arato MDR (chapter 3). Recently, shallow hand dug wells were excavated into the Quaternary deposits on the downstream side of the reservoir, to harvest subsurface water for various uses. The deposits were found to be pervious and water bearing in areas where sand and gravel (resulted from weathering of dolerite and limestone-shale-marl intercalation) predominate and along its contact with the underlying bedrock.

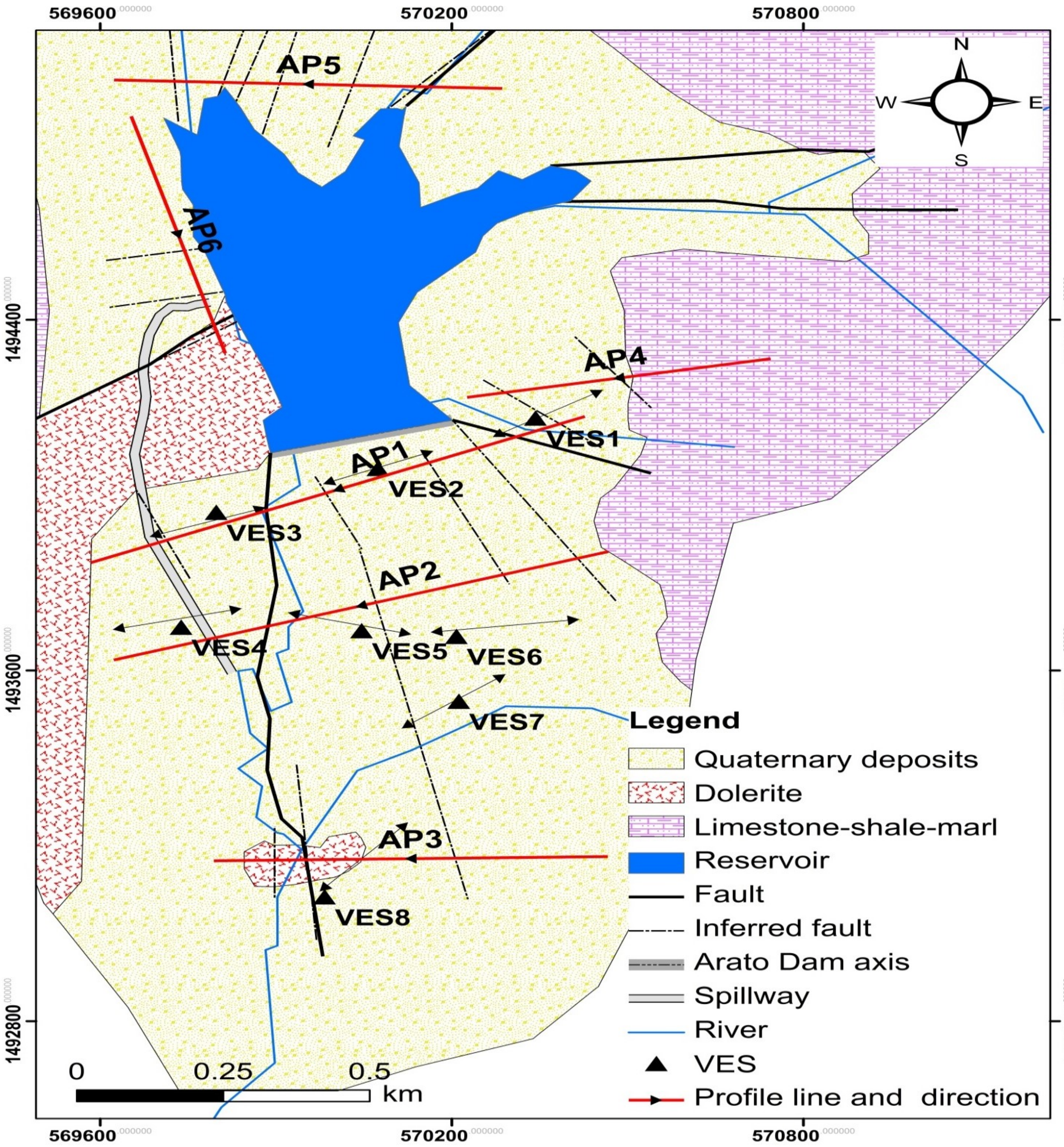


Figure 4.5. Geological map of Arato MDR. Locations of VES and ERP are shown. UTM Zone 37N coordinate system and lines with double arrow indicates electrode alignment direction for the VES.

Dolerite

Dolerite forms swarms of dykes, sills and irregular bodies within Mesozoic sedimentary sequences with varying width and length between few meters to several kilometers. It is characterized by dark grey colour, and exfoliation/spheroidal weathering (peeling off the outer layers of the rock surface) and massive nature. Degree of weathering of this rock varies from place to place; it is completely weathered along the contact with limestone-marl-shale and fault zones. The grain size of this unit ranges from medium to coarse. Generally, the degree of weathering of dolerite decreases with depth (chapter 3). This rock unit is exposed on the right abutment (west) and south of the MDR (Figs. 4.4 and 4.5). The thickness of the dolerite in the right abutment (west side) is not well documented. The sills have observed to be sub-horizontal following the bedding plane of the sedimentary rocks. Fractured and weathered dolerite sills and dykes with sufficient extent and with suitable topographic feature can form potential aquifers.

From the well log and field information in the area, the thickness and physical characteristics of the weathered and fractured layer of the dolerite intrusions are not uniform throughout the catchment where these intrusions are exposed. The thickness ranges from about 30 to 250 m in surface exposures in the area. It was also observed that most of the dolerite outcrops were intruded in between the sedimentary formations, but in the vertical section or log of some wells a thickness of up to 33 m (Fig. 4.6) is observed. Although the degree of both weathering and fracturing is relatively high at the upper part of the dolerite intrusions, the aquifer capacity of this part is low. This is due to the effect of the clayey weathering products from the overlying sedimentary rocks. The geological log from most wells depicts that the type of the aquifer within dolerite intrusion in the area is characterized by confined and unconfined aquifers (Fig. 4.6 and 4.7).

Limestone-shale-marl intercalation

This formation occupies an extensive area around Arato MDR and its environs. Limestone-shale-marl intercalation unit, which is part of the Agula Shale, covers large part of the area. Its colour is variegated (lateral and with depth); it varies between light grey, yellowish and brownish. This rock unit has an average thickness of about 30 m (Gelena, 2013) in the area. From this intercalation unit, the limestone subunit is relatively thicker than the others. These rocks are vastly affected by weathering and tectonic activities. Due to faulting and dolerite intrusion the bedding plane of this rock unit is tilted towards east (chapter 3). Joints are prominent on the east of Arato MDR. The degree of weathering diverges from place to place: completely weathered along the contact with dolerite, due to the roasting/baking effect of the dolerite intrusion and along fault zones, and slightly weathered at the north of the study area. A sinkhole with a significant diameter is observed on the eastern side (left abutment) of Arato reservoir. The presence of gypsum is observed in drilling logs in the area (Fig. 4.6).

Fig. 4.6 portrays the geological and hydrogeological log illustrating the typical aquifer systems in the area. The limestone layer is hard and well jointed having highest infiltration rate, while the shale and marl layers are soft and powdery having lower infiltration rate. Because of the inter-bedded fractured limestone and shale layers, groundwater exists under semi-confined condition in this unit. Boreholes drilled in this unit elsewhere are artesian (Yihdego, 2003). The relatively high permeability (greater than 10^{-4}cm/s) of this unit is due to its disturbance by the dolerite intrusion and tectonic joints and dissolution cavities in the limestone layer. The highly jointed parts of the limestone bed favor groundwater storage and movement.

According to Yihdego (2003) wells drilled in the limestone-shale-marl intercalation unit showed an average hydraulic conductivity and transmissivity value of 12.3 m/day (1.42×10^{-2}cm/sec) and 186 m^2/day respectively. In areas where it is thick, the limestone is the main aquifer system with highest hydraulic conductivity values ranging from 18.6 to 57.5 m/day (2.15 to 6.66×10^{-2}cm/sec) and transmissivity value of 336 to 403 m^2/day (Yihdego, 2003).

From the hydrogeological characteristics of the limestone-shale-marl intercalation it is clear that when it exists at foundation, abutments and reservoir, water losses will occur and water will drain toward downstream leaks and seeps or vertically downward to feed the aquifer system. This phenomenon is very common in many MDRs in northern Ethiopia, including Arato MDR. In many MDR water flows in concentrated paths and emerges downstream creating streams, or water infiltrates at the reservoir bottom through the permeable materials.

Geological structures

The main geological structures observed in the study area are faults and joints. The area is affected by minor and major faults. Mekelle Fault with strike direction of NW-SE is the major fault in the area (chapter 3, Fig. 4.4). Most of the tributaries of Arato River are controlled by minor geological structures. Inferred faults are identified in the study area, within limestone-shale-marl intercalation and between limestone-shale-marl intercalation and dolerite rocks. Most of the faults in this study area have a NE-SW orientation (Fig. 4.4).

The area is characterized by joints with NW-SE and NE-SW prevailing strike direction. These geological structures are more dominant in the limestone-shale-marl intercalation unit. According to the discontinuity histogram of presented in chapter 3 (Fig. 3.5), the dominant strike of discontinuities on east and west abutment of the Arato micro-dam is NW-SE and WNW-ESE respectively.

Hydrogeophysical investigations

Vertical electrical sounding (VES)

A total of 8 VES (Fig. 4.5) with Schlumberger array were conducted at the MDR to decipher the vertical variation at the point of soundings. Brief summary of the interpretations of the VES is given in Table 4.1.

VES data were interpreted based on local geological information, observation of natural outcrops and shallow hand dug wells in the downstream of the MDR. The interpreted true resistivity values vary from 5.74 Ωm to 1155 Ωm (Table 4.1). This wide variation in resistivity values is mainly attributed to the variation in geological units, degree of fracturing, weathering and water content. In addition to the overall geology, during interpretations it was recognized that topmost dry soils have greater resistivity in comparison to saturated soils (Zohdy *et al*., 1974); weathered and discontinuous rocks have lower resistivity than massive and compacted rocks.

Based on the results of the interpretation of VES1 and VES2 the saturated and pervious subsurface materials extend up to a depth of 14.5 m to more than 16 m. Considering the geology of the area the pervious layers are correlated to limestone-shale-marl intercalations (44.6 to 83.2 Ωm) with top clay cover (9.41 Ωm) and underlain by less weathered and fractured rocks of the same unit with resistivity values ranging from 306 to 385 Ωm. Generally, weathering and degree of discontinuity or aperture decreases with increasing depth due to overburden pressure. Permeability and porosity in the weathered zone of rocks vary throughout the rock profile. Porosity generally decreases with depth while permeability possesses a complicated relationship, depending on the extent of fracturing and the clay content (Chilton and Foster, 1995 in Yusuf *et al.*, 2011).

VES 1 and 2 are located at the downstream side of the dam foundation; hence the leakage beneath the dam body can be ascribed to the fractured and weathered limestone-shale-marl intercalation unit. Leakage becomes more serious in areas where fractured limestone dominates the intercalation unit than where shale or marl dominates.

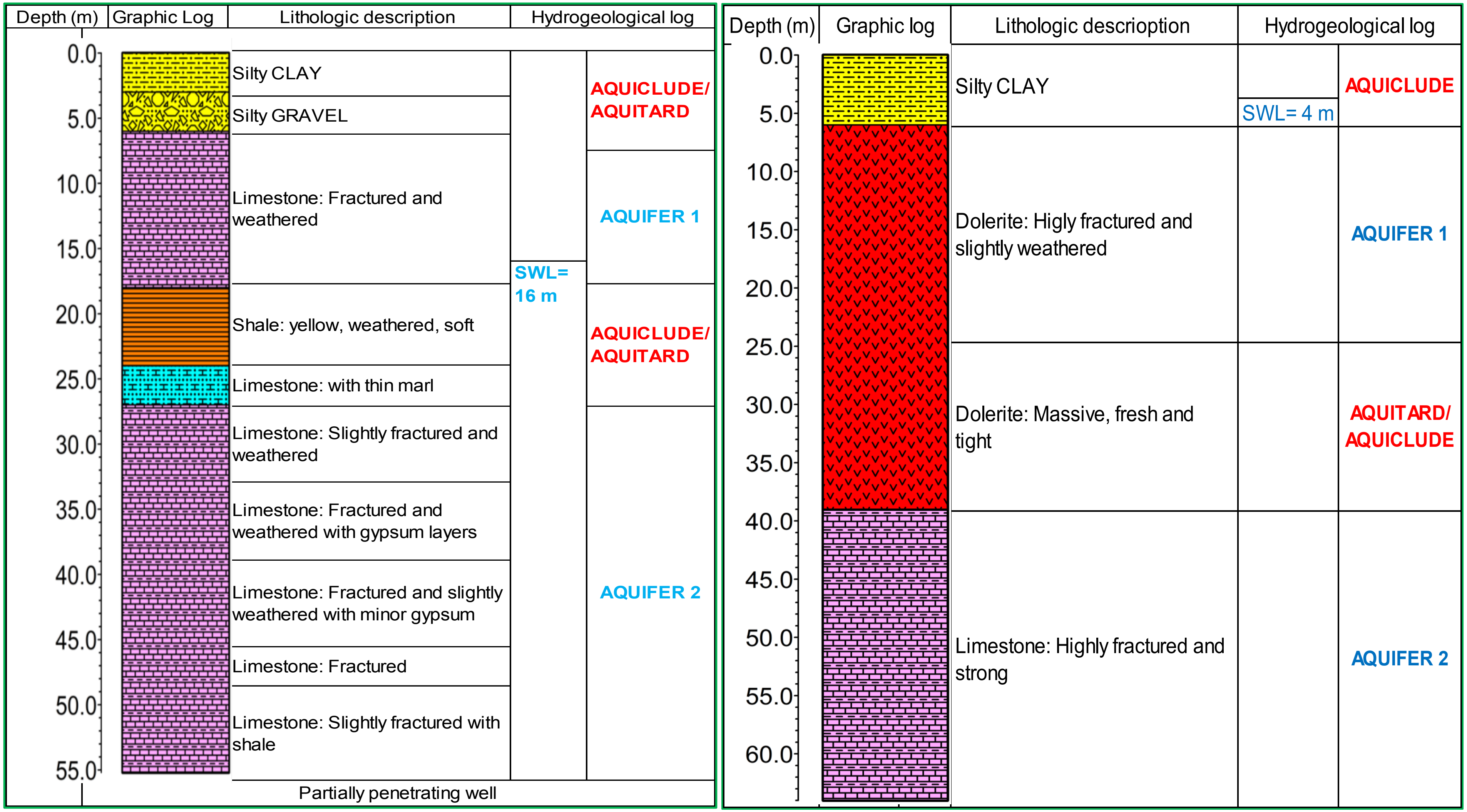


Figure 4.6. Lithological and hydrogeological log of a drilled well in limestone-shale-marl intercalation and dolerite units near Arato MDR (modified from Kassa, 2011 and Tigray Water Works Construction Enterprise, TWWCE). Left BH10 and right BH5 in Fig. 4.4.

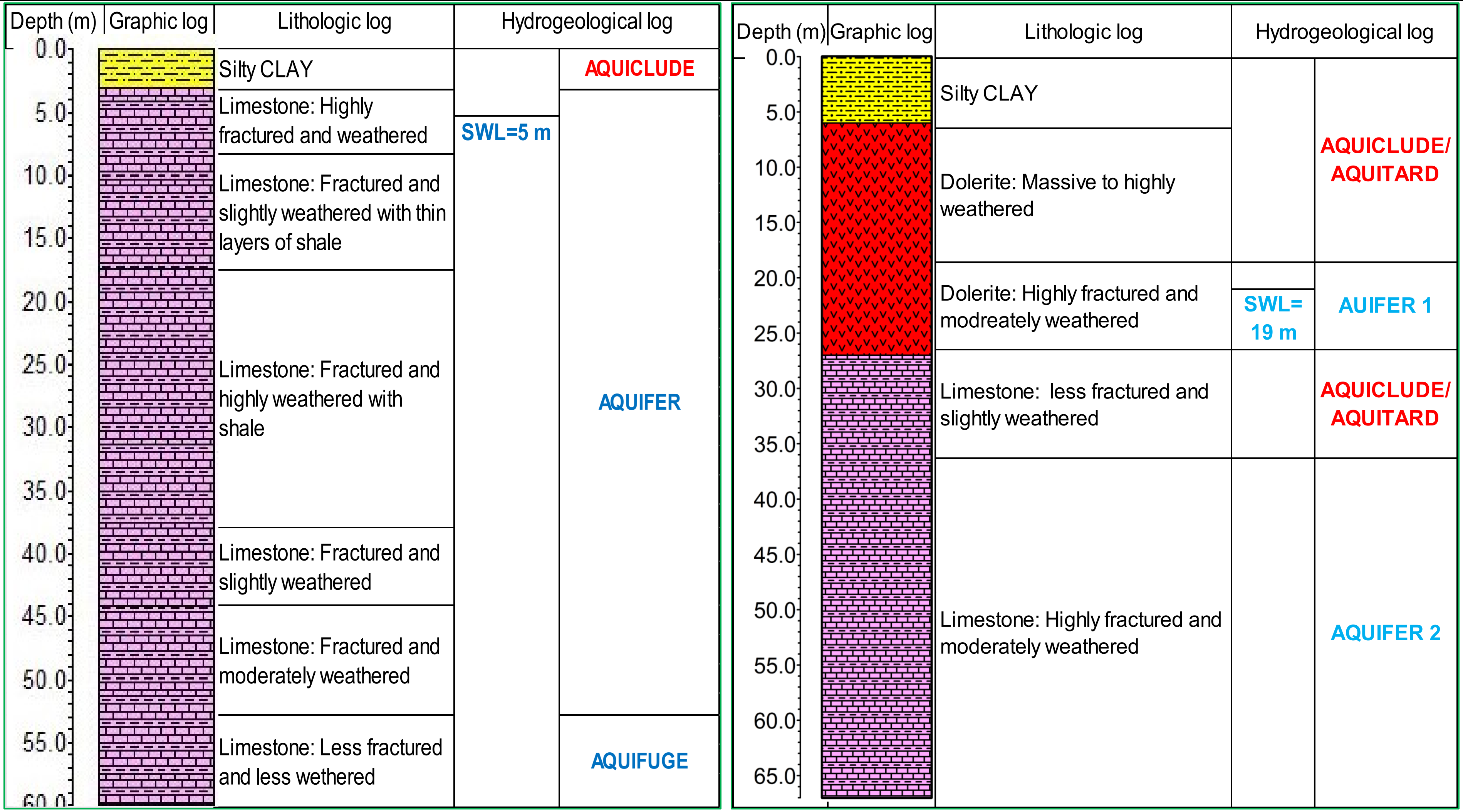


Figure 4.7. Lithological and hydrogeological log of a drilled well in limestone-shale-marl intercalation and dolerite unit near Arato MDR (modified from Kassa, 2011 and Tigray Water Works Construction Enterprise, TWWCE). Left SHW37 and right BH3 in Fig. 4.4

Table 4.1. Summary of the hydro-lithological interpretation of VES data from Arato MDR (VES data are included in Appendix C4 on CD).

VES	Layer (N)	Resistivity (Ω m)	Thickness (m)	Interpretation
1	1	83.2	6.9	Fractured, weathered and partially saturated limestone-shale-marl intercalation/ Quaternary deposit
	2	58	7.6	Fractured, weathered and saturated limestone-shale-marl intercalation
	3	385	15.7	Slightly fractured limestone
	4	143		Limestone-shale-marl intercalation
2	1	9.41	3.6	Moist top clay soil/Quaternary deposit
	2	44.6	12.5	Weathered, fractured and saturated limestone-marl intercalation
	3	306	34.5	Slightly fractured limestone
	4	84.9		Shale dominant limestone-shale-marl intercalation
3	1	117	4.4	Dry top clay soil/Quaternary deposit
	2	123	24.2	Fractured and slightly weathered dolerite
	3	238		Slightly fractured dolerite
4	1	17	1.2	Moist top clay soil/Quaternary deposit
	2	6.02	3.3	Saturated and completely weathered dolerite
	3	44.2	15.3	Saturated, weathered and fractured dolerite
	4	242		Fractured and slightly weathered dolerite
5	1	9.5	3.1	Moist top clay soil/Quaternary deposit
	2	50.3	18.7	Saturated, weathered and fractured limestone-shale-marl intercalation
	3	349		Fractured limestone
6	1	9.8	2.7	Moist top clay soil/Quaternary deposit
	2	52.9	15.8	Weathered, fractured and saturated limestone-shale-marl intercalation
	3	221		Fractured limestone
7	1	15.2	4.6	Moist top clay soil /Quaternary deposit
	2	35	14	Saturated, weathered and fractured limestone-shale-marl intercalation
	3	346		Fractured limestone
8	1	12.3	1.8	Moist top clay soil/Quaternary deposit
	2	5.74	3.0	Completely weathered and saturated dolerite (clayey soil)
	3	1155		Compacted dolerite

VES 3, 4 and 8 are located on dolerite unit overlain by Quaternary deposits of variable thickness. The first geoelectric layer was interpreted to be moist to dry top clay soil with a thickness that varies from 1.2 to 4.4 m, while the resistivity ranges from 12.3 to 117 Ωm. The second geoelectric layer was interpreted to be saturated and completely to slightly weathered dolerite with variable degree of fracturing. This unit is considered as the pervious aquifer, responsible for the circulation and movement of the leakage water from the reservoir. Some hand dug wells have been excavated in this area, after the construction of the MDR, for irrigation purposes. The water level in these hand dug wells varies from 0 (just at the surface) to 2.8 m below ground surface. The third geoelectric layer was interpreted to be slightly fractured to compacted dolerite which is considered as aquitard/impervious unit with resistivity values that range from 238 to 1155 Ωm. It is noteworthy to mention the shallow depth (only 4.8 m, Table 4.1) of the pervious layer and very high resistivity value of the third geoelectric layer or fresh dolerite (1155 Ωm) at VES 8. This result is explained by the fact that VES8 is located immediately near natural outcrop of dolerite (Fig. 4.5).

VES 5, 6 and 7 are located on the limestone-shale-marl intercalation unit overlain by Quaternary deposits of clayey types (Fig. 4.5). The first geoelectric layer which is the moist top clay soil varies in thickness from 2.7 to 4.6 m, while the resistivity ranges from 9.5 to 15.2 Ωm. The second geoelectric layer was interpreted to be the saturated, weathered and fractured limestone-shale-marl intercalation unit which is again responsible for the circulation of subsurface water. Its thickness varies from 14 to 18.7 m while the resistivity values range from 35 to 52.9 Ωm. The third geoelectric layer is a resistive unit with resistivity values that spread between 221 and 349 Ωm, which depict the presence of slightly fractured limestone dominated intercalation unit. This unit is assumed to be an aquitard or impervious layer.

Electrical resistivity profiling (ERP)

A total of 6 ERP measurements (three on the downstream side, one at the upstream, one at the left abutment (east) and one at the right abutment (west) of Arato MDR, Fig. 4.5) were conducted to identify lateral variations in resistivity along the profile lines. The graphical representation of the ERP measurements is presented in Fig. 4.8.

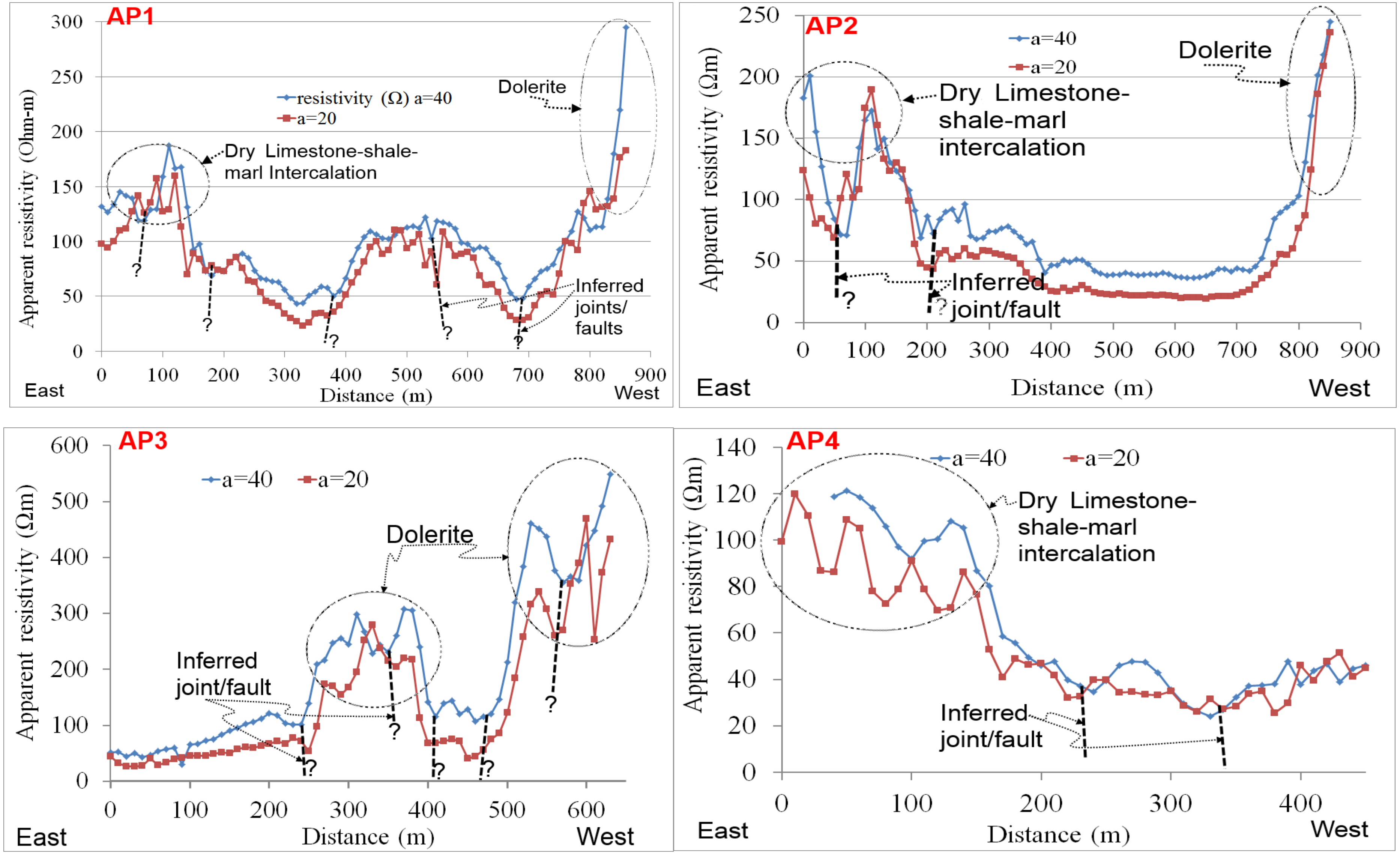
Due to the fact that ERP allows the detection of lateral changes in the resistivity of the subsurface materials, the presence of fracture zones and the degree of saturation of the ground can be determined (Kirsch, 2006). The presence of water in a pore space decreases the resistivity of the rock, thus profiling can be used to give an indication of water level depth (Vandecasteele *et al*., 2011) and leakage zone, which can be used in revealing the leakage path from the reservoir. The ERP data of the study area were interpreted qualitatively (Zohdy *et al*., 1974) from the plot of apparent resistivity and horizontal distance (Fig. 4.8).

The discontinuities that intersect the dam axis, dipping toward downstream are the most favourable for leakage of water from MDR (chapter 3). Vandecasteele *et al*. (2011) noted that seepage via the rock masses usually passes through the discontinuities.

The measured resistivity values of ERP data range from 19.25 Ωm to 548.5 Ωm. Based on the resistivity contrast of ERP data, some joints/faults were interpreted (Figs. 4.5 and 4.8). Profile lines AP1, AP2 and AP3 were executed on the downstream side of the reservoir parallel to the dam-axis (Fig. 4.5) with a horizontal distance of 860, 850 and 630 m from east side to west side respectively (Fig. 4.8). Profile AP1 and AP2 show more or less similar patterns with higher apparent resistivity on the west and east sides and lower resistivity in the central part of the profile. This large resistivity variation is attributed to variation in degree of saturation, weathering and fracturing and rock type. The high resistivity on the west side of the profiles was interpreted as dolerite based on the local geological map and direct field observation (Figs. 4.5 and 4.8), while the higher resistivity on the east side was interpreted as dry limestone-shale-marl intercalation.

The dolerite and limestone-shale-marl intercalation units outcrop at the western and eastern part of these profiles where high resistivity was measured. The central part of the profiles with relatively lower apparent resistivity was interpreted as saturated weathered and fractured limestone-shale-marl intercalation. This zone is assumed to be the leakage path from the reservoir. Multiple joints/fractures with relatively lower apparent resistivity were also interpreted along these profiles due to greater proportion of water infiltrating along these joints/fractures.

Profile AP3 shows a different pattern than AP1 and AP2 which is explained by the local geology or location of the profile line. The higher apparent resistivity at around a distance of 300 m and beyond 500 m was interpreted as dolerite (Fig. 4.8) whereas the low values at distances of 0 to 300 m and 400 m to 500 m are attributed to saturated, weathered and fractured dolerite. An outcrop of dolerite was observed during the field campaigns as portrayed in Fig. 4.5 along the profile line. The very low values encountered along the profiles give a possible structural interpretation like minor faults/joints. The approximate orientation of the joints/faults is N-S, i.e. nearly perpendicular to the dam axis or parallel to the presumed leakage path.


AP1
resistivity (Ω) a=40
a=20
Dolerite
Dry Limestone-shale-marl Intercalation
Inferred joints/ faults
Apparent resistivity (Ohm-m)
Distance (m)
East
West
AP2
a=40
a=20
Dolerite
Dry Limestone-shale-marl intercalation
Inferred joint/fault
Apparent resistivity (Ωm)
Distance (m)
East
West
AP3
a=40
a=20
Dolerite
Inferred joint/fault
Apparent resistivity (Ωm)
Distance (m)
East
West
AP4
a=40
a=20
Dry Limestone-shale-marl intercalation
Inferred joint/fault
Apparent resistivity (Ωm)
Distance (m)
East
West

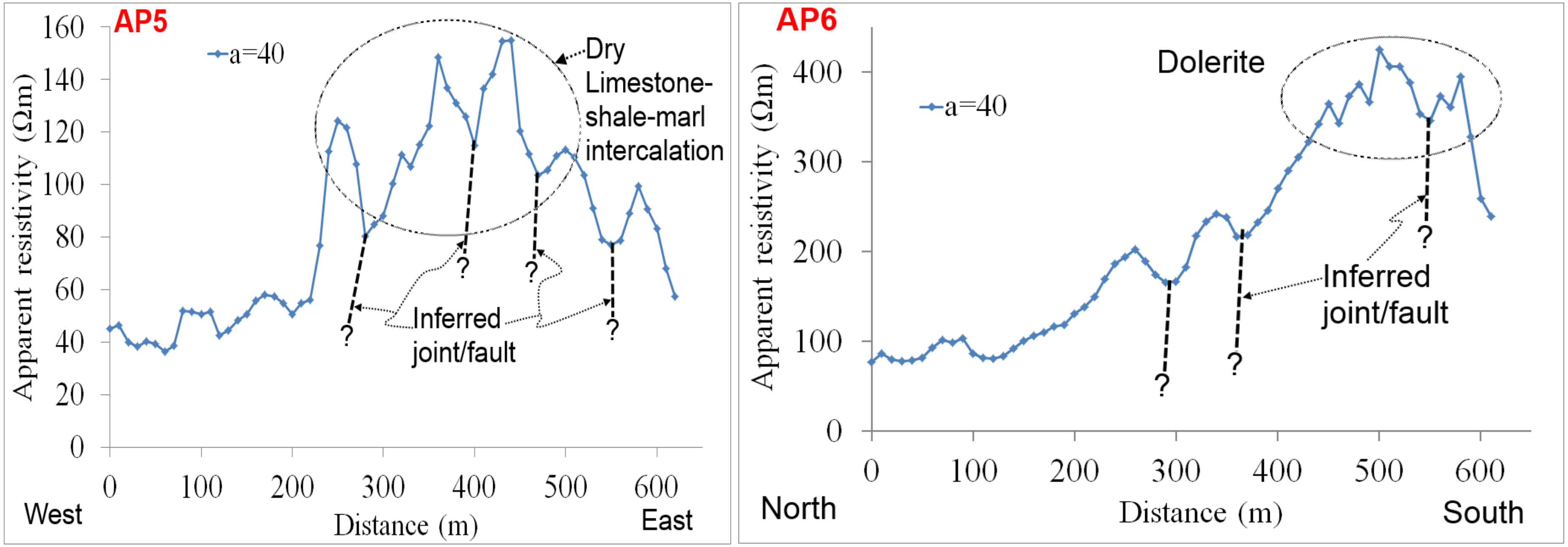


Figure 4.8. Graphical plot of ERP (apparent resistivity versus horizontal distance) for the six profile lines with lithological and structural interpretations. For localization of profile lines see Fig. 4.5. Raw data are included in Appendix C4 on CD.

Profile AP4 was executed on the left abutment side of the MDR with a length of 440 m and measurements were taken from east toward west direction (Figs. 4.5 and 4.8). The apparent resistivity along this profile varies from 24 to 121 Ωm. This wide resistivity variation is explained by variation in degree of weathering, fracturing and moisture content. The high resistivity anomaly was interpreted to be slightly weathered and fractured limestone dominating the intercalation unit, while the low resistivity anomaly was interpreted to be highly weathered, fractured and saturated limestone-shale-marl intercalation and saturated Quaternary deposits. The apparent resistivity dropped toward the reservoir area along the profile line, indicating higher moisture/water content.

Profile AP5 and AP6 were executed on the upstream and right side of the reservoir water body with a horizontal distance of 620 and 610 m respectively. Based on the local geology, the higher resistivity values at AP5 were interpreted to be dry limestone-shale-marl intercalation, while those at AP6 were interpreted as dolerite. Measurements collected near the reservoir water body and at small creeks and depressions were relatively low, which is explained by the presence of moisture from the reservoir water along joints and fractures (Fig. 4.8).

Hydrochemistry

Interpretation of the chemical constituents of water can provide insights into surface-groundwater interactions or surface water-aquifer connectivity. Dissolved constituents can be used as environmental tracers to track the movement of water. Some of the commonly used environmental tracers include parameters such as the major anions and cations (e.g. calcium, magnesium, sodium, chloride and bicarbonate) (Brodie *et al*., 2007).

Chemical composition of water provides additional information on its origin and geochemical evolution, facilitating the differentiation between reservoir and aquifer waters or a mixture of those waters (Table 4.2). Groundwater can have a chemistry that is distinctly different from the streams and leakages from surface reservoirs, and these characteristics can be used as indicators to discriminate groundwater discharge from leakage water from surface reservoirs.

The water samples collected from reservoir, shallow hand dug well (AHDW) and stream were analyzed for major cations and anions. In addition results of chemical analyses from boreholes (BH80 and SHW37) were obtained from existing archives from the area (Fig. 4.4). All the results of the chemical analyses are illustrated in the form of vertical column diagrams (Piper trilinear diagram and Stiff diagrams, Fig. 4.9) and in Table 4.3. Brodie *et al*. (2007) pointed out that piper diagram has the advantage for showing a large number of analyzed water samples in one plot to define distinct populations or trends.

It can be seen from Fig. 4.9 that the shape of the Stiff diagram and localizations in the Piper diagram (interwell analysis) clearly indicates that samples AHDW and Stream have chemical compositions similar to the reservoir water, whereas the other groundwater samples (SHW37 and BH80) do not. This information indicates that the source for the AHDW and Stream water downstream of Arato reservoir is water leaking from the reservoir. The residence times for water samples from ASHDW and Stream appear short in comparison to the water samples from borehole, resulting in little rock-water interaction compared to the reservoir water. Calcite dissolution has occurred in ASHDW and Stream, compared to the reservoir water, raising Ca^{2+} and HCO_3^- to some extent. Total dissolved solids in ASHDW and Stream is therefore somewhat increased (~360 mg/l), compared to reservoir water (229 mg/l). However, the unaffected groundwater in the area is much more mineralized and different than the pervious water samples points, due to stronger carbonate dissolution (raising HCO_3^-), and cation exchange (raising Mg^{2+} and Na^+). The raised concentration of K^+ in SHW37 could be attributed to clay resulting from weathering of shale and dolerite. In BH80 dissolution of gypsum from the limestone-shale-marl intercalation unit results in high SO_4^{2-} and Ca^{2+} concentrations, and a high mineralization. Table 4.2 shows saturation indices of calcite and gypsum. The contrasting chemistry between typical groundwater of the area, compared to the shallow hand dug well and stream downstream of the reservoir, which are very comparable to the reservoir water, confirms our assumption that the latter water is derived from leakage from the reservoir.

Table 4.2. Calcite and gypsum saturation indices

Code	SI calcite	SI gypsum
Reservoir	-0.02	-2.65
ASHDW	0.32	-2.04
Stream	0.51	-1.97
SHW37	-1.40	-3.28
BH80	0.94	-0.19

The piezometric map (Fig. 4.4) illustrates that both SHW37 and BH80 are upgradient with groundwater levels of 2411 and 2450 m (a. s. l.) respectively with respect to the MDR, while the groundwater level in the big diameter shallow hand dug wells, that were developed after dam construction in the downstream part, the water level ranges from 2397.8 to 2406.7 m (a. s. l.) (Table 4.4). This confirms that the water quality in SHW37 and BH80 cannot be affected by the reservoir. From the piezometric map it is possible to identify a main direction of the groundwater flow from NE to SW. In addition, the groundwater level measurements illustrate the distinction between the boreholes around the MDR and shallow hand dug wells immediately downstream of the MDR. From Table 4.4 it is clear that there are two groups of groundwater levels around the MDR. The boreholes (BH3 and BH5) have water levels < 2388 m (a. s. l.) while the large diameter shallow hand dug wells have water levels > 2397.8 m (a. s. l.). This can be explained by the fact that the reservoir water is feeding the nearby shallow aquifer and hence affects the water levels close to the reservoir. Prior to reservoir construction there were no shallow hand dug wells next to the MDR. At present, test pits excavated to similar elevation as the hand dug wells near Arato

MDR in adjacent catchments, and in the same catchment but far from the influence of reservoir, were found to be dry. This implies that the existence of shallow water levels downstream of the MDR is related to the leakage phenomenon from the reservoir. Local residents reported that swamps or wetlands exist on the downstream side of the MDR when reservoir level rises following the rain season. This situation was confirmed during our field visit in September-November 2014, in which irrigated land was abandoned due to the presence of small swamps which were not existent prior to dam construction.

Leakage zone and path

The need to reduce the risk of failure or to control water loss has led to costly remedial measures that are planned and executed without a comprehensive understanding of the leakage problem, its path and mechanism. Contreras and Hernandez (2010) reported that a large quantity of technical and economic resources are spent without positive outcomes due to the lack of adequate characterization to determine water origin, preferential paths, recharge zones, and transit time. A lack of appropriate leakage investigation and monitoring can result in maintenances or remedial measures that are unsuccessful in controlling or reducing leakage. Sufficient and complete information about the engineering geology and hydrogeology of the problem that allows understanding of the leakage zones and path is crucial.

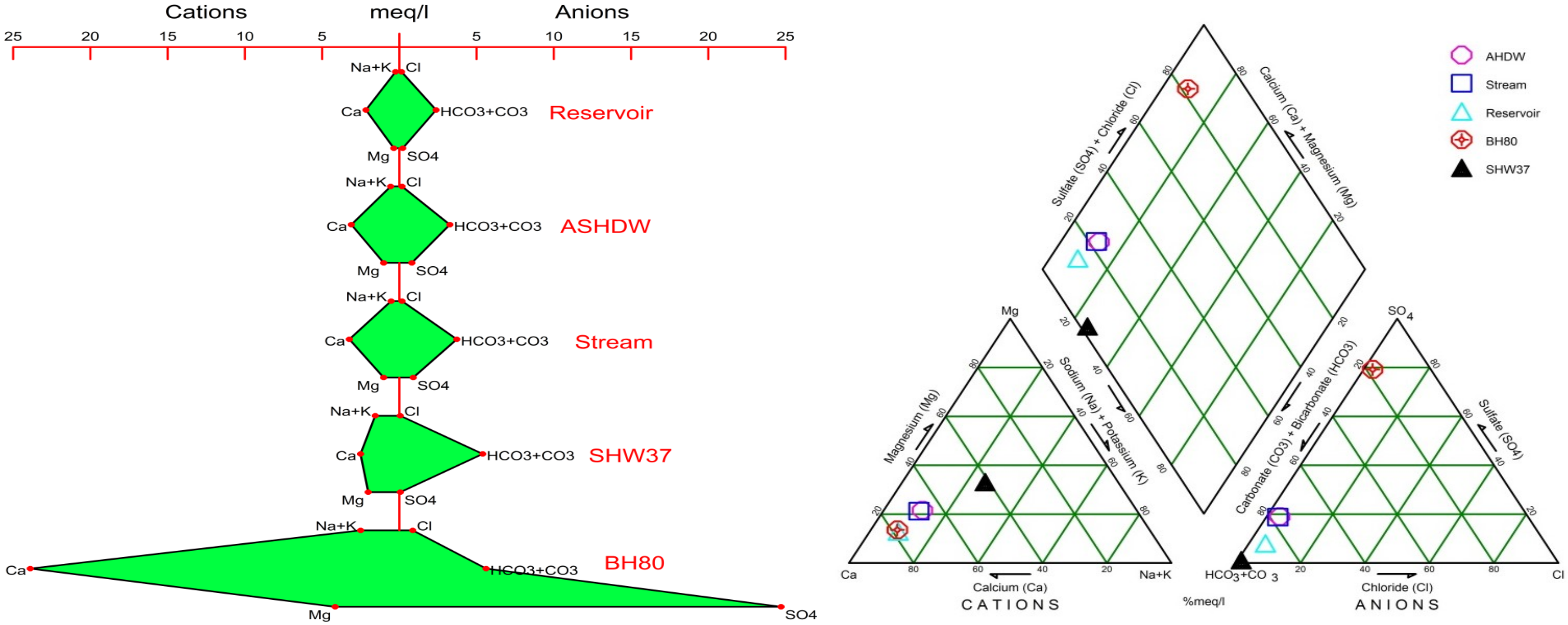


Figure 4.9. Stiff and Piper diagrams for reservoir, shallow hand dug well, stream and borehole (SHW37 and BH80) water samples.

Table 4.3. Summary of the hydrochemical data from Arato MDR and its environs.

Code	East (mE)	North (mN)	Elev (m)	EC (mS/cm)	TDS (mg/l)	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	$SO4^{2-}$	NO_3^-
							(mg/l)							
Reservoir	570103	1493125	2424	292	228.80	7.61	43.35	4.35	3.50	3.50	145.20	4.98	10.53	12.74
ASHDW	569958	1493336	2398	436	351.42	7.70	62.30	12.30	12.30	1.03	199.50	6.17	38.90	18.75
Stream	569905	1493090	2393	448	366.44	7.82	64.85	12.35	11.50	1.17	226.90	6.13	43.28	0.08
SHW37	574181	1493850	2416	1037	739.53	6.18	50.30	24.50	12.60	39.60	329.40	2.00	3.20	0.82
BH80	576048	1494893	2480	2350	1404.90	7.55	478.80	50.49	55.00	4.40	342.60	30.72	1187.00	3.96

Table 4.4. Groundwater level measurements from boreholes and big diameter hand dug wells. For locations see Figs. 4.4 and 4.10.

Boreholes/Groundwater[1]					**Large diameter shallow hand dug wells/Leakage water**[2]			
Borehole ID	**Elevation (m)**	**Depth (m)**	**Water level (m. b. g. l.)**	**Water level (m. a. s. l.)**	**Hand dug well ID**	**Elevation (m)**	**Water level (m. b. g. l.)**	**Water level (m. a. s. l.)**
BH1	2261	60	21	2240	AHDW1	2409	2.3	2406.7
BH2	2410	70	11	2399	AHDW2	2402	1.1	2400.9
BH3	2409	67	21	2388	AHDW3	2402	0.3	2401.7
BH4	2377	62	19	2358	AHDW4	2402	0.5	2401.5
BH5	2391	64	4	2387	AHDW5	2400	1.2	2398.8
BH6	2436	58	5.5	2430.5	AHDW6	2399	1.2	2397.8
BH7	2405	63.5	18	2387	AHDW7	2401	1.2	2399.8
BH8	2411	72	21	2390	AHDW8	2401	1.6	2399.4
BH9	2243	70	13	2230	AHDW9 (**ASHDW**)	2398	0	2398
BH10	2321	55.2	18	2303				
BH11	2288	60	9	2279				
BH12	2267	51	16.7	2250.3				
BH80	2480	60	30	2450				
SHW37	2416	60	5	2411				

Note:[1]all are drilled boreholes. [2]all are excavated manually and occasionally by excavator, diameter ranges from 2 to 5 m and depth ranges from 3 to 8 m.

Based on geological, geophysical, hydrogeological and hydrochemical methods, it was possible to delineate the leakage zone and its path (Figs. 4.10 & 4.11). The leakage path is from the central and left reservoir bank/foundation and directs in a slight curved shape toward the downstream creating a flowing stream and feeding the shallow aquifer starting from the toe of the dam. Eight shallow hand dug wells were excavated in this area to exploit the infiltrated water from the reservoir for small household irrigation and drinking purposes. Field observations and data analysis/interpretations show that the limestone-shale-marl intercalation unit could be responsible and the main cause for the leakage. This unit is affected by discontinuities of syngenetic (developed contemporaneously with the rock) and epigenetic (developed after the formation of the rock) forms, while the dolerite unit is less affected by the discontinuities. The leakage path and mechanism have been analyzed and diagnosed with the different methods mentioned. Geophysical methods (VES1 and VES2) show that the pervious zone in the central foundation and left abutment extends to a depth of about 14 m to 16 m below surface. The low resistivity geological formation in the downstream side of the dam extends up to a depth of about 20 m which is explained by presence of discontinuities, weathering and saturation.

The reservoir lies entirely within the Quaternary deposit underlain by the leaky limestone-shale-marl intercalation of the Agula Shale, although the southwest reservoir rims and abutment are composed of dolerite unit. Due to this situation, controlling the quantity of leakage that occurs through this unit may be difficult and expensive by an upstream or reservoir blanket. Installation of a cut-off wall at the upstream toe of the dam could be the best option. Proper design and construction, exploiting and managing the shallow hand dug wells in the downstream of the dam may be considered as a second alternative solution to the problem.

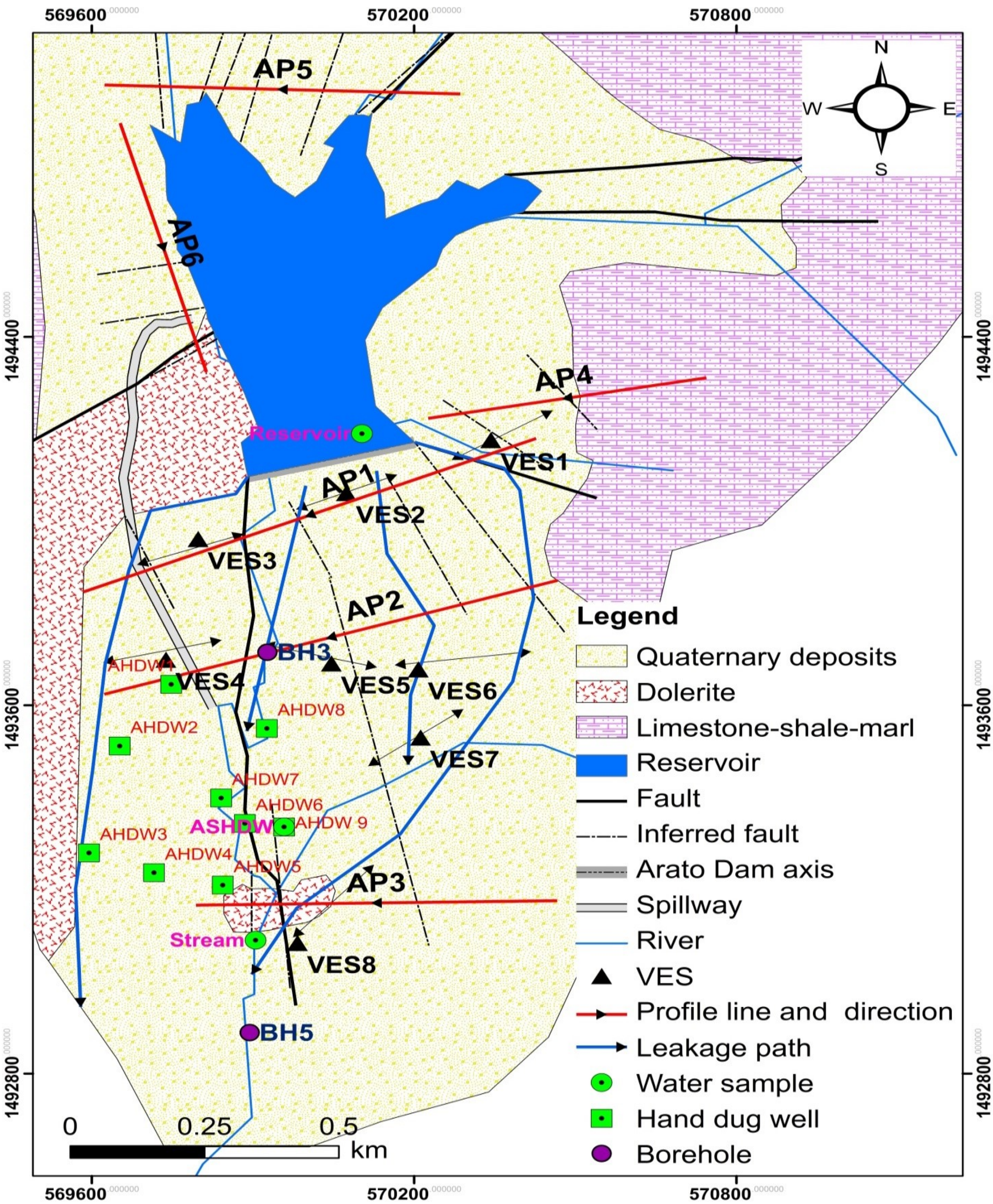


Figure 4.10. Leakage zone and path from the reservoir. Large diameter hand dug wells and boreholes next to MDR and water sample points are indicated.

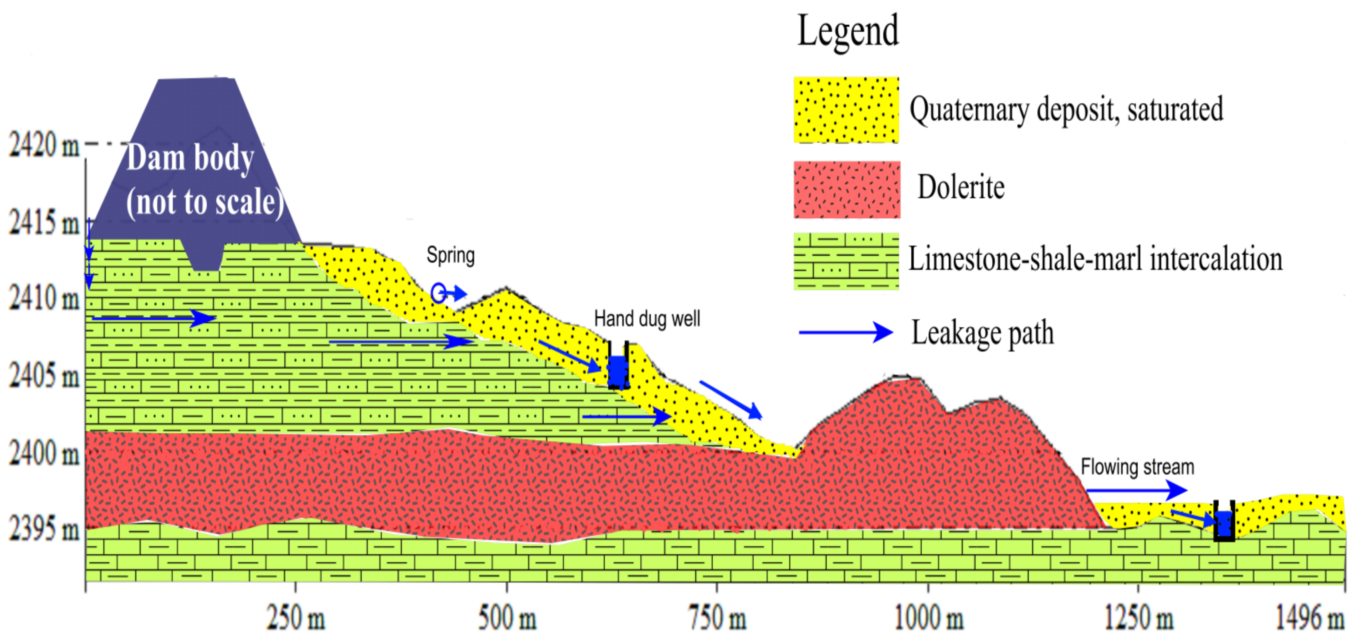


Figure 4.11. Simplified conceptual geological model illustrating the mechanism of leakage in two dimensional view. Cross-section taken from dam body to downstream direction (N-S). Horizontal axis is distance and vertical axis is elevation above sea level taken from digital elevation model. Dam body is sketched on top.

CONCLUSION AND RECOMMENDATION

Arato MDR is dominantly covered with three lithological units: Quaternary soil deposits, dolerite and limestone-shale-marl intercalation unit. The geological, hydrogeological, hydrogeophysical and hydrochemical data analysis reveals that there is a hydraulic connection between the impounded reservoir and the downstream leakage discharge zone. The limestone-shale-marl intercalation unit of Agua Shale is found to be the leaky formation and responsible for the inefficient performance of the project in terms of water loss via leakage.

The relatively low resistivity data recorded up to a depth of 16 m to 20 m in the downstream side of the dam were inferred to be generally due to highly conductive material, likely the water saturated and pervious limestone-shale-marl intercalation unit and Quaternary soil deposits, and partly due to deep weathering of the dolerite unit**.** The highly resistive materials in the area were found to be massive dolerite and dry limestone dominated intercalation unit (Agula Shale).

Hydrochemical data from reservoir water, from downstream shallow hand dug well and stream water confirmed these waters to be of the same origin, such that the source for the subsurface and stream water is from the impounded reservoir.

The available hydrogeological information concerning the limestone-shale-marl intercalation unit confirms it to be the main water bearing formation in the area in the form of a multi-layer aquifer system.

Installation of a cut-off wall at the upstream toe of the dam could be the possible solution to minimize the leakage problem underneath the dam foundation and left abutment. In addition the installation of a grout curtain up to the depth of fresh dolerite and limestone-shale-marl intercalation unit can be used as a remedy to prevent leakage. From the geophysical survey, the depth to tight and massive formation was estimated to be in the range of 16 to 20 m. It is generally recommended to perform drilling and Lugeon test to check the hydraulic conductivity and groutability of the rock units. As an alternative, proper utilization of the water in the shallow wells from the leakage zone in the downstream part of the MDR may also be conceived as a target without incurring additional costs of maintenance.

Future planning, design and construction of MDRs in the area shall be based on sound understanding of the geomorphology/topography, geology, geo-hydrology and engineering geology of the site.

ACKNOWLEDGEMENT

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Contribution of authors

Name of author	**Role of the author in this chapter**
Gebremedhin Berhane	*Was responsible for all the aspects of the study, data collection, field data collection, VES & profiling layout design, interpretation and writing the article/chapter*
Samuel Kebede	*Field VES and ERP data collected together with Gebremedhin Berhane*
Tesfamichael Gebreyohannes	*Shared ideas on interpretation and on field data collection*
Kristine Martens	*Contributed and shared ideas on VES data interpretation*
Marc Van Camp	*Share ideas on interpretation*
Kristine Walraevens	*Was the supervisor in the study, and critically reviewed and approved the article*

Shallow hand dug well (about 4m deep) with diver installed inside a pipe at downstream of Arato MDR ©2015 Gebremedhin Berhane.

CHAPTER 5

Response of a shallow aquifer to Micro-Dam Reservoir leakage and natural groundwater recharge: a water balance model approach

This chapter is based on Gebremedhin Berhane, Marc Van Camp, Tesfamichael Gebreyohannes, Nawal Alfarrah, Kristine Walraevens (submitted). Response of a shallow aquifer to Micro-Dam Reservoir leakage and natural groundwater recharge: a water balance model approach.

ABSTRACT

Runoff, recharge and response of a shallow aquifer to Arato MDR leakage were assessed using Soil Conservation Service Curve Number (SCS-CN), soil moisture balance (SMB) and diver (automatic data logger) measurements for 182 days in the MDR and a shallow hand dug well of 4 m deep. Recharge was also estimated using the chloride mass balance (CMB) and water table fluctuation (WTF) methods. Results show that the estimated yearly runoff from the catchment was 48.8 mm (7.7% of the rainfall; 0.71×10^6 m^3 over the catchment), while yearly groundwater recharge was estimated at about 104 mm, 92.8 mm and 100 mm using SMB, CMB and WTF methods respectively (corresponding to some 1.41×10^6 m^3 over the catchment). Moreover, based on the water balance model of Arato MDR, the leakage amount from the reservoir was estimated at 13.2 mm/day which corresponds roughly to about 1353 m^3/day or 0.25×10^6 m^3 of water in 182 days. The estimated leakage is considerably higher than the seepage foreseen during the initial design of the project (9965 m^3/year). The results of the automatic diver data loggers show a continuous water level decline in the reservoir, while constant water level in the shallow well during the dry period, confirming the strong interaction between the surface water in the reservoir and the groundwater in the shallow aquifer found next to the reservoir. The result of this research project shows the importance of using actually measured climatic and physical characteristics of a watershed rather than using data from literature, in reservoir and other water resources planning. It also emphasizes the importance of adequate site investigation to reliably quantify hydraulic conductivity for leakage estimation.

INTRODUCTION

In chapter 4 the geological, geophysical and engineering geological conditions and leakage mechanism of Arto MDR was presented. In this chapter a quantitative estimate of leakage rate and overall water balance of the MDR and groundwater recharge of the area is discussed. One of the most important problems in water resources development is to describe and explain the different water balance components or partitioning of precipitation into the different variables of the water balance model. Understanding the rainfall (P)–runoff (RO)–recharge (Rech) nexus is one of the useful approaches for sustainable water quality and quantity management; in the planning and design of water harvesting and flood control structures; and for developing watershed management plans in degraded dryland regions. Drylands cover approximately 41% of the Earth's surface and approximately 10 to 20% of these regions are experiencing degradation processes (Vieira et al. 2015 and references therein). Land degradation is severe in Ethiopia (Adimassu *et al*., 2014; Mekonnen *et al*., 2015a, b; Tesfaye *et al*., 2014) and results in declining agricultural productivity, reservoir siltation and deterioration of biodiversity. A comprehensive exploration of driving factors influencing land degradation evolution can provide information needed to effectively combat further deterioration in a fragile environment involving serious soil erosion, extensive exposure of bedrocks, decrease in soil productivity, etc. (Lanckriet *et al*., 2016; Xie *et al*., 2015; Xu and Zhang, 2014). Hydrological phenomena (runoff, water balance and surface water-groundwater interaction) are amongst the most important factors contributing to land degradation and vice versa; on the other hand, hydrological interventions help for future sustainable and optimum planning of water harvesting and for restoration of a catchment. Knowledge of surface water–groundwater interaction is important in ecological and water resource development and management. The degree to which surface water will interact with groundwater depends on such factors such as the position of the surface water bodies relative to groundwater flow systems, bed morphology and bedrock material's hydraulic conductivity and climate. The climatic factors, mainly precipitation, are particularly important for shallow aquifers, which often rely on it for groundwater recharge.

To develop a sustainable water resources strategy for the future and evaluate the leakage rate, understanding the rainfall-runoff-recharge system of an area is needed. Soil erosion, desertification and deforestation have also a link to the water component nexus.

Detailed studies (geophysical, geotechnical drilling, hydro-geochemistry) were conducted at selected MDRs in Tigray, Ethiopia, one of which is Arato (chpaters 3 and 4). Arato MDR is one of the 92 MDRs in Tigray and has suffered from serious leakage since its construction in 1997. The results of previous engineering geological, geophysical and hydrogeochemical studies (chpaters 3 and 4) show strong hydraulic connection between the reservoir and leakage zones in which a limestone-shale-marl intercalated unit is pervious (chpater 3 and 4). The objective of this chpateris to provide an evaluation of the water balance of Arato MDR, in view of the leakage phenomenon and its relationship and impact upon the adjacent shallow aquifer.

DESCRIPTION OF THE SITE

The Arato MDR is located about 25 km east of Mekelle City (Fig. 5.1a). It was designed with a dam height of 20 m and gross reservoir capacity of 2.59×10^6 m^3 to harvest runoff from a catchment area of 20.7 km^2 to be used for irrigation purposes during the dry season. Arato MDR is typical for many irrigation schemes that have leakage problems. Figure 5.1 shows the location of Arato MDR and its surrounding. The topographic elevation of the Arato study area ranges from 2400 m to 2560 m (a. s. l).

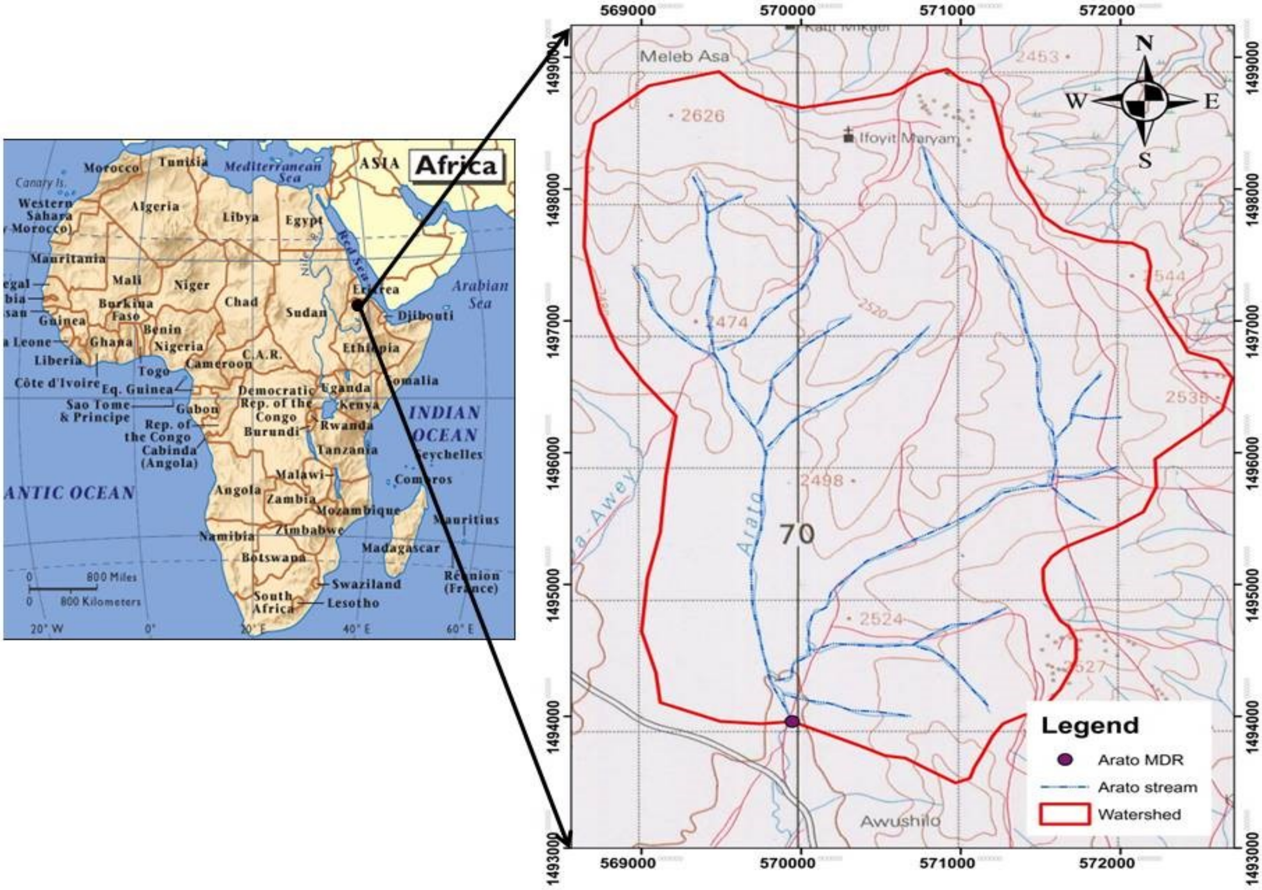

Figure 5.1. Location map of Arato MDR and its watershed showing stream network and contour lines. UTM Zone 37N coordinate system. Source for back ground topographic map from Ethiopian mapping agency.

The mean annual rainfall in the area, based on Mekelle meteorological stations, is slightly higher than 600 mm with the maximum amount recorded during July and August (Fig. 5.2). More than 70 to 80% of precipitation on a yearly basis is falling in the “Kiremt” (summer) season, June to September. In some years rainfall starts late (July) and rainfall in March, April, May and June is very insignificant.

The mean minimum temperature variation ranges from about 9°C in December to 13°C in May and June, while the mean maximum temperature ranges from 22°C in December to about 27°C in June.

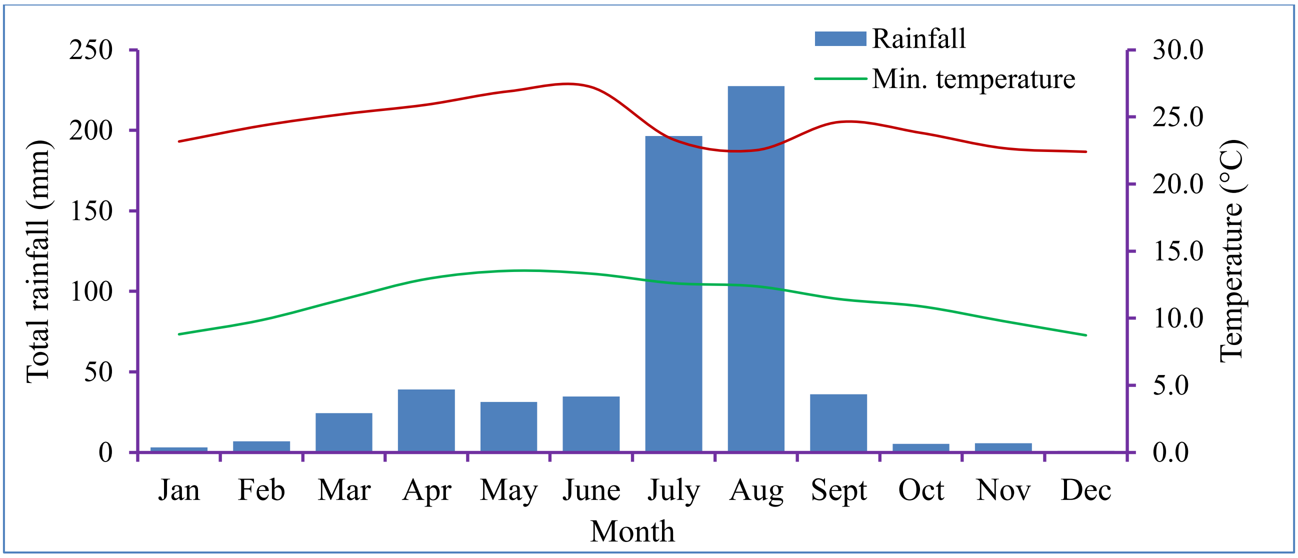

Figure 5.2. Average monthly rainfall and minimum and maximum temperature from Quiha/Mekelle Airport station (Ethiopian Meteorological Agency data, 1960-2006).

Geological and hydrogeological conditions of the site are described in chapter 3 and 4. The Arato area is covered with Mesozoic sedimentary rocks (Agula Shale with beds of limestone) and Paleo-Neogene (Paleo-Pliocene) Volcanics (Mekelle Dolerite). The mineralogical composition of limestone and dolerite are summarized below from thin-section analysis conducted in the present study.

Table 5.1. Summary of mineral composition of limestone and dolerite units from Arato MDR.

Sample	Limestone1	Limestone2	Limestone3	Dolerite1	Dolerite2	Dolerite3
Calcite (%)	92	70	71	-	-	-
Plagioclase (%)	5	2	-	39	43	37
Clay (%)	-	25	-	-		-
Opaque (Fe-oxide) (%)	3	3	6	12	15	15
Fossil (%)	-	-	20	-	-	-
Pyroxene (%)	-	-	-	32	32	33
Biotite (%)	-	-	-	17	10	10
Amphibole (%)	-	-	-	-	-	3
Chlorite (%)	-	-	-	-	-	2
Rock Name	**Limestone**	**Argillaceous Limestone**	**Fossiliferous Limestone**	**Dolerite Porphyry**	**Dolerite Porphyry**	**Dolerite Porphyry**

MATERIALS AND METHODS

Establishment of meteorological station

Since the existing meteorological stations are far (about 20 km) from the study site, a new meteorological station (0569909mE/1492773mN at about 2394 m.a.s.l.) was established on 18 July 2014 for the purpose of this research (Fig. 5.3). It includes a manual rain gauge and minimum-maximum thermometer. Rainfall and min-max temperature were recorded daily from 19/07/2014 to 16/01/2015 for 182 days.

Installation of diver water level sensors

Diver (DIVERCE®) water level sensors or data loggers manufactured by Schlumberger Water Services (Canada) were installed in the reservoir and in a shallow hand dug well (SHDW) adjoining the reservoir on its downstream side (Fig. 5.3). The diver in the reservoir had a measuring range for height of water column above the diver of 20 m; the diver in SHDW had 10 m range. These divers were programmed to measure pressure record water levels (pressure exerted by water column plus atmospheric pressure) at 30 minute intervals. Divers were installed inside a pipe to protect them from damage. Since the MDR does not have a tower to lower the diver vertically, a pipe was laid down on the upstream slope of the dam in order to house the diver (Fig. 5.3a). When the sensor at tip of the diver is in contact with water it records the pressure vertically above the sensor.

The diver water level sensor measures the total pressure (P_T), from which, after compensating for atmospheric pressure, the piezometric head can be deduced. To compensate for the atmospheric pressure, a barometric diver was also kept at the meteorological station that records only atmospheric pressure (P_A). The water pressure (P_w) was determined using the equation:

$$P_w = P_T - P_A \qquad (1)$$

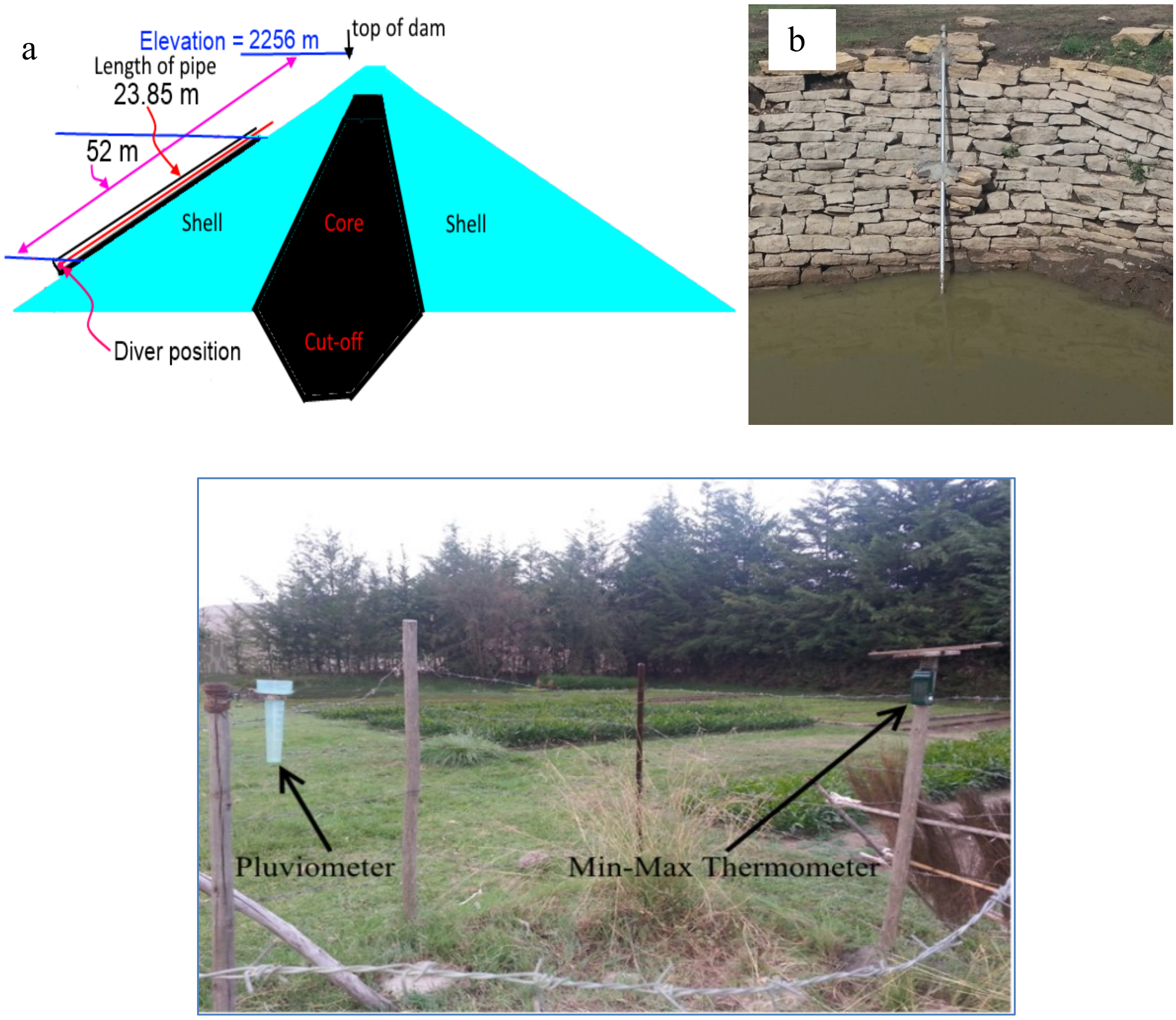

Figure 5.3. Diver installation: a) installation details of the diver in MDR, b) installation of diver in SHDW, c) photo showing meto-station.

Runoff (RO)

The Soil Conservation Service Curve Number (SCS-CN) method (USDA-SCS, 1985) was used to estimate the runoff of the area based on actual meteorological records at the site. A weighted average CN was used for the catchment based on land use, hydrologic condition and hydrologic soil group. The land use map and soil texture of the catchment were established from field observations, Google map, aerial photograph and limited existing laboratory test results. Table 5.2 shows existing laboratory test results compiled from reports showing variability in texture.

Table 5.2. Grain size distribution of soil samples taken from the dam site (Hagos, 1995 and Berhane, 1999). Sample locations are from farm land at the dam axis (LL= liquid limit, PL= plastic limit and PI=plasticity index, NP= non-plastic).

S. No	Sample location	sand fraction	silt fraction	Clay fraction	LL	PL	PI	USDA Soil Classification	Hydraulic conductivity
		(%)							**(cm/sec)**
1	DDA1	44	40	16	44	21	23	Loam	not available
2	DDA2	88	9	3	NP	NP	NP	Loamy sand	not available
3	DDA3	3	7	90	65	27	38	Clay	not available
4	Chichat UP	6	12	82	63.7	30.4	33.3	Clay	1.0×10^{-7}

The SCS-CN method is widely employed in various hydrologic models to simulate surface runoff (Jeon *et al*., 2014). Direct surface runoff from the SCS-CN method is expressed by:

$$RO = \frac{(P-I_a)^2}{P-I_a+S} = \frac{(P-\lambda S)^2}{P+(1-\lambda)S} = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad (2)$$

$$I_a = \lambda S = 0.2S$$

where RO is direct surface runoff; P is precipitation; *S* is potential maximum retention after runoff begins (Jeon *et al*., 2014) and λ is a dimensionless parameter varying from 0 to 1. *S* is estimated from the curve number (CN) value as follows:

$$S = 25.4(\frac{100}{CN} - 10) \qquad (3)$$

For λ a value of 0.05 was estimated for Hagere Selam area (northern Ethiopia) by Descheemaeker et al. (2008) and Hawkins et al. (2002) and Woodward et al. (2003) also recommended 0.05 and others even lower value (e.g. Mishra *et al*., 2003, ~0.01). In the original development of the CN method, the initial abstraction ratio (*Ia*/*S* or λ) is assumed to have a value of 0.2 and in most studies λ is simply set to this value. In this study the original value of 0.2 was adopted and gave reasonable result as confirmed by independent techninque (see below).

The runoff estimated with SCS-CN was also compared with the runoff obtained from the actual measurements using the diver data logger in the reservoir after resevroir water elevations are converted into volumes considering the respective reservoir area into account at the beginning and end of the rain season.

To estimate the catchment yield the following equation was used.

$$\Delta V_R = RO \times A_c = RC \times P \times A_c \tag{4}$$

Where: ΔV_R = volume of water generated, RC = runoff coefficient (portion of rainfall that becomes direct runoff, $RO = RC \times P$), A_c= area of catchment and P = precipitation.

Reference evapotranspiration (ETo)

ETo is one of the important components in water balance model and is a function of many factors (including weather, crop characteristics, and environmental factors). In this study the FAO Penman-Monteith equation (Allen *et al.*, 1998) was used to estimate ETo. It is expressed mathematically as follows:

$$\text{ETo} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5}$$

Where ETo = reference evapotranspiration (mm/day), R_n=net radiation at the crop surface (MJm^{-2}/day), G=solar heat density (MJm^{-2}/day), γ = psychrometric constant ($kPa^{\circ}C^{-1}$), u_2= wind speed at 2 m height (m/s), e_s= saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), e_s-e_a=saturation vapour pressure deficit (kPa), Δ=slope of the saturation vapour pressure curve ($kPa^{\circ}C^{-1}$).

Estimation of the reference evapotranspiration was performed on a daily basis (for 182 days) using the FAO ETo calculator/program (FAO, 2009).

Groundwater recharge (Rech)

The main objective of recharge estimation in this chapter was to understand the extent of natural recharge in the area, obtain idea about contribution of the leakage and natural rechangre on the shallow aquifer next to the dam and to check if the different techniques give comparable results.

Recharge was estimated using the Soil Moisture Balance (SMB) method (Thornthwaite and Mather, 1957):

$$\text{P} = \text{AET} + \text{RO} + \Delta\text{SW} + \text{Rech} \tag{6}$$

Where AET= actual evapotranspiration, ΔSW=change in soil water storage over a time step and Rech= groundwater Recharge or drainage.

The SMB model is a lumped model that tracks soil water storage through time and the entire watershed is treated as one unit. Water is stored in the soil reservoir until the soil water storage (SW) exceeds the field capacity, at which point recharge takes place. Determining the soil water balance requires keeping track of the accumulated potential water loss (APWL) and the amount of water in the soil (SW). It can be used for modeling at daily, weekly or monthly time steps. In the present study, a daily time step was used for an observation period of 182 days.

Calculations to determine SW and APWL (Table 5.3) are performed for each day using daily precipitation (P), referenc evapotranspiration (ETo) and runoff (RO) in an excel sheet.

Table 5.3. Daily soil-moisture balance (SMB) calculations (Thornthwaite and Mather, 1957; Bakundukize et al., 2011).

Situation in the catchment	**SW**	**APWL (negative)**	**Rech**
Soil is drying (P-RO)-ETo < 0,	$= PAWexp(\frac{-APWL_t}{PAW}) + PWP$	$= APWL_{t-1} + ((P - RO) - ETo)$	$= 0$
Soil is wetting, (P-RO)-ETo > 0 but $(SW_{t-1} + (P - RO) - PET) \leq (PAW + PWP)$	$= SW_{t-1} + ((P - RO) - ETo)$	$= -PAWln\left(\frac{SW_t - PWP}{PAW}\right)$	$= 0$
Soil is wetting above field capacity, (P-RO) -ETo > 0 but $(SW_{t-1} + (P - RO) - PET) > (PAW + PWP)$	$= PAW + PWP$	$= 0$	$= ((P - RO) - ETo) - (PAW + PWP - SW_{t-1})$

When P>ETo, AET=ETo, when P<ETo, AET=ΔSW+P, PAW=Plant available water, PWP= water content at permanent wilting point; Field capacity = PAW+PWP.

The model requires accurate and local rainfall data, ETo, plant available water (PAW) (difference between volumetric water content at field capacity (FC) and permanent wilting point (PWP)) and runoff (RO) as an input. The rooting depth and PAW was estimated from Thornthwaite & Mather (1957) table on the basis of vegetation cover and soil texture. With a rooting depth of 0.8 m a PAW of 200 mm was taken for this study based on moderate rooted cereals and clay loam as the dominant cover and soil type of the catchment, respectively.

In addition, groundwater recharge was also estimated using the chloride mass balance (CMB) method where chloride is an environmental tracer (Allison and Hughes, 1978; Eriksson and Khunakasem, 1969; Ting *et al*., 1998) and water-table fluctuation (WTF) (Healy and Cook, 2002; Scanlon *et al*., 2002) methods for comparison.

The chloride mass-balance method compares total chloride deposition at the surface with chloride concentrations in groundwater as measured in samples from wells assuming chloride to be a conservative ion. Recharge (Rech) is estimated as (Ting *et al*., 1998):

$$\mathrm{Rech} = \frac{\mathrm{P_{eff}Cl_P}}{\mathrm{Cl_{gw}}} \qquad (7)$$

where P_{eff} is the effective precipitation (mm); Cl_P is the chloride concentration of precipitation, including dry deposition (ppm) and Cl_{gw} is the constant chloride concentration of groundwater (ppm). Effective precipitation is the amount of precipitation that is actually added and stored in the soil after the runoff is removed. Rainwater and groundwater samples were collected from the area. Rainwater and groundwater were sampled in 2014 directly from rain drops and from the shallow hand dug well where the diver was installed respectively. All water samples were analyzed at Ghent University, Laboratory for Applied Geology and Hydrogeology, Belgium.

The 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. Fluctuations in piezometric levels of phreatic aquifers usually reflect variations in overall meteorological conditions or recharge (Van

Camp and Walraevens, 2013). Groundwater recharge (Rech) is calculated as (Healy and Cook, 2002):

$$Rech = S_y \frac{\Delta h}{\Delta t} \qquad (8)$$

where S_y is specific yield, h is water-table height, and t it time.

The method is best applied to shallow water tables that display sharp water-level rises and declines (Healy and Cook, 2002). The present study site has a typical shallow aquifer which shows water level rise during the wet season due to direct natural groundwater recharge and leakage from MDR.

Water balance model for Arato MDR

A conceptual water balance model was developed with consideration of the actual situation of the area and available data and previous understanding of the region. The water balance model is graphically presented in Fig. 5.4. The water balance model over a given time period, such as a month or hydrological year, considers inflow in the form of runoff (RO) from the watershed and direct rainfall (PR) at the surface of the reservoir, and outflow in the form of evaporation from the water surface (ER), livestock water consumption (Live), water released through spillway (Spill) and outlet (Out) and loss due to leakage (Leak) (Fig. 5.4).

The equation that follows can be adopted based on the basic law of conservation-of-mass/volume.

Change in volume of water in Reservoir = Input volume to Reservoir – Out put volume from Reservoir

The above simplified equation can be expanded as follows for Arato MDR. The water balance model was executed for dry and wet periods to estimate leakage (Leak) and runoff (RO) respectively. RO can be determined independently from this model without considering the result from CN method. This approach helps to compare and contrast the results from two independent methods.

$$\Delta \boldsymbol{WL_R} \times \boldsymbol{A_R} = [\boldsymbol{RO} + (\boldsymbol{PR} \times \boldsymbol{A_R})] - [(\boldsymbol{ER}) + (\boldsymbol{Live} \times \boldsymbol{T_{total}}) + \boldsymbol{Spill} + (\boldsymbol{Out} \times \boldsymbol{T_{out}}) + (\boldsymbol{Leak} \times \boldsymbol{A_R} \times \boldsymbol{T_{total}})] \quad (9)$$

The change in volume in the reservoir can be expressed based on the reservoir water level change as follows:

$$\Delta V_R = V_{R2} - V_{R1} = \Delta WL_R \times A_R \quad (10)$$

where: $$A_R = \frac{A_{Ri} + A_{Rf}}{2} \quad (11)$$

Reservoir water loss due to evaporation from the surface of the reservoir is determined from potential evapotranspiration due to lack of pan evaporation at or near the study site. Winter (1981) suggested that the direct use of data from pans located some distance away from the water body (under study) can result in significant errors. Penman (1948) gives factors that range from 1.25 to 1.67 to convert reference evapotranspiration rates to an open water surface. Doorenbos and Pruitt (1984) list empirical factors (or crop coefficients) for conversion of reference evapotranspiration to open water body evaporation. For dry environment with strong wind (comparable to the present study site) an empirical factor of 1.2 is suggested for all type of water bodies. Teka et al. (2013) in their study in northern Ethiopia assumed that the open water evaporation is 10% (factor of 1.1) higher than the ETo. Near the study site (northern Ethiopia) Abdulkadir (2009) used a factor of 1.33 to convert potential evapotranspiration into reservoir evaporation. For the present study a factor of 1.33 (Abdulkadir, 2009) was adopted to convert reference evapotranspiration into reservoir water evaporation.

$$ER = 1.33 \times ETo \times A_R \quad (12)$$

Moreover the inflow due to direct rainfall on the surface of the reservoir water body was estimated as:

$$RI = PR \times A_R \quad (13)$$

where

ΔV_R = change in reservoir volume (m^3)

ΔWL_R= reservoir water level variation (m)

A_R = average reservoir area (m^2)

V_{Ri} =reservoir volume at initial time (m^3)

V_{Rf} = reservoir volume at final time (m^3)

A_{Ri} = reservoir area at initial time (m^2)

A_{Rf} =reservoir area at final time (m^2)

PR = direct rainfall on reservoir (m)

RO = runoff (m^3)

RI = direct rainfall input on reservoir surface (m^3)

ER = evaporation loss from reservoir (m^3)

ETo = refrence evapotranspiration (m)

Rech = direct recharge

T_{total}= number of days

Out = daily or hourly reservoir loss through outlet (m^3/day)

T_{out} = outlet operation time (days or hours)

Live = daily reservoir loss due to Livestock consumption (m^3/day)

Leak×A_R×Ttotal = reservoir loss due to leakage (m^3)

Spill = spillway overflow (m^3)

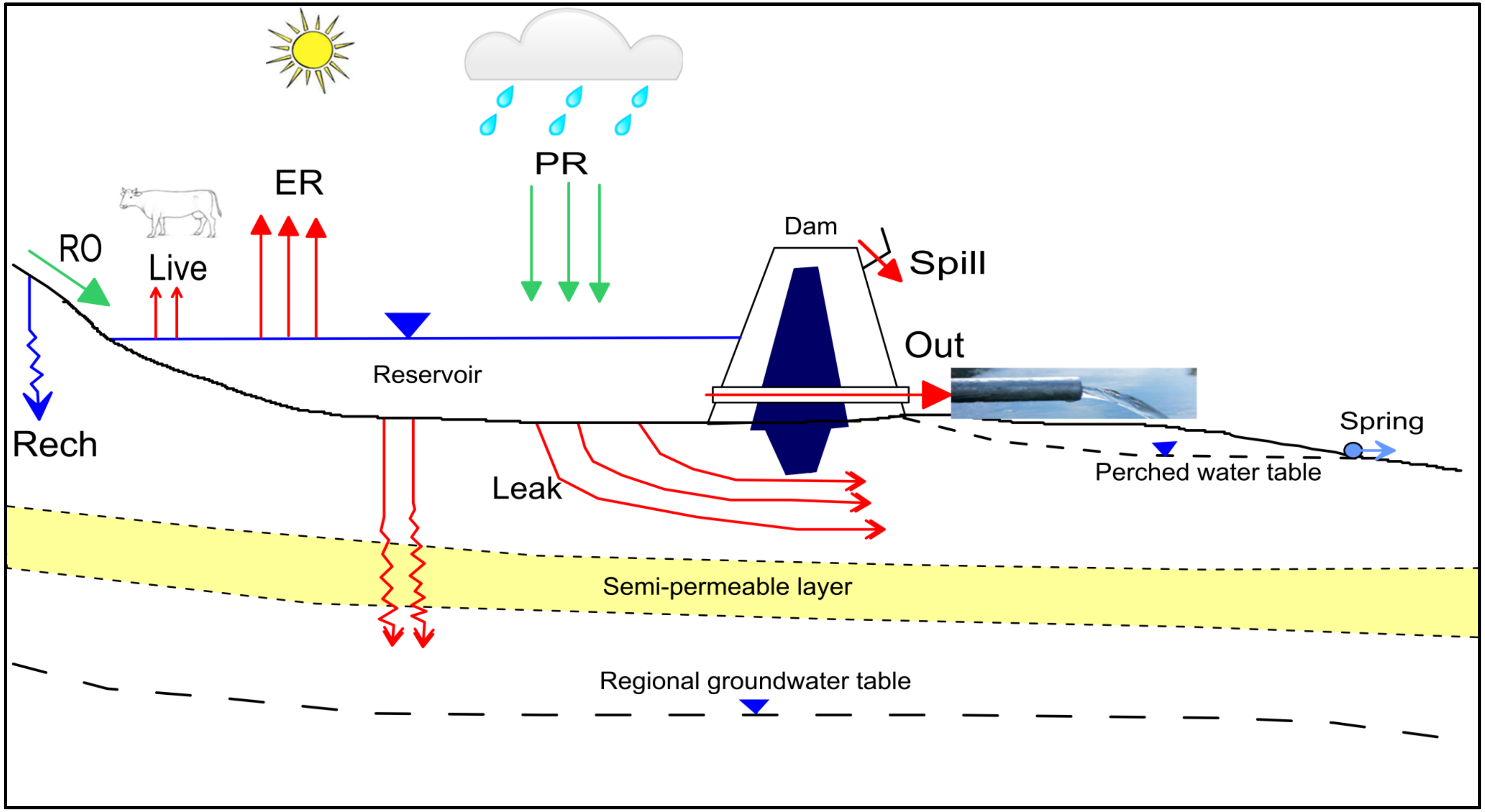

Figure 5.4. Schematic representation of water balance components of Arato MDR.

RESULTS

Resutls from water level sensors

The results of the diver water lelvel data loggers at the MDR and SHDW in relation to daily rainfall are show in (Fig. 5.5). Note that the rise in reservoir water level and groundwater level in the SHDW resumes following the start of rainfall on the 20th of July, 2014. Water level observations were started only at the very beginning of the rain season, because rain was late in 2014. It lasted less than three months. Considering the rainfall pattern or hydrological year of the region it is logical to assume that the full wet period was contained within the 182 days and during the remainder of the hydrological year, runoff and groundwater recharge may be assumed to be negligible.

The total rainfall during the 182 days was about 633 mm with only 55 rain days with individual totals that range from 2 to 37 mm of rain. Reservoir and groundwater levels were rising a maximum of about 6 and 2 m respectively, but rise in groundwater level (SHDW) was not complete because the well started to overflow. During the period of measurable SHDW rise (until overflowing) a cumulative rainfall of 446 mm was recorded, while for the rise in the reservoir, it was about 530 mm.

The hydraulic gradient between the reservoir and the SHDW (with diver) was estimated at about 0.043 taking the elevation of the reservoir and groundwater levels at 2424 and 2398 m and horizontal distance of about 600 m.

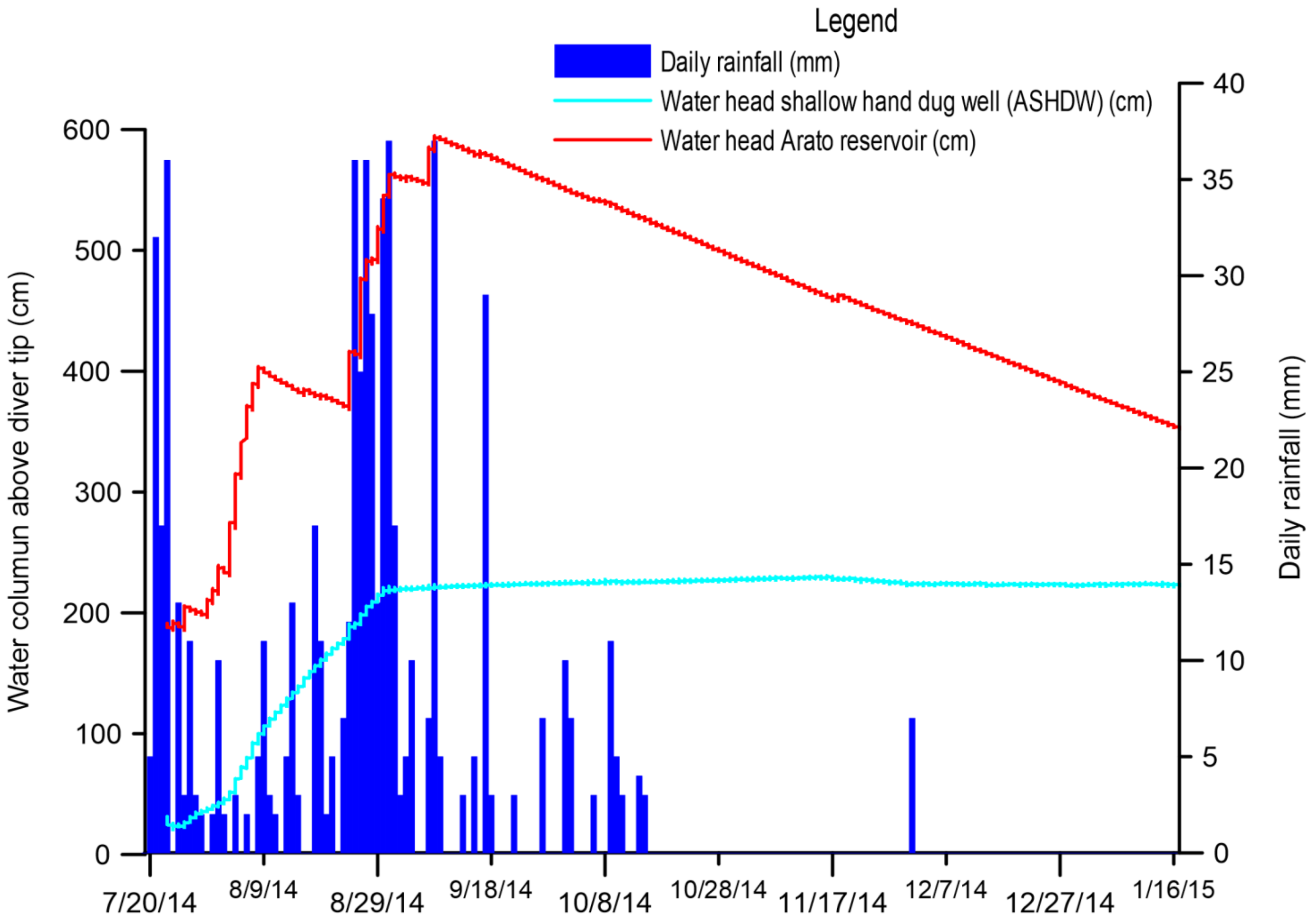

Figure 5.5. Diver data from reservoir and shallow hand dug well, compensated for atmospheric pressure, in relation to rainfall (19/7/2014 to 24/11/2015). Rainfall and Temperture data are included in Appendix C5 on CD.

Runoff (RO)

A weighted CN was used for the whole watershed based on land use and soil type.The catchment area (Fig. 5.6) is dominantly farm land with minor marginal land where grass develops during the rainy season. The grain size distribution of four soil samples from the area show them to be classifiable as loamy sand, loam and clay (Table 5.2). However, the samples come from small parts of the catchment and were not collected for this purpose and presented, and discussed here merely to show variations in soil texture across the watershed, whereas the dominant or representative soil type for the watershed is clay loam, based on field observations and pervious studies of Gebreyohanes (2009) and Kassa (2011). The presence of shale in the catchment is generally responsible for the formation of dominant silty and clayey soils. For CN estimation clay loam soil with poor to fair hydraulic condition and hydrologic soil group C was considered typical (Gebreyohannes, 2009; Kassa, 2011) (Table 5.4). Farmers in the area plough and treat their plots following the topography in the form of contours and a contoured treatment or practice was considered for the area. Locally on the grass lands minor terraces were also observed. CN value was weighted accounting for surface area of the different land uses and resulted to 79.6 for the whole watershed (Table 5.4). Studies from Hagere-Selam/Tembien area (semi-arid highlands of northern Ethiopia) by Descheemaeker et al. (2008) resulted to wide range of CNs (CN=29–97) for different land use/cover and for young exclusure CN of about 76.9 were obtained. This study further pointed out that runoff in younger, poorly restored (degraded) areas can be relatively accurately predicted with the CN method.

Table 5.4. Weighted CN for the whole catchment.

Land use	Area (sq.km)	Area ratio	Hydraulic condition	Hydrologic soil group	Curve Number	Weighted CN	Sum weighted CN
Grass land/Bush	2.87	0.2	fair	C	70	14	**79.6**
Farm land/small grain	11.58	0.8	poor	C	82	65.6	

Considering 79.6 as the weighted CN for the whole catchment (Table 5.4) with a corresponding potential maximum retention (S) of 65.1, the runoff generated from the catchment is 48.8 mm during the 182 days, which is nearly 7.7% of rainfall (633 mm) or a runoff coefficient of 0.077. Only 13 rainy days generated runoff, ranging from 0.2 to 6.5 mm, from 55 rainy days with precipitation ranging from 2 to 37 mm. Different study results from Tigray and other parts of Ethiopia are presented in Table 5.5 for comparison.

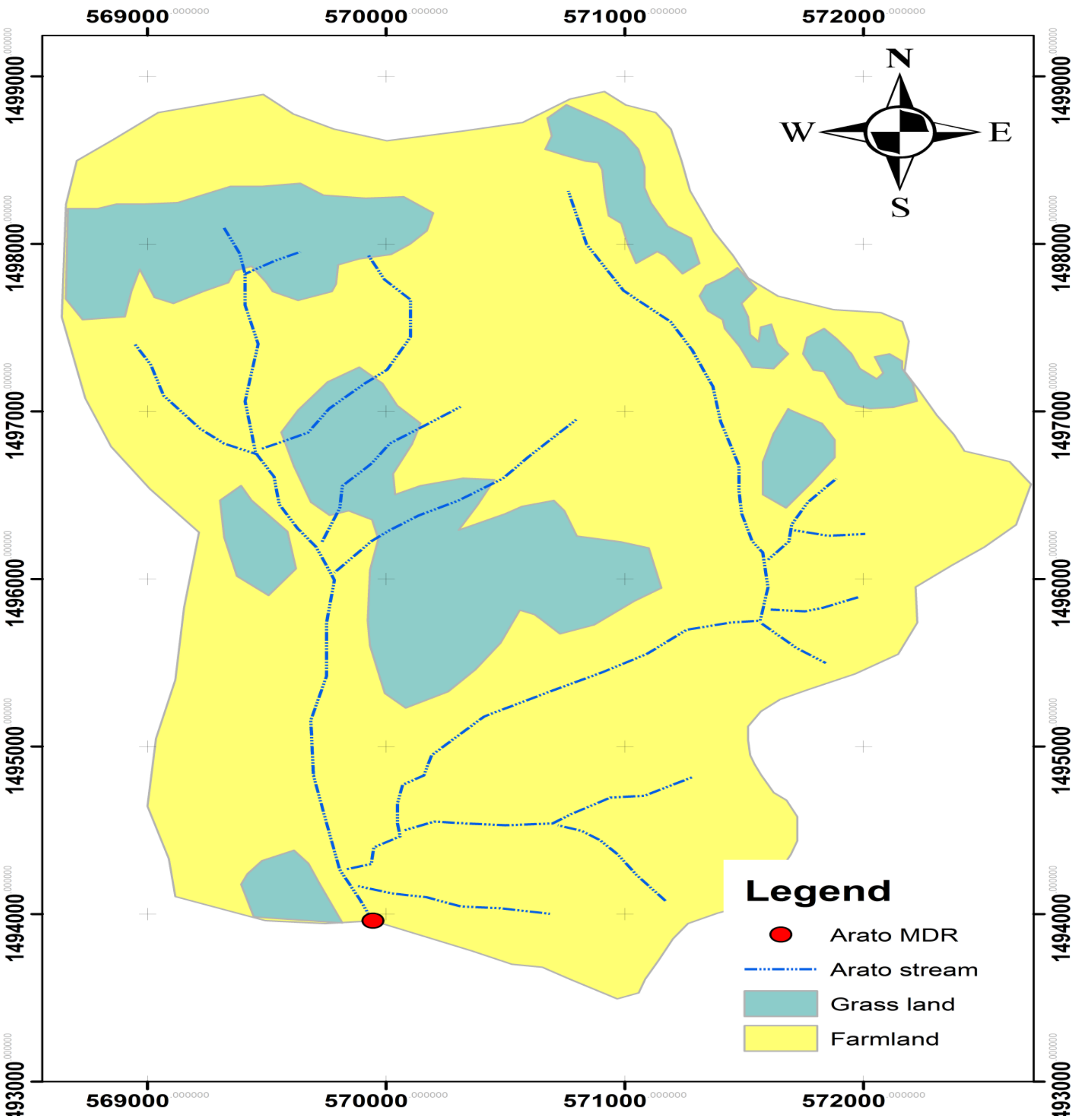

Figure 5.6. Simplified land use map of Arato watershed.

Table 5.5. Estimated runoff and recharge per year in different parts of Ethiopia compiled from different sources expressed as percentage of rainfall in parentheses.

Source	Area	Runoff	Recharge	Method
Mekelle Area (e.g. Aynalem, Ilalla, Maileba catchments): Tekeze Basin				
Cherent and Eshete, 1982			195 mm (30%)	
DEVECON, 1993			195 mm (30%)	
WWDE, 2007			26%	WATBAL
Hussien, 2000	104 km^2		57 mm (9%)	Water balance and base flow separation
Teklay, 2006	104 km^2	26 mm	35 mm (5.3%)	Thornthwaite & Mather (1995)
Yihdego, 2003			53 mm (9.2%)	Water balance
Kahsay, 2008	104 km2		30 mm (4.5%)	CMB
Zeru, 2008	104 km2		11%	MODFLOW
Teferi, 2009	104 km2		32 mm (5%)	WATBAL
Gebreegziabher *et al*. 2009	95 m^2	65.3 mm (15.5%)		Field experiment
Nyssen *et al*. 2010	121 km^2	55 mm (15%)		Field experiment
Nyssen *et al*. 2010	200 ha	26.5 mm (8%)		Field experiment
Vandecasteele *et al*. 2011	4 km^2		167 mm	WATBUG (Wilmott 1977)
Girmay *et al*. 2009	20 m^2	3.8–21%		Field experiment at Maileba MDR
Arefaine *et al*. 2012	340 km^2	40 mm (7%)	66 mm (12%)	WetSpass
This research – **Arato**	14.5 km^2	**48.8 mm (7.7%)**	**104.1 mm (16.4%)***	**CN and Thornthwaite & Mather soil moisture balance method**
			92.8 mm (16 %)*	**CMB**
			100 mm (15%) for 44 days	**WTF**
Central highlands of Ethiopia (e.g. Holetta Agricultural Research Center): Awash Basin				
Adimassu and Haile, 2011	110 m2 (22m×5m)	169.53mm (32.3%)		Field experiment in a plot covered with wheat
Adimassu et al. (2014)	210 m2 (35m×6)	145–325 (19–28%)		Field experiment
Selamyihun (2004)	0.078 km2	102–258 (23 -51%)		Field experiment (Vertisols)

*For 182 days (19/7/2014-16/1/2015), but contribution of rainfall to run-off and groundwater recharge during dry period can be assumed minor and negligible.

Recharge (Rech)

Groundwater recharge occurs when there is a rainfall surplus and the soil moisture is satisfied to its field capacity. Recharge estimation using SMB model is summarized in Table 5.6 and Fig. 5.7. The recharge was 104 mm, corresponding to about 16% of the rainfall. Recharge was occurring only in 7 days (4 days in August and 3 days in September). The maximum daily recharge was 25.6 mm, while the minimum was 5.3 mm. The total ETo and AET for the considered period of 182 days were about 888.5 and 509 mm respectively.

Table 5.6. Recharge estimation using SMB model, CMB and WTF methods (period of 19/7/2014 to 16/1/2015). Precentage of rainfall is indicated in bracket.

Method	P (mm)	RO (mm)	ETo (mm)	P-RO-ETo	Rech (mm)
SMB (mm)	633	48.8	888.5	-304.3	104.1
		(7.7%)			(16.4%)
CMB (mm)					92.8
	633				(15%)
WTF (mm)					100
	633				(15%)
	446				(22.5%)

Recharge was also estimated using CMB. Chloride concentration for rainwater was about 0.98 mg/l and for groundwater it was 6.17 mg/l and the effective rainfall is 584.2 mm for the observation period. Using equation 7, recharge was estimated at about 92.8 mm which is about 15% of the total precipitation.

In addition to the above methods, the recharge of the research area was estimated using actual measurement of the water table fluctuation in the hand dug well using diver data logger (Fig. 5.5). Only part of the observation period was considered for this method, because when groundwater starts to overflow, recharge is no more reflected by rising water level. For this method a groundwater table rise of 200 cm within a period of 44 days (19/07/2014 to 31/08/2014) was taken.

Based on the soil types in the recharge area an average specific yield of clay and silt was considered (S_y=0.05) from (Johnson, 1967). The estimated recharge was found to be 100 mm which is 22.5% of precipitation (P_{rise}=446 mm) during the water table rise or 15% of the total precipitation during the whole observation period.

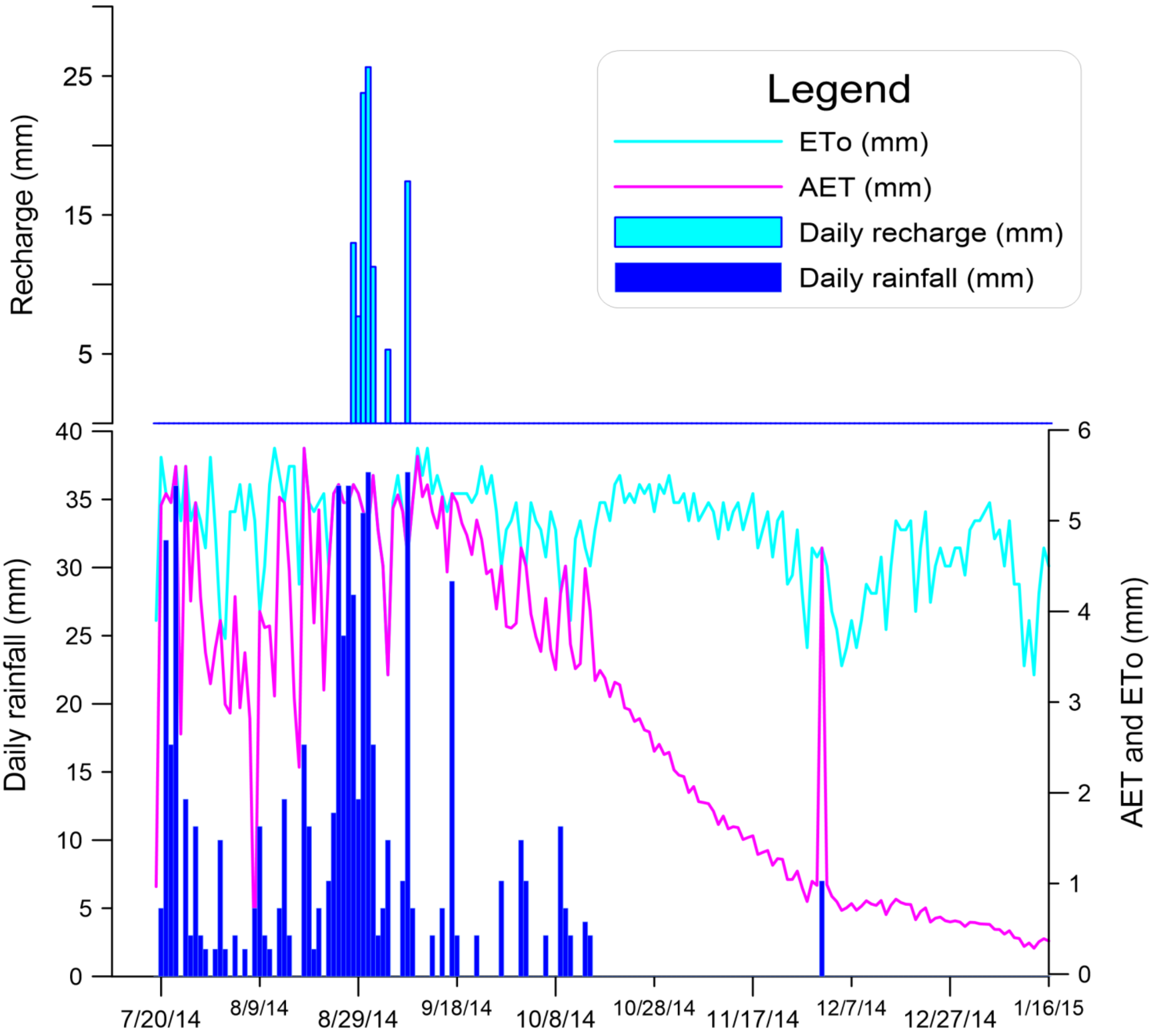

Figure 5.7. Daily distribution of ETo, AET and recharge in relation to rainfall for the observtion period (19/07/2014 to 16/01/2015).

Arato MDR water balance model

The water balance of Arato MDR can be conceptualized based on Fig. 5.8. After distinguishing the known and unknown variables or components of the model it is possible to solve for the unknown components considering the dry and wet seasons separately.

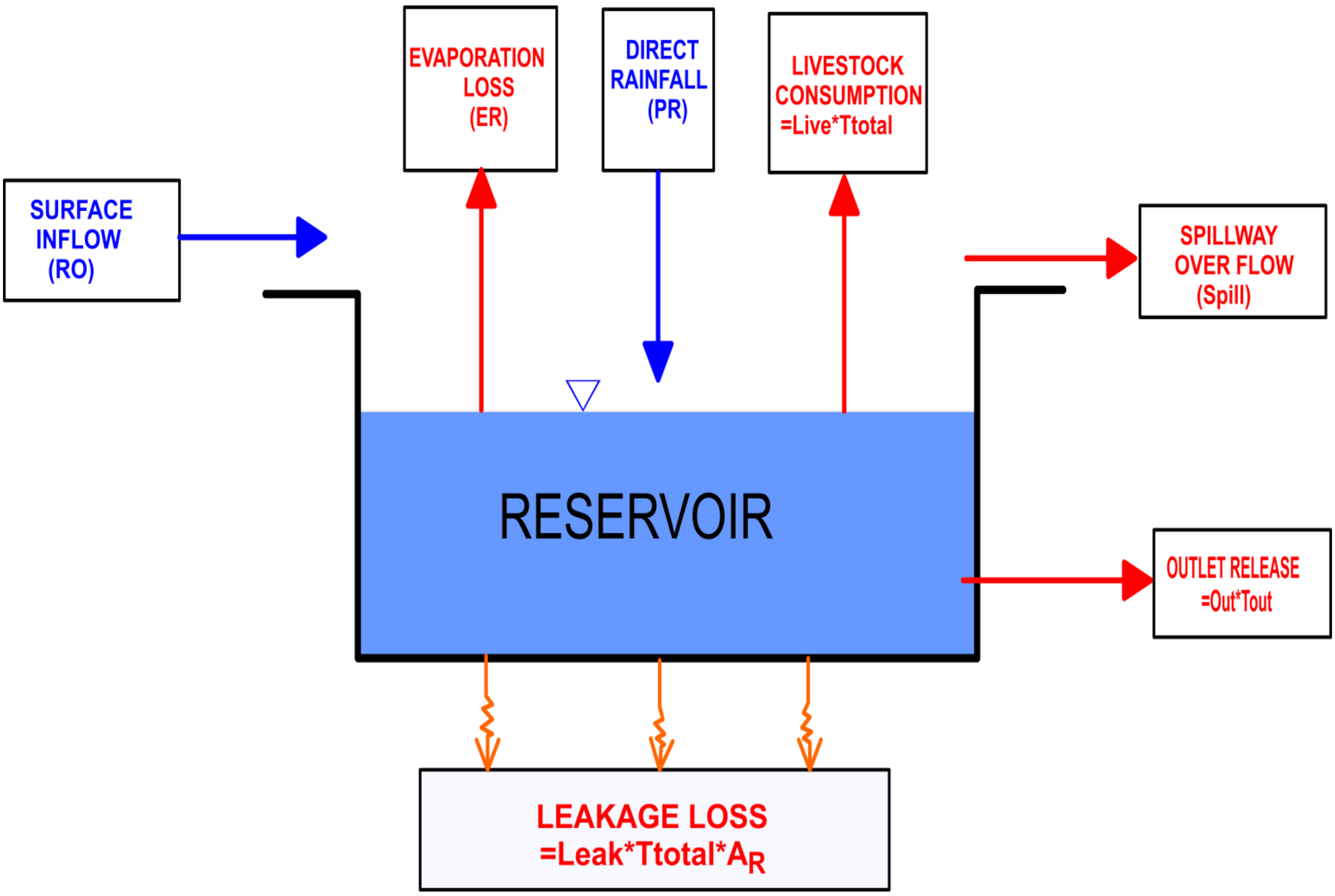

Figure 5.8. Water balance model (components) for Arato MDR.

Arato MDR has never been filled to its maximum reservoir level since its construction and consequently, there was no spillway overflow. Moreover during the observation period (19/07/2014 to 16/1/2015) there was no irrigation or outlet release and livestock consumption was negligible. Accordingly, in the water balance equation with all other components known, direct inflow (runoff, RO) and leakage loss (Leak) remain unknowns (Table 5.7). The RO estimated using CN method will be considered later separately to estimate leakage for the whole observation period.

Table 5.7. Wet observation period (19/07/2014-9/09/2014): Wet season water balance (53 days).

Symbol	**Unit**	**Value**	**Remark**
V_{Ri}	m^3	2.5×10^4	19/07/2014 (From Area-storage-elevation curve, Fig. 5.9)
V_{Rf}	m^3	45×10^4	9/09/2014 (From Area-storage-elevation curve, Fig. 5.9)
ΔV_R	m^3	42.5×10^4	
A_{Ri}	m^2	2×10^4	19/07/2014 (From Area-storage-elevation curve, Fig. 5.9)
A_{Rf}	m^2	14×10^4	9/09/2014 (From Area-storage-elevation curve, Fig. 5.9)
A_R	m^2	8×10^4	
ΔWL_R	m	6.00	
ER	m^3	2.85×10^4	
PR	m	0.53	
RI	m^3	4.24×10^4	
RO	m^3	Unknown?	
A_c	m^2	14.5×10^6	There is discrepancy with the design of dam (for design 20.7 km^2 was considered)
T_{total}	day	53	
ETo	m	0.2679	
$Out\times T_{out}$	m3	0	No loss of reservoir water through outlet during observation period
T_{out}	day	0	Was not operational during observation period
$Live\times T_{total}$	m^3	0	No livestock consumed water during the observation period
Leak	m/day	Unknown?	

The leakage component can be determined during the dry period when there is no inflow. For estimating leakage an observation period from 17/10/2014 to 16/01/2015 was considered with the knowledge that there is no surface runoff and meaningful direct rainfall that contribute to the change of reservoir volume during this period (Table 5.8). The diver data logger showed continuous decline in water level during this period mainly attributed to evaporation and leakage.

First evaporation loss and direct input from rainfall on reservoir can be estimated using equations 12 and 13 and, it turns out to be 5.77×10^4 m^3 and 0 m^3 respectively. Using equation (9) Leak isestimated at about 112,300 m^3 in 83 days (1353 m^3/day) considering the corresponding area (10×10^4 m^2) is corresponds to 13.5mm/day.

Assuming leakage to be constant in time, the leakage amount in 182 days is about 0.25×10^6 m^3.

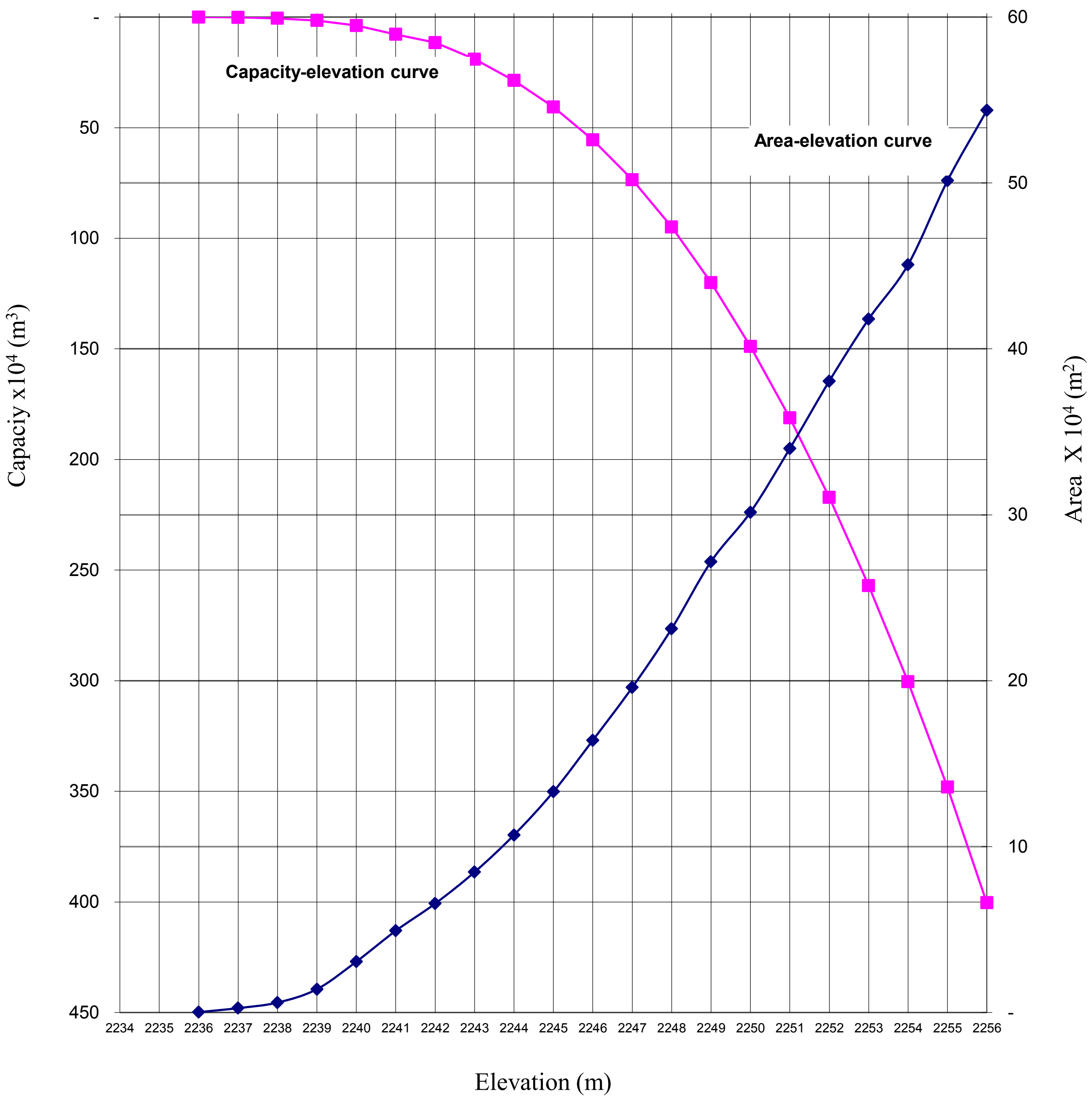

Figure 5.9. Area-storage-elevation curve for Arato MDR (Hagos, 1995).

Table 5.8. Dry observation period (17/10/2014 to 16/01/2015): dry season water balance (83 days).

Symbol	Unit	Value	Remark
V_{Ri}	m^3	35×10^4	17/10/2015 (From Area-storage-elevation curve, Fig. 5.9)
V_{Rf}	m^3	20×10^4	16/01/2015 (From Area-storage-elevation curve, Fig. 5.9)
ΔV_R	m^3	-15×10^4	(From Area-storage-elevation curve, Fig. 5.8)
A_{Ri}	m^2	12×10^4	17/10/2015 (From Area-storage-elevation curve, Fig. 5.9)
A_{Rf}	m^2	8×10^4	16/01/2015(From Area-storage-elevation curve, Fig. 5.9)
A_R	m^2	10×10^4	
ΔWL_R	m	-1.7	Diver (pressure transducer) data
ER	m^3	5.77×10^4	
PR	m	0	No rainfall during dry period
RI	m^3	0	No direct rainfall on reservoir surface during dry period
RO	m^3	0	No runoff during dry period
A_c	m^2	14.5×10^6	There is discrepancy with the design of dam
T_{Total}	(days)	83	
ETo	m	0.4341	
Out×Tout	m^3	0	No loss of reservoir water through outlet during observation period
T_{out}	m^3	0	Was not operational during the observation period
Live×Ttotal	m^3	0	No livestock consume water during the observation period
Leak	m/day	Unknown?	

Once the leakage loss is determined from the dry observation period, the wet season's water balance (Table 5.7) can be solved to determine runoff (RO). First evaporation loss and direct input from rainfall on reservoir surface can be estimated using equations (12 and 13) and it turns out to be 2.85×10^4 m^3 and 4.24×10^4 m^3 respectively.

Then using equation (9) and adjusted leakage loss for the number of days in wet season can be used to estimate the surface runoff (RO) and results to about 0.64×10^6 m^3 (44.14 mm).

So, the total inflow (input) is the sum of direct runoff from the catchment and direct rainfall on the surface of the reservoir, which is equal to 0.68×10^6 m^3. Without considering the input from direct rainfall on the reservoir (0.64×10^6 m^3), it is slightly lower compared with the runoff estimated using curve number (0.71×10^6 m^3) and much lower than the initial design capacity of the reservoir (2.5×10^6 m^3). This runoff value obtained from diver measurements has to be considered as an observed and reliable estimate over the observation period. The slightly higher value obtained using SCS-CN method might be attributed to the various factors associated to the catchment characteristics and with the estimated parameters in the calculation of ETo.

Now having determined the runoff using CN method and reservoir leakage loss using the reservoir water balance model, the leakage loss in the wet period was calculated (equation 9).

Table 5.9. Wet season water balance (53 days) for estimation of leakage using RO from CN method.

ΔWL	6 m	Water level rise
A_R	8×10^4 m^2	
PR	0.53 m	
ER	2.85×10^4 m^3	Evaporation from reservoir surface
RI	4.24×10^4 m^3	Input from direct rainfall
RO	0.71×10^6 m^3	
Ttotal	53 days	Total observation period
Leak	Unknown? (m/day)	

Considering the above values and unknowns in Table 5.9 and executing the equation gives a reservoir loss due to leakage (Leak) of about 4602 m^3 per day (0.24×10^6 m^3 in 53 days) which corresponds to 57.5 mm/day. So, during the wet season 34% and 38% of the runoff from CN and water balance methods respectively, is leaking.

DISCUSSION

Water level changes

Reservoir water level rise is a function of runoff from rainfall over the catchment area and direct rainfall on the surface of the reservoir. Water level rise in the SHDW does not show a strong relationship with individual rainfall events. The slope of the rise appears constant irrespective of the amount of rainfall on a daily basis. The reason for this might be due to the continuous replenishment of the aquifer via leakage from the MDR situated on its upstream side. From September onwards, the reservoir level continuously declines, while the groundwater level in the SHDW remains constant. Field observation showed that the well was full and was overflowing to the ground surface. This indicates that, at least during the dry period, the water coming to the SHDW is directly from Arato MDR. This conclusion is confirmed using manual water level measurements and hydrochemical analysis in chapter 4. Quite opposite situation was observed at non-leaking Tsinkanet MDR by Gebreyohannes (2009), with no interaction between reservoir and nearby shallow aquifer, where the reservoir level remains constant for months, while groundwater level in shallow aquifer declines.

Runoff and recharge processes

Water balance analysis is a tool for understanding the hydrological processes, to assess efficiency of water utilization and used as input to optimal design and operation of water harvesting schemes. Reliable long-term data are not available in many developing countries like Ethiopia (Collick *et al*., 2009), which makes understanding the hydrological responses challenging. This situation leads to improper sizing or design of reservoirs, culverts, storm pipes, etc. For example, out of 92 MDRs constructed in Tigray, 21 (22%) of them have serious inflow problem and 56 (61%) of them have siltation problems (chpater 2) attributed to lack of reliable hydrological data.

Table 5.5 summarizes the runoff and recharge estimations by different methods in the region. The results obtained in the present study are similar to other research results from the area (Table 5.5). Runoff start to be generated beyond a minimum rainfall of 13 mm. Collick *et al*. (2009) reported after 10 mm of rainfall runoff occurs on 20% of degraded areas of Andit Tid and the Yeku watersheds (from the Ethiopian highland area). Girmay *et al*. (2009) conducted field experiments in 2006 at Maileba MDR (in the same region), and obtained a runoff of coefficient of 3.8%, 8%, 10.8% and 21% for exclosure, Eucalyptus plantation area, grazing land and cultivated land, respectively. Araya *et al*. (2011) also reported mean runoff coefficients over three years that varies from 12 to 26% from an experiment with dominantly clay and clay loam soils and different tillage practices in Adigudom (northern Ethiopia). In addition, Arefaine *et al*. (2012) estimated surface runoff for Illala sub-basin, in which Arato MDR is embedded, at about 7% of rainfall using the WetSpass model. The studies from Tigray region are consistent with the present results in contrast with those from studies in other regions (see also Table 5.5). Selamyihun (2004) estimated RC from central Ethiopian highland Vertisols (different region) using calibrated curve numbers, resulting in a range of values varying from 23% to 51%, which is equivalent to 102–258 mm. Another study from the central highlands of Ethiopia by Adimassu *et al.* (2014) reported an annual runoff volume of about 145 mm (19% of rainfall) for a plot with soil bunds and 325 mm (28%) for fallow land. Adimasu and Haile (2011) also reported 169.53 mm (32.3%) from a field experiment in a plot covered with wheat in the central highlands of Ethiopia. Implementation of soil and water conservation practices and exclosures reduce runoff and enhance local infiltration of rainwater (Vandecasteele, 2007; Walraevens *et al.*, 2015) and this has ultimately resulted in reversing land degradation and forest transition or greening over the last three decades in Tigray (Belay *et al.,* 2015; De Mûelenaere *et al.*, 2014).

The yield of the catchment from surface runoff during the observation period was estimated at about 0.71×10^6 m^3, which is only 34% of the initial design of the project which was 2.5×10^6 m^3 (Hagos, 1995) and higher than the yield obtained by Gebreyohannes (2009, 2013) using WetSpass method, that is 0.096×10^6 m^3. It must be emphasized that the present estimation is based on actual data only for a period of 182 days, disregarding any contribution of runoff during the remaining period of the hydrological year.

The recharge estimated using SMB can be considered as annual assuming negligible recharge during the rest of the year. Similarly the recharge from CMB is annual by its nature, but the recharge from WTF method represents only 44 days. Mekeonnen *et al*. (2015a, b) explained the importance of small sediment storage structures in relation to infiltration and sediment trapping and concluded that these structures slow down the speed of runoff and give time for infiltration and sediment deposition. According to Stroosnijder (2009) on a survey of 181 medium-sized dams in the Eritrean Highlands 31% were completely silted up, 52% were partly silted up and only 17% did not suffer from siltation. These conditions clearly indicate the need for an integrated land and water management tied with water harvesting planning like MDRs.

Leakage from reservoir

The core issue of this paper is to assess leakage rate quantitatively and to confirm conclusions drawn in previous studies using geological, geophysical and hydrogeological approaches (chapter 3 and 4). The leakage rate from the dry period water balance (13.5 mm day^{-1}) is high compared to the results obtained by Yazew (2005), i.e. 0.9 and 0.4 mm day^{-1} for Gumselasa and Korir MDRs respectively, which are 35 km south and 26 km north respectively of the Arato MDR. Gumselasa MDR is built on dolerite and shale dominant sedimentary rock foundation and reservoir while Korir MDR is entirely on shale dominant sedimentary rock. Both of the schemes are operational as their leakage rates are low. The leakage for Arato MDR is about 15 and 34 times higher than Gumsalasa and Korir MDRs. During initial design of the project an annual seepage loss of 9965 m^3 was foreseen. The difference between the actual leakage amount for 182 days and the initial annual design is about 0.24×10^6 m^3. So, about 15% of the stored water from runoff (CN method) is leaking during the 83 days dry period. The leakage (4602 m^3 day^{-1} or 57.5 mm day^{-1}) during the wet period obtained, considering runoff from CN, is higher than the values obtained from the dry season water balance model (1353 m^3 day^{-1}) of the reservoir. Apparently, the steep rise in water level in the reservoir over a short period immediately triggers strong leakage, whereas leakage amounts drop during the dry period, with recessing water levels in the reservoir. This is an order of magnitude, not to be considered an exact figure, because every time during the year there is a change in water level attributed to various reasons. This change in hydraulic head affects the leakage and evaporation rate.

The estimated leakage doesn't tell us the location where the reservoir is actually leaking. This can be explained by linking with site geology and hydrogeology. The right abutment and central foundation of the MDR is covered with dolerite, while the left abutment is limestone-shale-marl intercalation units. Similarly, the reservoir area is covered with both units. In places, surficial Quaternary alluvial deposits exist along depressions and river course. Hydrogeologically, from reported hydraulic conductivities for the different formations (chapters 3 and 6), it can be concluded that the dolerite and shale layers are less pervious than the limestone. Hence, the limestone layers in the limestone-shale-marl intercalation unit must be responsible for the leakage of the MDRs. In addition, the weathered and fractured top part of all units was found to be pervious and liable to leakage. Maps and sections explaining the site geo-hydrology are reported in chpaters 3 and 4). Moreover, conventional geological and geophysical techniques (vertical electrical sounding and profiling) allowed to delineate the leakage zone and understand its mechanisms as reported in chapter 4.

The leakage in the area has an indirect or unintended positive impact on local farmers by improving their livelihoods by introducing small scale irrigation from shallow hand dug wells and diverting streams emanating from reservoir leakage.

Considering an average groundwater recharge of 98.9 mm from the three methods, a runoff of 48.8 mm from CN method and actual evapotranspiration of 509 mm from Thornthwaite and Mather soil moisture balance method, it is possible to compare with the total rainfall in the area for the considered period. The total rainfall (P) is about 633 mm while the sum of the three components

(RO+AET+Rech) is equal to 656.7 mm. These values are generally comparable and give confidence in the application of the different methods in the area.

CONCLUSION

The groundwater recharge in the study area was estimated using different approaches. The natural recharge was estimated at 104 mm, 92.8 mm and 100 mm using SMB, CMB and WTF methods, corresponding to some 1.41×10^6 m^3. Assuming recharge during the rest of the year (dry period) in the area is negligible, the results from SMB and CMB can be considered as a yearly recharge, while that of WTF is for 44 days, covering an important part of the rainy period. The runoff was estimated using the SCS-CN and water balance approaches. The result from SCS-CN was about 0.71×10^6 m^3, while from the water balance approach based on diver logger data, it was about 0.64×10^6 m^3. It was possible to estimate the leakage from the reservoir using the water balance model approach for the observed first part of the dry period; it corresponds to 13.2 mm/day, or 112,300 m^3 for the 83 days of dry period observation (1353 m^3/day). With the same water balance model and using the runoff (RO) estimated by CN method, the leakage loss during the wet period was found to be 4602 m^3 per day (0.24×10^6 m^3 in 53 days) which corresponds to 57.5 mm/day.

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Contribution of authors

Name of author	Role of the author in this chapter
Gebremedhin Berhane	*Was responsible for all the aspects of the study, data collection, field instrument installations, water level sensors, meteo-station, interpretation and writing the article/chapter*
Marc Van Camp	*Provide technical support on diver installation and data downloading*
Tesfamichael Gebreyohannes	*Provide logistical and technical support during fieldwork*
Nawal Alfarrah	*Contributed and shared ideas on data interpretation*
Kristine Walraevens	*Was the supervisor in the study, and critically reviewed and approved the article*

Electrical resistivity profiling survey at the downstream side of Adishuhu MDR (top) and downstream view of Hizaetiwedicheber MDR (bottom). Both are water logged areas following the construction of the MDRs ©Gebremedhin Berhane.

CHAPTER 6

Geological and geophysical investigation of water leakage from two micro-dam reservoirs, northern Ethiopia

This chapter is based on Gebremedhin Berhane, Mogos Amare, Tesfamichael Gebreyohannes, Kristine Walraevens. Geological and geophysical investigation of water leakage from two micro-dam reservoirs, northern Ethiopia, Journal of African Earth Sciences.

ABSTRACT

Water resources are essential to human development activities and to eradicate extreme poverty and hunger. Geological problems of two water harvesting Micro-Dam Reservoirs (MDRs) were evaluated from leakage perspectives in the northern part of Ethiopia, East Africa. Conventional geological mapping, discontinuity and weathering descriptions, test pits and geophysical methods were used to characterize the hydrogeological features of the MDRs. Vertical Electrical Sounding (VES) and Electrical Rsisitivity Profiling (ERP), were executed using Terrameter SAS (signal averaging system) 1000 manufactured by ABEM, Sweden, with Schlumberger and Wenner array configuration respectively. It was concluded that the foundations of both MDRs, except the right abutment for Adishuhu which is partly composed of dolerite, are pervious due to the presence of thin bedding planes, joints, weathered materials and fault. The presence of water in the downstream toe of the MDRs, at depressions, existing test pits and test pits excavated during the present study which lie within the seepage zone demarcated during surface geological mapping, correspond with the electrical resistivity study. The results of the electrical resistivity survey (ERP and VES) were merged with the geological and structural mapping and the observation of seepage zones, for the delineation of weak zones responsible for leakage. Monitoring of the leakage (reservoir water and groundwater levels), both manually and using automatic divers, is recommended, along with monitoring of the stability of the embankments and the discharge or flow downstream of the MDRs.

INTRODUCTION

In the previous chapters 2, 3, 4 and 5 detail post constructon evaluations related to leakage problem at MDRs (Arato and Hashenge) with considerable intrusive dolerite outcrops were evaluated following different techniques. In this chapter two MDRs with no major outcrop of dolerite intrusion are evaluated following geological and geophysical techniques (VES and ERP).

Water resources are essential to human development processes and to achieve the Millennium Development Goals (and now the Sustainable Development Goals) that seek, *inter alia*, to eradicate extreme poverty and hunger, achieve clean water and sanitation, and ensure environmental sustainability (Hanjra et al., 2009). Due to urbanization, expanding economic activities and drought, about 13% of the world's population does not have access to safe drinking water (WHO and UNICEF, 2010) and water for other uses (e.g. for irrigation to secure food sufficiency). With the current trend of water demand, water shortage will become even more intense and approximately half of the world's population will suffer from major water scarcity by the year 2030 (UNESCO-WWAP, 2009). Similarly, access to fresh water for different uses is beyond the reach of the majority of the rural population in East Africa. Construction of dams or water harvesting structures (WHSs) is, therefore, necessary for providing a stable and continuous water supply for different uses. Sufficient water supply is also needed to maintain and continue the development of the country and sub-Saharan African region, which was realized over the last decade. Within the non-resource-rich country group, there are several countries such as Ethiopia, Mozambique, and Rwanda that have achieved sustained high growth rates for over a decade (World Bank, 2013a, b).

WHSs are being used to collect and store runoff from impermeable surfaces in many parts of the world to resolve water scarcity (Frot *et al*., 2008 and references therein). A micro-dam reservoir

(MDR) is required to impound water, and its design and construction must be capable of preventing the uncontrollable leakage of reservoir water around and beneath its structure.

The principal objectives WHSs are to change the agrarian systems to widespread small-scale irrigated agriculture and to gradually attain self-sufficiency in food production (Aberra, 2004; Abdulkadir, 2009; Berhane, 2010; Desta 2005; Gebreyohannes *et al*. 2013; Girmay *et al*., 2012; Gonzalez-Quijano, 2006; Haregeweyn *et al*., 2005, 2006; Nedaw and Walraevens, 2009). However, the success of these initiatives has been limited for various reasons, including: leakage, siltation, insufficient run-off and poor water management. Many seepage problems and failures of dams have occurred worldwide because of many reasons. Inadequate seepage control measures or incomplete cleanup and preparation of the cores, foundations, and abutments are among factors which can result in dam failure (Lee *et al*., 2005; ODNR, 2003).

One of the areas where such efforts (such as the construction of MDRs) have been exercised is the northern extreme part of Ethiopia (Tigray National Regional State, TNRS) (Fig. 6.1). Many parts of Ethiopia, like the northern part, have long been neglected by the previous regimes and thus land degradation, poverty, armed conflicts and mass emigration contributed to low agricultural production and reduced income of the population (Aberra 2004). In Tigray, rain-fed agriculture is the main source of food production. Temporal and spatial fluctuations of rainfall result in low food production, which is attributable to droughts or unfavorably wet conditions. So, WHSs such as MDRs play a great role in improving food security and livelihoods of the local people in particular and the nation at large.

Water leakage from reservoirs can give rise to severe consequences, especially when a high rate of water flows in loose unconsolidated or fractured terrain. Considerable water leakage from reservoirs makes it difficult to attain the planned storage capacity. Whenever leakage velocity reaches critical value, erosion takes place giving rise to suffusion and subsidence, which can lead to the collapse of dams (Ogilvy *et al*., 1969; James, 1968). This emphasizes the importance of understanding the mechanisms and identification of water leakage from reservoirs.

This chpater is aimed at assessing and evaluating the engineering geological and hydrogeological conditions of two MDRs and at identifying the main causes and characteristics of leakage problems. The results presented will bridge to some extent the lack of engineering geological and hydrogeological data for the area, which are relevant for selection and designing of new MDRs and other WHSs, and to implement anti-leakage remedial measures.

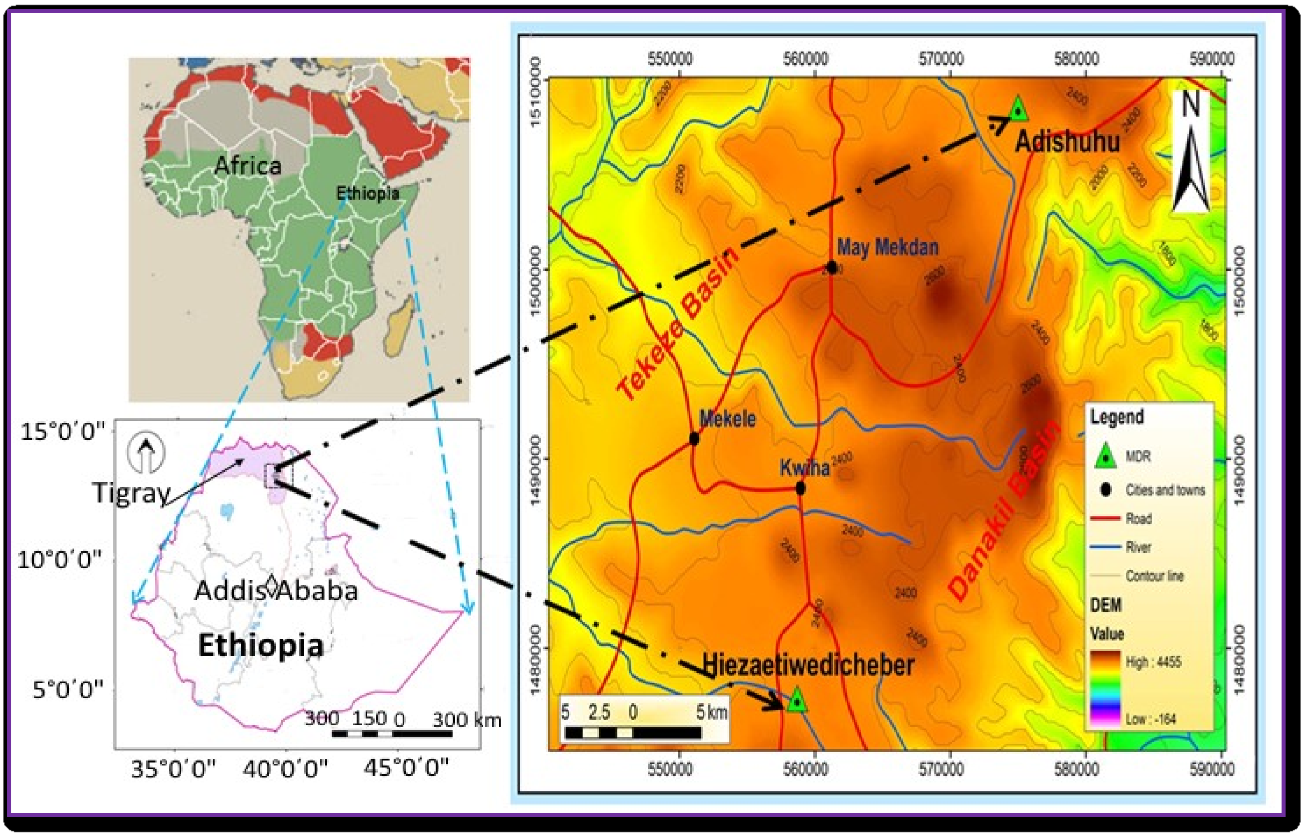


Figure 6.1. Simplified location map of the study area (Adishuhu and Hizaetiwedicheber MDRs). (DEM data source from ETHIO-GIS data sets/SRTM, http://dds.cr.usgs.gov/ srtm/version2 _1/SRTM3/Africa/).

SELECTION OF STUDY AREAS AND STATEMENT OF THE PROBLEM

Over the years, although the state of the art in earth dam construction in Ethiopia has been developed rapidly, earth dam failures are still occurring in various ways. Hence, experience gained from post construction evaluation studies will contribute to effective treatment and design modifications of other dams (Singh and Varshney, 1995). An inventory of the 92 MDRs in the area with their respective problems and geology showed that of the main problems highlighted, siltation and leakage were found to be highly linked to geological conditions (chapter 2). These problems were found to be very serious in MDRs located in sedimentary rocks. Siltation was found to be more significant in areas where shale is the dominant rock type,whereas leakage is more common in areas where limestone predominates.

More detailed studies (geophysical, geotechnical drilling, hydro-geochemistry) were conducted at two MDRs (chapters 3 and 4), with their foundation and reservoir geology mainly covered with dolerite and limestone-shale-marl intercalation units (Fig. 6.2). The results of these studies indicate the presence of hydraulic connection between the impounded reservoirs and the downstream leakage discharge zones. The limestone-shale-marl intercalation unit of Agula Shale was found to be the permeable formation and responsible for the inefficient performance of the projects in terms of water loss. The dolerite intrusion resulted in brecciation of the sedimentary rocks at the contact. Hence, the intruded dolerite causes of higher hydraulic conductivity within the limestone-shale-marl intercalation unit.

Adishuhu and Hizaetiwedicheber (HWC) MDRs were selected for post construction evaluation studies as representative leaking MDRs for the region. The leakage problem is significant. Their current capacity is to irrigate about 10% and 50% respectively of their planned irrigable land (Table 6.1). Both are located in the central part of the Mekelle Outlier, 45 km to the northeast and 28 km to the southwest respectively of the regional capital Mekelle City (Figs. 6.1 & 6.2). Typical characteristics of the two MDRs are presented in Table 6.1.

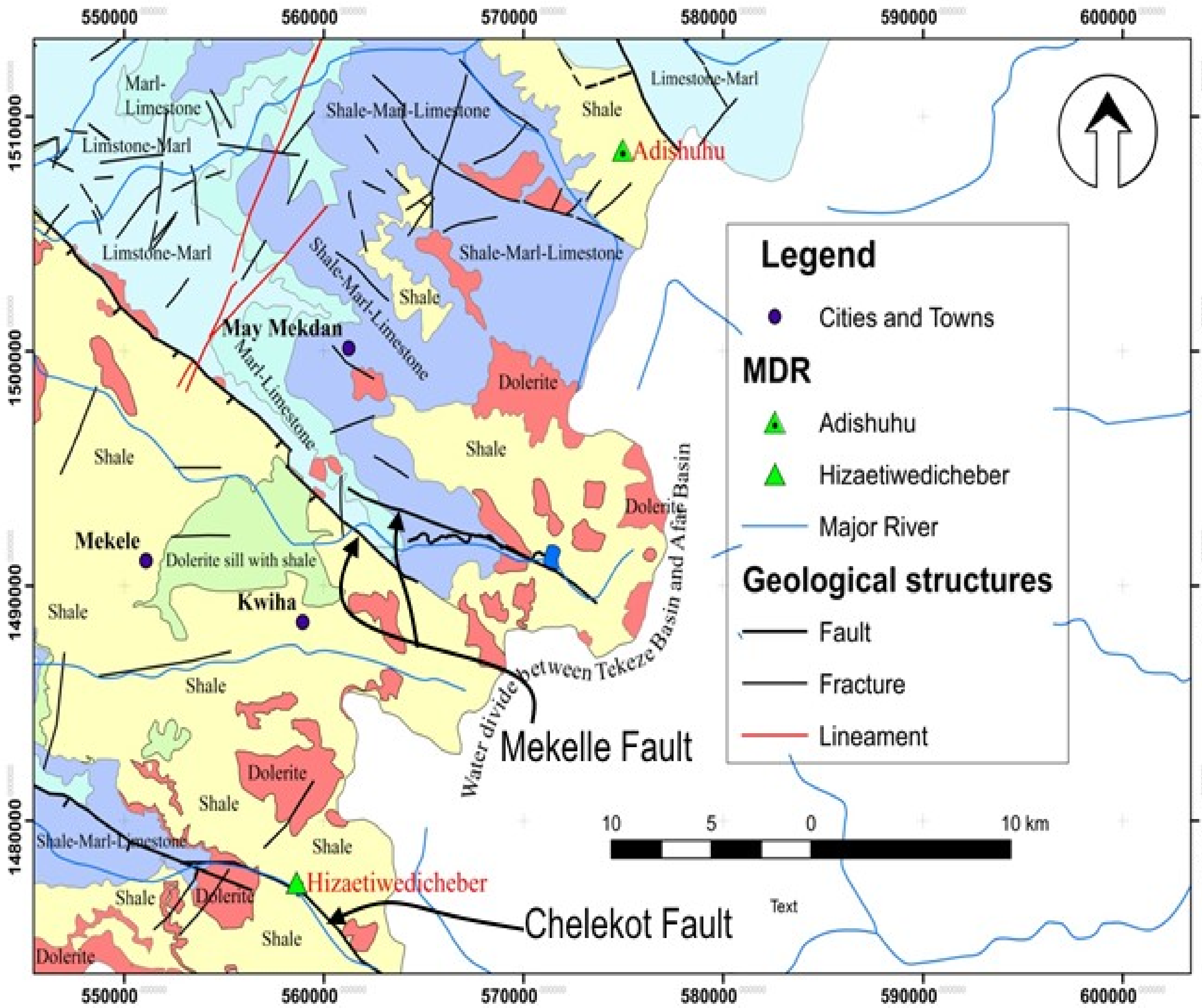


Figure 6.2. Simplified geological map of Adishuhu and Hizaetiwedicheber MDRs (modified from Gebreyohannes *et al*., 2010).

Table 6.1. Characteristic features of the two MDRs.

Name of MDR	UTM (Zone-37)		Dam height (m)	Crest length (m)	Gross capacity (Million m^3)	Designed Command area (hectare)*	Catchment area (km^2)
	X	Y					
Adishuhu	574937	1508567	10.6	495	1.0	40	9.4
Hizaetiwedicheber	558645	1477362	15.5	598	1.24	80	33

* *planned irrigable land from the reservoir*

In addition to the leakage problem, the two MDRs were selected by taking into account the following factors and criteria: (1) representative geological set-up of the area where many leaking

MDRs are found; (2) reservoirs that have sufficient inflow or availability of catchment/drainage area in relation to their storage capacity; (3) evidence of new springs and wetlands; and (4) availability of suitable land for irrigation. Moreover, specific to these MDRs is the geology; in contrast to previously investigated MDRs, where the association of dolerite with the limestone-shale-marl intercalation unit was observed to be responsible for the leakage (chapter 3 and 4), the dolerite unit is only present with small coverage at Adishuhu and non-existent at Hizaetiwedicheber. More than 75% of MDRs in Tigray are constructed at least in part on sedimentary rocks, and out of 58 MDRs solely constructed on sedimentary rocks, 36 (62%) have a leakage problem.

METHODOLOGY

The approaches used in this work include geological outcrop and structural geological mapping, geophysical survey and laboratory analysis (Table 6.2). Geological and structural studies were conducted using black and white aerial photos (1:50,000) flown in 1994 by Ethiopian Mapping Agency (EMA), existing geological maps and mapping in the field along selected routes to ascertain the existence of certain lithologies at the surface, and mapping of discontinuity structures in the field.

Table 6.2. Summary of activities and data types from Adishuhu and Hizaetiwedicheber MDRs.

Adishuhu MDR	Hizaetiwedicheber MDR
Conventional geological mapping • *Discontinuity description* • *Weathering description*	Conventional geological mapping • *Discontinuity description* • *Weathering description*
9 test pits	-
6 soil samples collected for index test	-
3 VES	3 VES
6 horizontal electrical resistivity profiling	4 horizontal electrical resistivity profiling

Detialed geological mapping (1:1000) for the dam sites, resevoirs and sourrounding areas were carried out using a grid system were profile (observation) lines were set down in N-S direction at 100 m interval while the baseline in E-W direction at both MDRs (details are given in chapter 3).

Geological logs were collected from (from Tigary Water Works Construction Engerprise (TWWCE) and Hadis, 2012) the existing boreholes around Hizaetiwedicheber to obtain information about the variation of geological units with depth. The borehole log data were utilized for identification of geological units liable to leakage in the study area.

Engineering geological field investigations were conducted by giving more attention on differentiating the sediments and rock units from groundwater circulation perspectives, focusing on engineering geological characteristics such as degree of fracturing, spacing and aperture of joints, the extent and degree of weathering, type of infill materials in the fractures, thickness of formations, size, shape, sorting of grains and proportion of clay in soils.

On the basis of these investigations sites were identified for geophysical investigations. Geophysical studies are commonly applied to assess and monitor the structural integrity of earthen dams (Bedrosian *et al*., 2012) and to detect leakage from water storage structures like MDRs. Electrical resistivity methods are most commonly used to identify zones of anomalous seepage or leakage (Bedrosian et al. 2012). Electrical resistivity profiling (ERP) is the most extensively used electrical technique for engineering applications. Horizontal resistivity profiling surveys are used to detect and map potential seepage paths (Panthulu *et al*., 2001 and references therein). Vertical electrical sounding (VES) on the other hand is used to distinguish between successive layers with contrasting resistivities as a function of depth.

The numbers of VES and resistivity profiles were determined by the suitability of topography of the selected sites. Electrical resistance of a volume of material between electrodes was measured. Geo-electrical investigation was conducted to delineate formations, distinguish between alluvial deposits and rock layers and establish the depth to the water table, so as to locate possible potential routes of groundwater circulation and identification of discontinuities. The VES and resistivity profiling were executed using Terrameter SAS (signal averaging system) 1000 manufactured by ABEM, Sweden. Detailed techniques, procedures and interpretations are presented in chapter 4.

Schlumberger configuration and Wenner array were used for VES and resistivity profiling respectively. Six VES (three at each MDR) were carried out (with half current electrode distance AB/2 ranging from 1.5 to 500 m) and a total of 10 electrical resistivity profiles.

Soil and rock descriptions, discontinuities and laboratory tests were carried out according to the methods suggested by the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM, 1978, 1981a, b). Excavation of test pits/trenches for in situ observations, exposure description and discontinuity measurements using slope face and scanline mapping methods were conducted during the course of all fieldworks.

Eight hand-dug test pits and one trench were excavated with shovels and picks at Adishuhu MDR to a maximum depth of 1.3 m due to the presence of subsurface water at shallow depth.

RESULTS

Geology of the MDRs

Quaternary deposit

Summary of the geology of the two MDRs is presented in Table 6.3. Alluvial deposits are confined to small depressions and water courses. Residual soils are also very limited in extent. The reservoir area and downstream side of the two MDRs are covered by Quaternary deposits. These deposits are observed along the course of tributaries and topographic and structurally controlled depressions and flat landforms. The alluvial sediments consist of soil grains ranging from pebbles to poorly sorted mixtures of clay, silt, and sand.

Table 6.3. Summary of the geology of Adishuhu and Hizaetiwedicheber MDRs.

Localities	Adishuhu MDR	Hizaetiwedicheber MDR
Left Abutment	Limestone-shale-marl intercalation	Limestone-shale-marl intercalation
Central Foundation	Quaternary deposit overlying limestone-shale-marl	Quaternary deposit overlying limestone-shale-marl
Right Abutment	Limestone-shale-marl intercalation and dolerite sill	Limestone-shale-marl intercalation
Reservoir	Quaternary deposit overlying limestone-shale-marl	Quaternary deposit overlying limestone-shale-marl
Spillway	Limestone-shale-marl intercalation/siltstone/dolerite	Limestone-shale-marl intercalation

Dolerite

The dolerite outcrops in the area are in the form of sills and dykes (Fig. 6.2) and are related to Oligocene flood basalt magmatism in Ethiopia (Kuster *et al*., 2005). The sills intruded mainly the upper parts of the limestone-shale-marl intercalation unit (Jurassic Shale and Limestone) and display generally concordant to sub-concordant relationship with the horizontally bedded sedimentary rocks. Erosion of the sills and dykes led to development of steep cliffs and in some places flat topography. The major flow paths within the dolerite sills seem to be the WNW-ESE aligned faults and the NNE-SSW aligned fractures which are common in the area (Gebreyohannes *et al*., 2010) (Fig. 6.2). The dolerite is medium grained, dark greenish to black in colour, highly weathered and massive (Fig. 6.3a) and in places display spheroidal weathering with the core body containing fresh and hard material. Only the right flank or abutment slope of Adishuhu is underlain by a dolerite sill, while no dolerite is observed at Hizaetiwedicheber dam axis and its reservoir. The hydraulic conductivity of the dolerite in Mekelle and the surrounding area is in the range of 0.02 to 1 m/day (Hussein, 2000), while Gebreyohannes (2009) reported about 0.13 m/day. In general the dolerite and shale layers are less pervious than the limestone.

Siltstone

Siltstone is exposed at Adishuhu at limited localities, particularly in the northern and southern part (Fig. 6.4). It is very fine grained, light yellowish in colour, weak in strength, moderately weathered and jointed. It looks platy and thinly bedded. This unit is exposed above the maximum level of the reservoir and is of little concern with regard to leakage.

Limestone-shale-marl intercalation

The limestone-shale-marl intercalation (Fig. 6.3b, c) is the major sedimentary formation found at both MDRs**.** This group is comprised of mainly shale, with minor intercalations of limestone and marl. The shale in the area is predominantly laminated with thin intercalated limestone layers that are light yellowish colour. The shale is characterized by fine grained texture, fissile and variegated colour. The unit was intruded by a network of dolerite sills and dykes of variable thickness ranging from few centimetres to kilometres at various localities in the study area. The beds are mostly horizontal (Fig. 6.3c), but inclined or tilted in the fault zone and near dolerite intrusions and shows strong anisotropy and heterogeneity in terms of hydraulic conductivity.

In some places, the shale layer is thick with small hydraulic conductivity, while the limestone layer in this intercalation is fractured and has dissolution cavities that are characterized by relatively high hydraulic conductivity. Gebreyohannes (2009) reported the hydraulic conductivity of limestone-shale-marl intercalation as 1.4 m/day in his study for the Geba basin, where the present study sites are located.

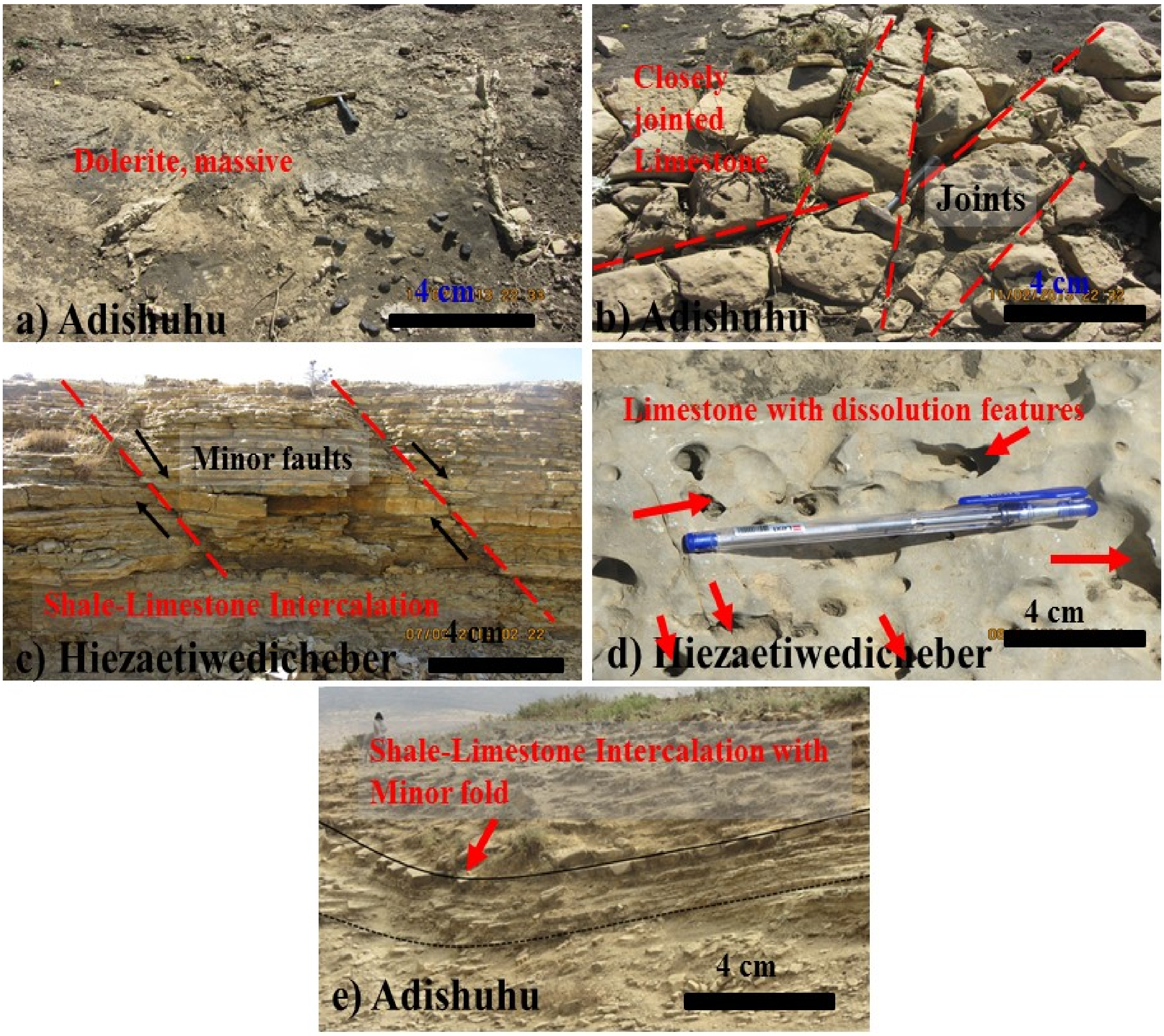


Figure 6.3. a) Outcrop of massive dolerite, b) Highly jointed limestone, c) cyclic shale-limestone intercalation with extensive horizontal joints and sub-vertical minor faults, d) Limestone with dissolution features (some of them interconnected) and e) Minor fold on shale-limestone intercalation.

Limestone

Limestone and related carbonate rocks vary widely in their suitability as foundations for dams and reservoirs. Thinly bedded, faulted, jointed and cavernous limestone presents serious problems at dams and reservoir sites (chapter 3 and 7). With reference to the MDRs, this unit was found exposed at the northern part of Hizaetiwedicheber. It is micritic in texture, black to yellowish in colour, closely jointed with many of the joints vertical and horizontal or parallel to bedding plane or unloading joints. In this unit, dissolution or karstification features were observed (Fig. 6.3d).

The limestone is the main aquifer system, with highest hydraulic conductivity values ranging from 10.6 to 31.4 m/day (Hadis, 2012).

It is important to highlight the need for adequate large scale geological mapping to evaluate the impact of small rock and soil units for the construction of dams as is clearly shown in Figs. 6.2, 6.4 and 6.5. Small outcrops, including the Quaternary deposit are omitted in Fig. 6.2 but shown on Figs. 6.4 and 6.5.

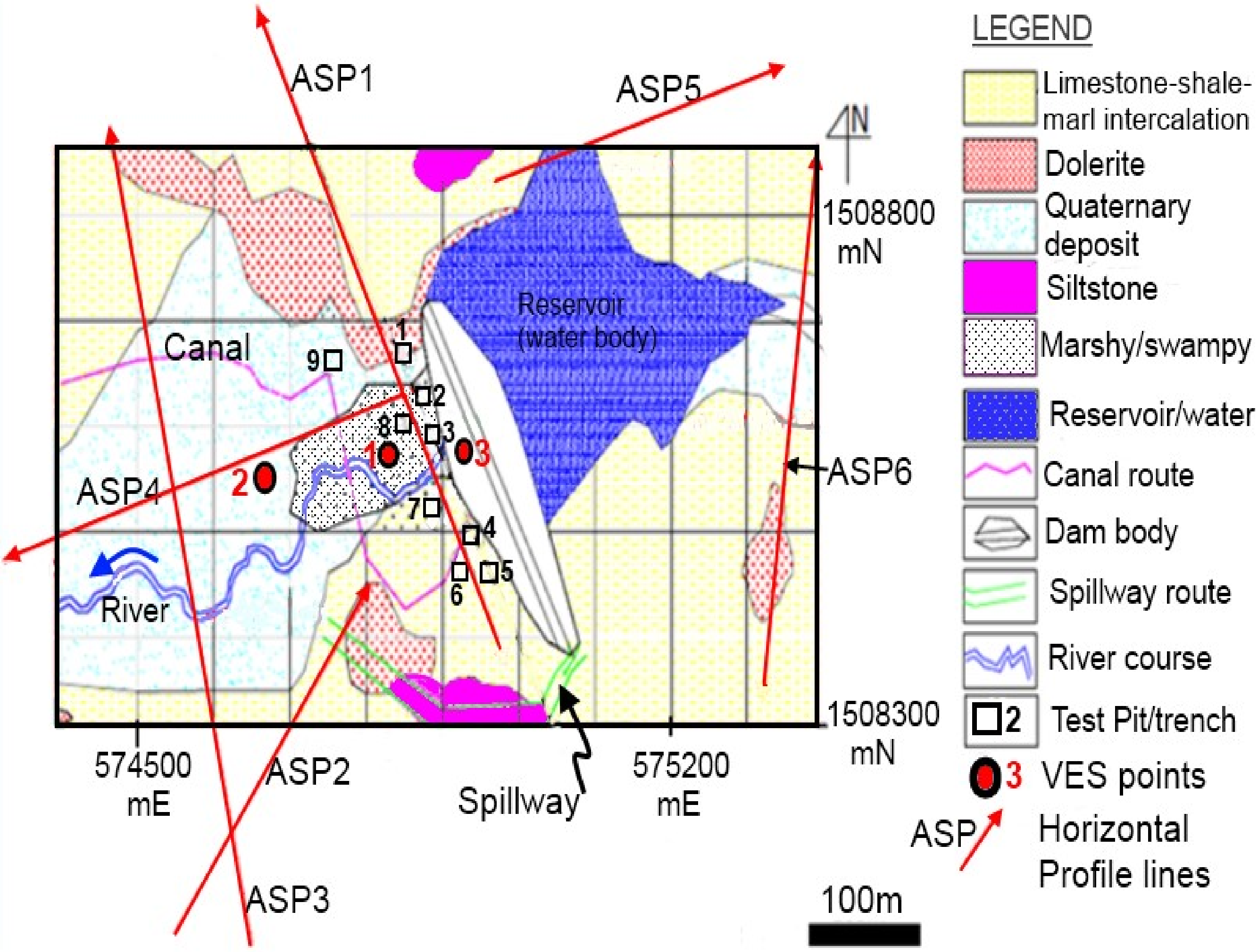


Figure 6.4. Geological map of Adishuhu MDR and its environ. Electrode spread for VES survey was in North-South direction. ASP= AdiShuhu electrical resistivity Profiling.

Geological structures

The regional Chelekot Fault passes across the dam-axis and reservoir area of Hizaetiwedicheber MDRs (Fig. 6.2), but no regional fault was observed at Adishuhu MDR. Evidence of slickensides and other minor faults (Fig. 6.3c) were observed at Hizaetiwedicheber. Major geological structures with orientations of N-S, E-W and NW-SE are common (Fig. 6.2). Hadis (2012) also reported similar geological structures in the area.

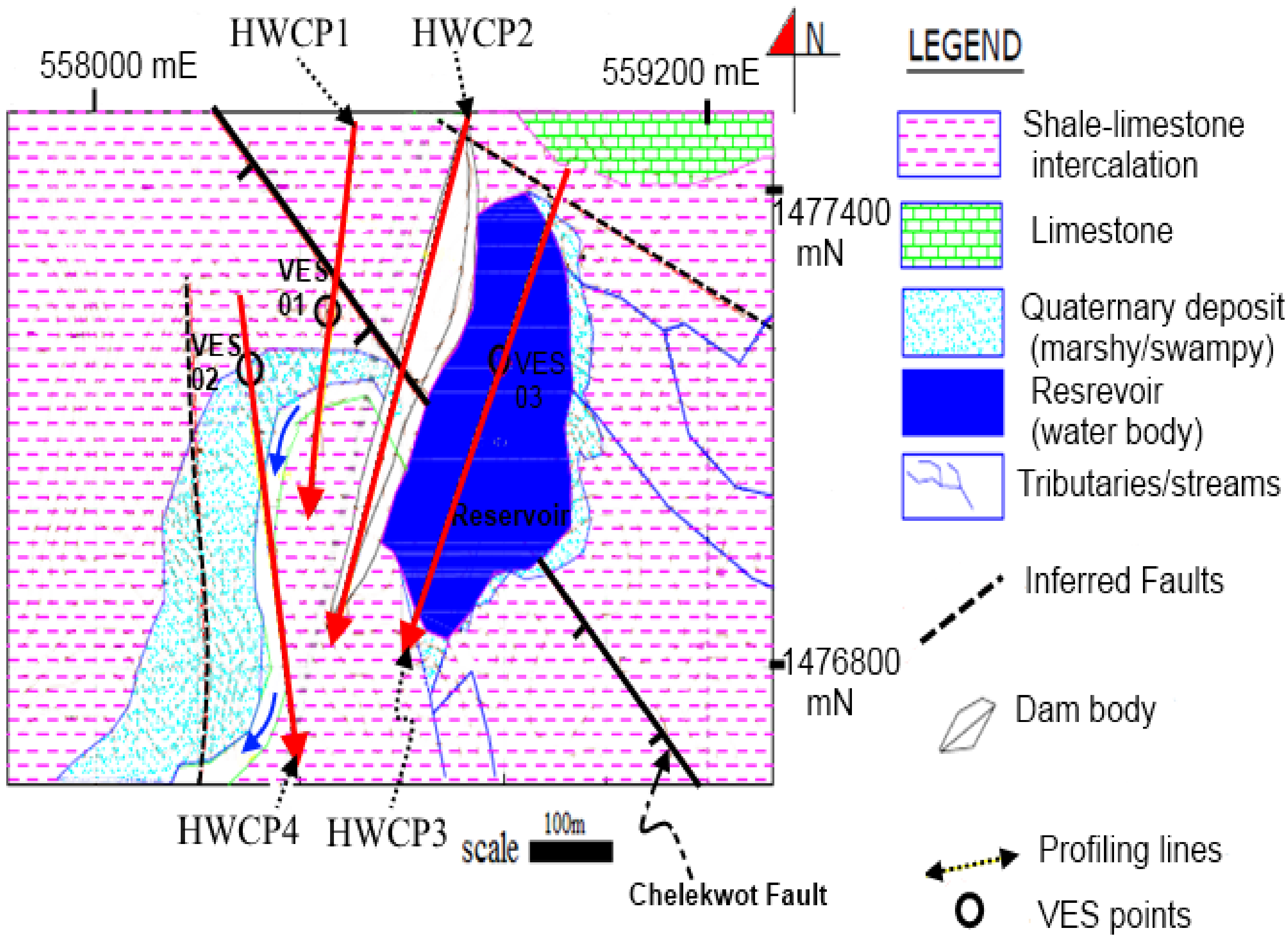


Figure 6.5. Geological map of Hizaetiwedicheber MDR and its environ. HWCP= Hizaetiwedicheber electrical resistivity Profile.

Joints are common in the study area (Fig. 6.3b, c). The strikes of the joints are generally parallel to the faults of the area and seldom perpendicular. Most of the joints are vertical or perpendicular to the horizontal bedding planes and some of them are horizontal or parallel to bedding planes.

Minor folds are also observed resulting from dolerite intrusion or tectonic effects. These structures were observed at both sites; in the case of Adishuhu these structures are found near the spillway route (Fig. 6.3e) and at Hizaetiwedicheber on the upstream side of the reservoir along a river bank. Table 6.4 presents discontinuity parameters collected from both MDRs (abutments and periphery of the reservoirs).

For Adishuhu, joint sets J1 and J2 are more or less perpendicular to the dam axis while J3 and J4 intersect the dam axis (N25°W) at different angles (Fig. 6.6a). This kind of pattern in relation to the dam axis direction plays an important role in determining leakage potential next to the bedding planes. The bedding planes are tight compared to the joints. Similarly, for Hizaetiwedicheber, all the joint sets intersect the dam axis (N20°E) at various angles (Fig. 6.6b). This is explained by the fact that the strike of most of the discontinuities at Hizaetiwedicheber is parallel or sub-parallel to the major Chelekot fault strike. It is also clear that at their intersections, the apertures are wide and have high connectivity for water circulation and leakage.

Not only the strike direction, but also the dip directions play an important role for leakage and stability of the MDRs. Joint sets J1 and J3 at Adishuhu dip downstream, i.e. in a favourable direction for leakage potential. At Hizaetiwedicheber, only J3 dips parallel to dam axis (N20°E) while all the remaining discontinuities are dipping toward the downstream direction or away from storage or reservoir area. There was no evidence in the field for water leakage along the periphery of both reservoirs, but leakage toward the downstream underneath the dam body was indicated by the presence of many springs, marshy areas, flowing small streams etc. which were either non-existent before construction of the MDRs, or have increased in size and discharge.

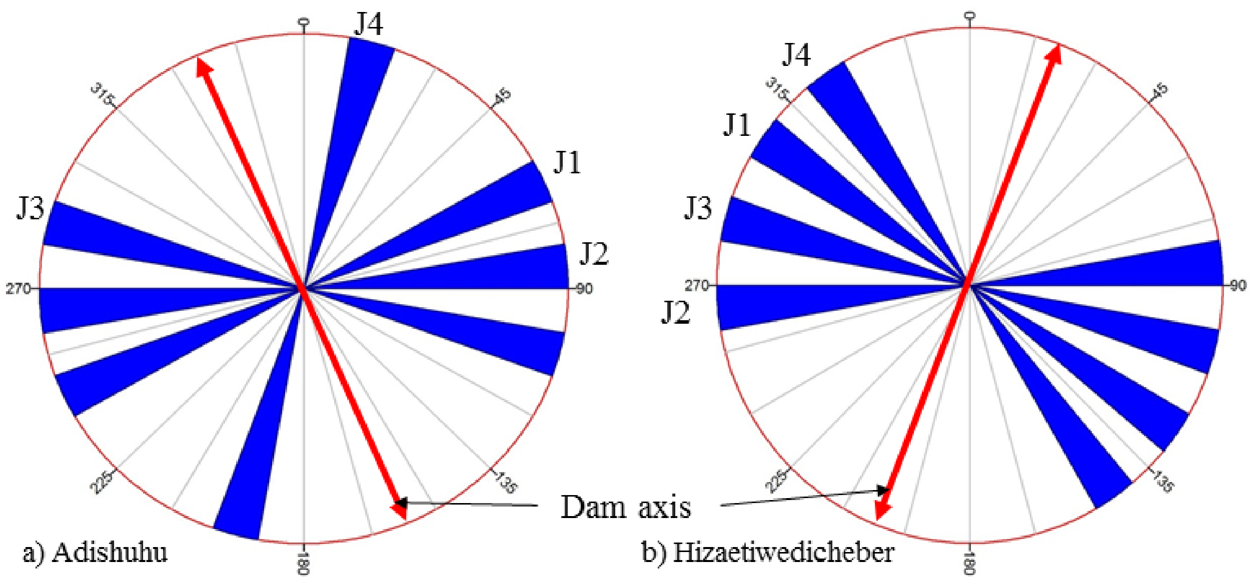


Figure 6.6. Rose diagram of the most common joint sets at both MDRs. Orientation of dam axis is indicated.

Table 6. 4.Typical characteristics of discontinuities from the two MDRs.

Joint Set	Strike	Dip/dip direction	Spacing (m)	Persistence (m)	Aperture (mm)	Rock type	Location*
Adishuhu MDR							
J_1	065°	10°/155°	0.2-1.2	<2	~ 2	Limestone-shale-marl	RA
J_2	080°	15°/350°	0.6-2.5	<0.5	~ 1	Limestone-shale-marl	LRR
J_3	280°	80°/190°	3	<1	~ 1	Limestone-shale-marl	LA &RA
J_4	010°	10°/100°	0.1-0.15	2-3	~ 2	Limestone-shale-marl	LA &RA
Hizaetiwedicheber							
J_1	300°	20°/210°	0.5-1.3	2.5	~ 2	Limestone-shale-marl	LA & RA
J_2	080°	12°/170°	0.5-1.3	3	~ 3	Limestone	LA & RA
J_3	280°	60°/10°	0.6	1	~ 1	Limestone-shale-marl	LA
J_4	320°	15°/230°	1	2.6	~ 2	Limestone-shale-marl	LA

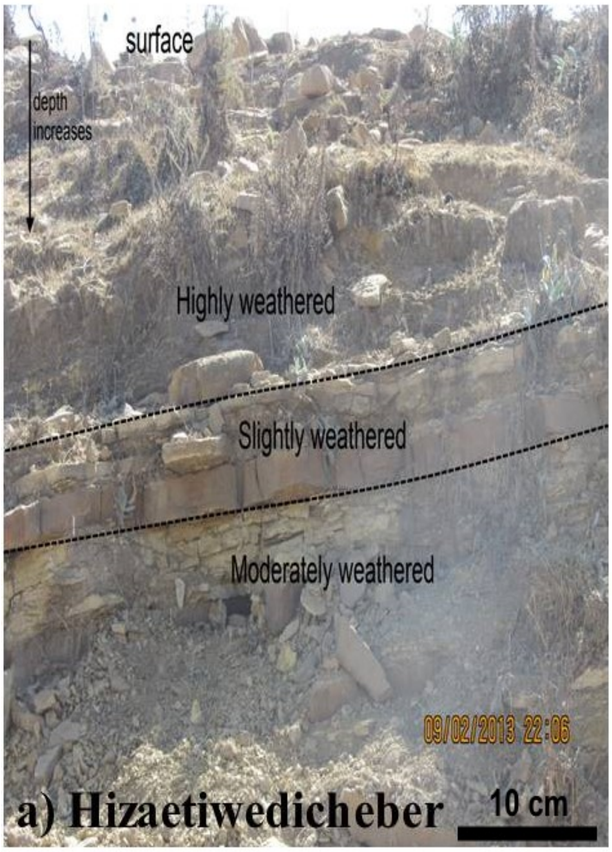
*Note: RA= Right abutment, LRR= Left rim reservoir, LA= Left abutment

Weathering

The assessment of rock weathering is a problem which is repeatedly faced by engineers in foundation design (Saunders and Fooks, 1970) and in water harvesting structures. The process of weathering produces significant changes in almost all the chemical and physical properties of a rock, and it is widely recognized that these processes have an effect on the engineering properties of a rock mass. The general characteristic of residual soils is the large variability of their engineering properties (e.g. hydraulic conductivity) both vertically and horizontally in the weathering profile.

Weathering is an important factor that determines the presence of porosity and hydraulic conductivity. Hydraulic conductivity and porosity vary with degree of weathering and not necessarily with depth. The variation is also a function of clay content and fracturing. These variations were observed in hand dug test pits, natural rock exposures and geophysical survey results (Figs. 6.7 & 6.8).

Hydraulic conductivity commonly increases with depth in the weathering profile, until sound rock is found, where low hydraulic conductivities are usually encountered. Superficially, residual soils allow fractures to remain open, resulting in easier penetration of water and hence higher permeability (Fookes, 1997). In cyclically stratified rocks of different types, the variability is even more complex. The degree of weathering varies not necessarily with depth (Fig. 6.7), i.e. it is possible to find highly weathered rock mass at greater depths than where moderately weathered rock mass is encountered. This variation, which is attributed to various factors (e.g. rock type, clay content, porosity, etc.), is common at the two MDR sites (Fig. 6.7).



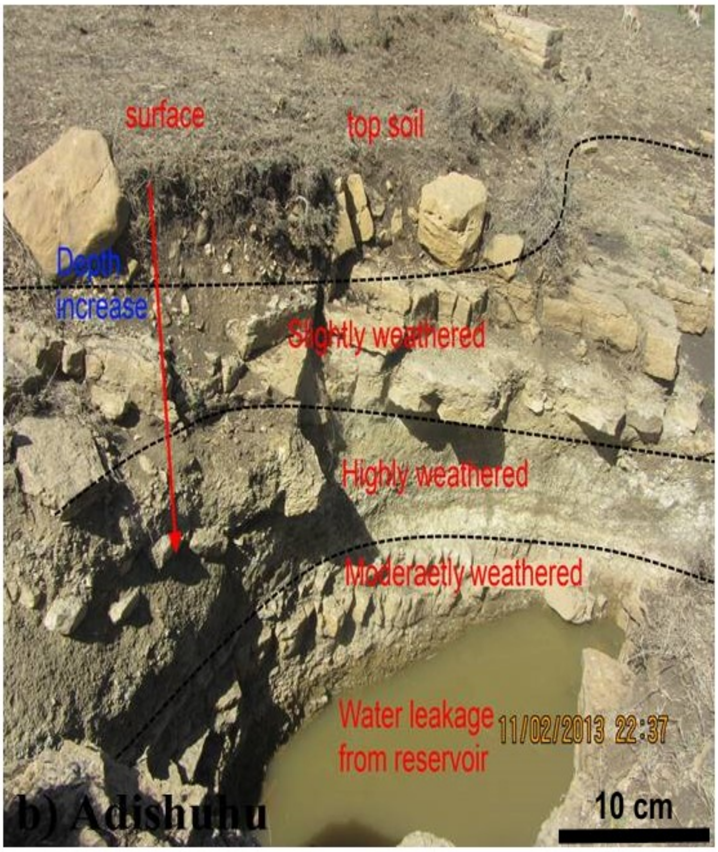


Figure 6.7.Weathering variability of rocks with depth a) Hizaetiwedicheber and b) Adishuhu.

Test pit and laboratory results from Adishuhu MDR

From the test pits and trenches excavated at Adishuhu, six soil samples were collected for laboratory analysis (Table 6.5). Using the unified soil classification system (Venkatramaiah, 2006), the soil samples were classified into CL (clay of low plasticity), MH (elastic silt), GW (well-graded gravel), GM (silty gravel) and SW-SM (well graded sand with silt and gravel) (ASTM, 2006) (Table 5). The plasticity ranges from non-plastic to medium plastic with a plasticity index ranging from 0 to 26.6%. According to the description of plasticity of fine soils in terms of range of the plasticity index (IAEG 1981), the clayey soils are low to medium plastic, while the well-graded gravel (GW), silty gravel (GM) and well graded sand (SW-SM) soils are non-plastic. This indicates that the non-plastic materials, which are weathering products of the underlying bedrock, are relatively pervious.

Table 6.5. Summary of laboratory test results from Adishuhu MDR (for location of test pits see Fig. 6.5) (LL= Liquid Limit; PL= Plastic Limit; PI= Plasticity Index). Log and field photo of test pits are included in Appendix C6 on CD.

Test Pit	Depth (m)	Lithologic Type	LL (%)	PL (%)	PI (%)	Grain size (%)				Origin	USCS
						Gravel	Sand	silt	Clay		
TP1	0.2-1.0	Weathered dolerite	Non-plastic			54	16	27.1	2.9	residual	GW
TP2	0.5-1.3	Limestone-shale-marl	53.1	28.9	14.6	13.6	3.4	13.4	69.6	residual	MH
TP3	0.5-1.0	Black clay soil	39.7	25.1	26.6	5.0	1.14	3.83	81.7	alluvial	CL
TP4	0.5-1.0	Black clay soil	46.6	20	24.2	13.6	3.4	13.4	69.6	alluvial	CL
TR5	0.2-0.6	Dolerite	Non-plastic			51	16	16.6	16.4	residual	GM
TP6	0.6-1.2	Limestone-shale-marl	Non-plastic			20	72	6	1	residual	SW-SM

Geophysical Survey

VES and EP results from Adishuhu and Hizaetiwedicheber MDRs

The VES field data were interpreted using IPIwin2 software to obtain the resistivity of the near subsurface and subsequently interpret possible lithologic units. All interpretations of VES and ERP are based on field observations and geological knowledge of the area (including borehole logs in the larger surroundings), but were not supported by drilling data at the sites themselves. There were neither existing boreholes at the VES points nor at nearby area. The resistivities of various layers of interpreted models and their corresponding thicknesses are shown in Tables 6.6 and 6.7. The maximum half-current electrode separations (AB/2) used at Adishuhu were 150 m, 220 m and 500 m for AS-VES-3, AS-VES-1 and AS-VES-2 respectively, while 220 m was used for all VESs at Hizaetiwedicheber. Very good fitting (RMR<5%) was obtained between the observed and model data for all soundings. Raw data of VES and Electrical Profiling are included in Appendix C6 on CD.

AS-VES-2 was located downstream of Adishuhu MDR on relatively swampy ground and shows a three layer structure. The first and second layers show a highly conductive material: based on local geology, it corresponds to saturated silty clay and cyclic limestone-shale-marl intercalation units. The third layer which is relatively resistive is interpreted as slightly weathered limestone-shale-marl intercalation and dolerite sill units. Similarly, the other VESs are interpreted as shown in Tables 6.6 and 6.7.

Table 6.6. Interpreted layers (resistivity, thickness and depth to bottom of layer) in the electrical model at Adishuhu MDR.

Layers	Resistivity value (Ω.m)	Layer thickness (m)	Depth (m)	Altitude (m)	Interpreted lithology
	AS-VES-1(maximum AB/2= 220m)				
1	81.1	0.674		2287.7	Dry silty clay (Quaternary deposit)
2	9.97	9.76	0.674	2287	Saturated cyclic limestone-shale-marl layers
3	56.4	-	10.4	2278	Slightly weathered cyclic limestone-shale-marl
	AS-VES-2 (maximum AB/2= 500m)				
1	1.38	0.0857		2097.1	Saturated silty clay
2	16.3	37.8	0.0857	2097	Saturated cyclic limestone-shale-marl layers
3	235	-	37.9	2059	Slightly weathered limestone-shale-marl and dolerite
	AS-VES-3 (maximum AB/2= 150m)				
1	106	0.768		2297.8	Dry compacted soil (dam body)
2	6.5	0.434	0.768	2297	Saturated silty clay soil
3	16.7	21.9	1.2	2296.6	Saturated cyclic limestone-shale-marl layers
4	63.5	-	23.1	2274.7	Slightly weathered cyclic limestone-shale-marl

EP results from Adishuhu and Hizaetiwedicheber MDRs

Resistivity profiling using Wenner configuration with a 60 m current electrode separation (i.e. a=20 m) at Adishuhu and 90 m current electrode separation (a=30 m) at Hizaetiwedicheber were performed to map the variation of resistivity approximately at 20 m and 30 m depth respectively. Traverses were made in different directions but mainly parallel to the dam axis or perpendicular to river courses. The variations of apparent resistivity with distance are shown in Figs. 6.8 and 6.9 and their locations are shown in Figs. 6.4 and 6.5.

Table 6.7. Interpreted layers (resistivity, thickness, depth to bottom) in the electrical model at Hizaetiwedicheber MDR.

Layers	Resistivity value (Ω.m)	Layer thickness (m)	Depth (m)	Interpreted lithology
HWC-VES-1 (maximum AB/2= 220m)				
1	20.4	0.747		Dry silty clay (Quaternary deposit)
2	1.99	1.02	0.747	Saturated Quaternary deposit (silty clay)
3	23.2	47.6	1.76	Saturated cyclic limestone-shale-marl layers
4	73.4	-	49.4	Slightly weathered cyclic limestone-shale-marl
HWC-VES-2 (maximum AB/2= 220m)				
1	8.67	4.44		Partially saturated silty clay
2	2.61	5.51	4.44	Saturated cyclic limestone-shale-marl layers
3	63.3	-	9.85	Slightly weathered limestone-shale-marl& dolerite
HWC-VES-3 (maximum AB/2= 220m)				
1	21	0.745		Dry sediment at the floor of the reservoir
2	1.76	0.856	0.745	Saturated and pervious bed rock (moderately weathered limestone-shale-marl)
3	22.1	43.4	1.6	Slightly weathered cyclic limestone-shale-marl layers (pervious)
4	71	-	45	Slightly weathered cyclic limestone-shale-marl& dolerite

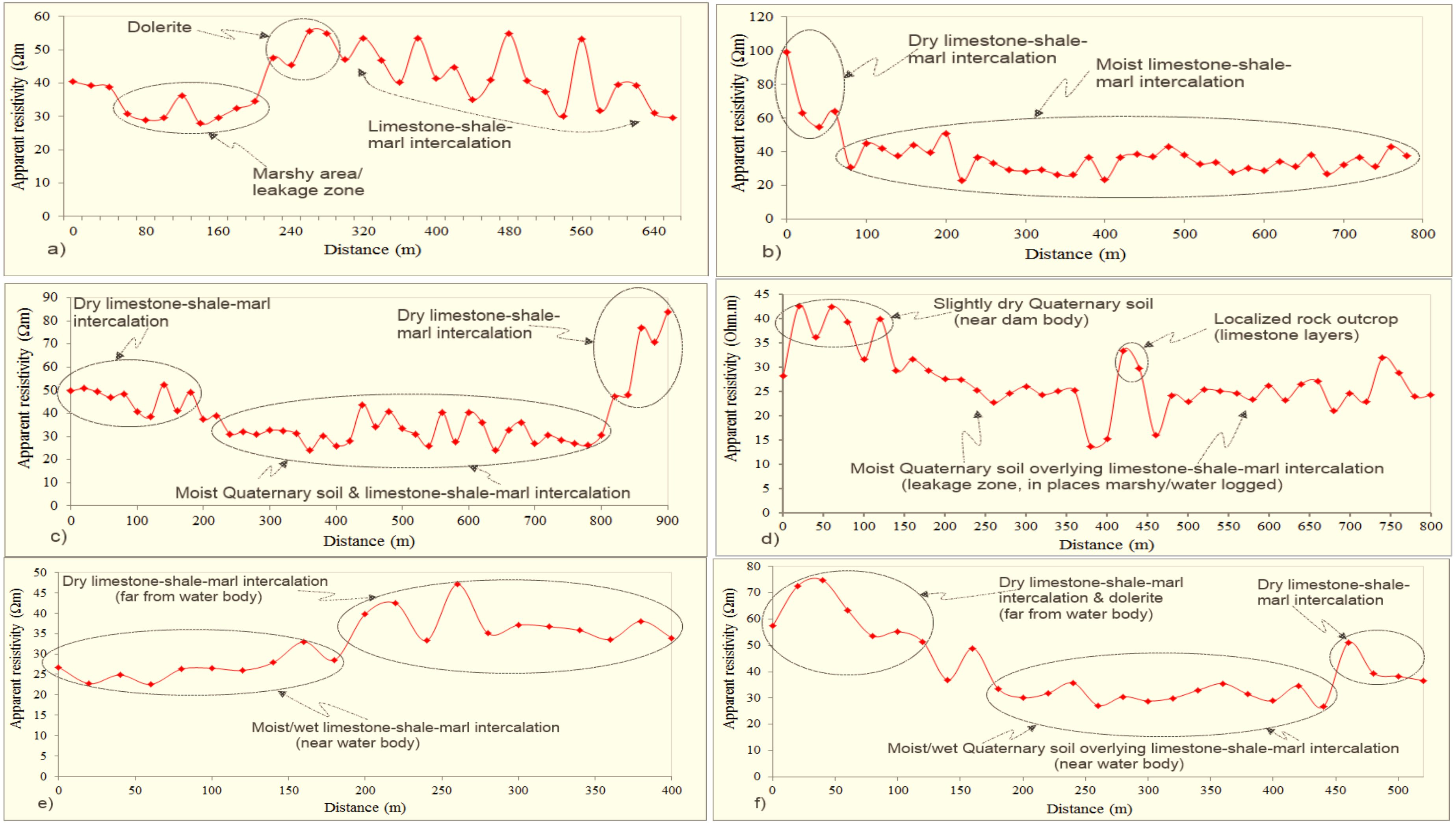


Figure 6.8. Resistivity profiling plot for Adishuhu MDR: a) ASP1 (SE-NW), b) ASP2 (SW-NE), c) ASP3 (SSE-NNW), d) ASP4 (NE-SW), e) ASP5 (SW-NE) and f) ASP6 (SSW-NNE). For locations see Fig. 6.4.

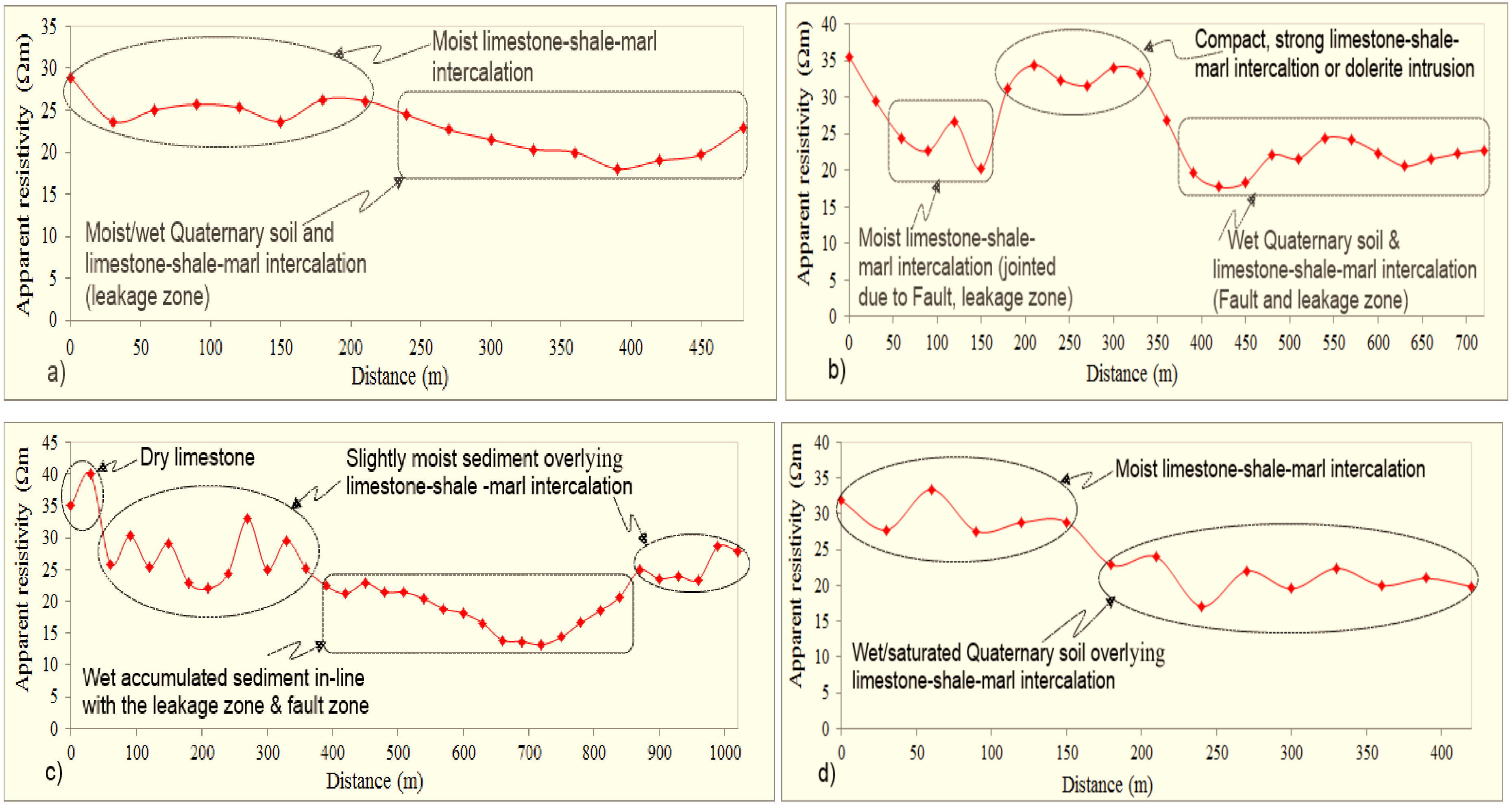


Figure 6.9. Resistivity profiling plot for Hizaetiwedicheber MDR. a) HWCP1, b) HWCP2, c) HWCP3 and d) HWCP4, orientation is in N-S direction for all profiles. For location see Fig. 6.5.

DISCUSSION

The geoelectrical cross-sections produced for both MDRs (Figs. 6.10 and 6.11), supported by the geological and structural mapping, illustrate the situation of leakage and geological set up of the dam sites and their environs. The 2-dimensional mechanism of leakage or subsurface water circulation was interpreted from the cross-sections. It shows that leakage or flow of water immediately below the dam foundation to a depth of about 10 to 15m is very high. The finding of the geophysical surveys is also supported by field observations (marshy/water logged, new springs). In addition, the test pits excavated at Adishuhu MDR suggest water leakage from the reservoir due to the presence of water at shallow depth next to the dam body.

The geoelectric cross-sections produced for the two MDRs have distinct features which reflect the actual geology in the ground. The various layers at Adishuhu are generally horizontally stratified, while in the case of Hizaetiwedicheber, the layers deviate from the horizontal and show presence of minor faulting. This can be explained in relation to the regional and local geology of the two sites.

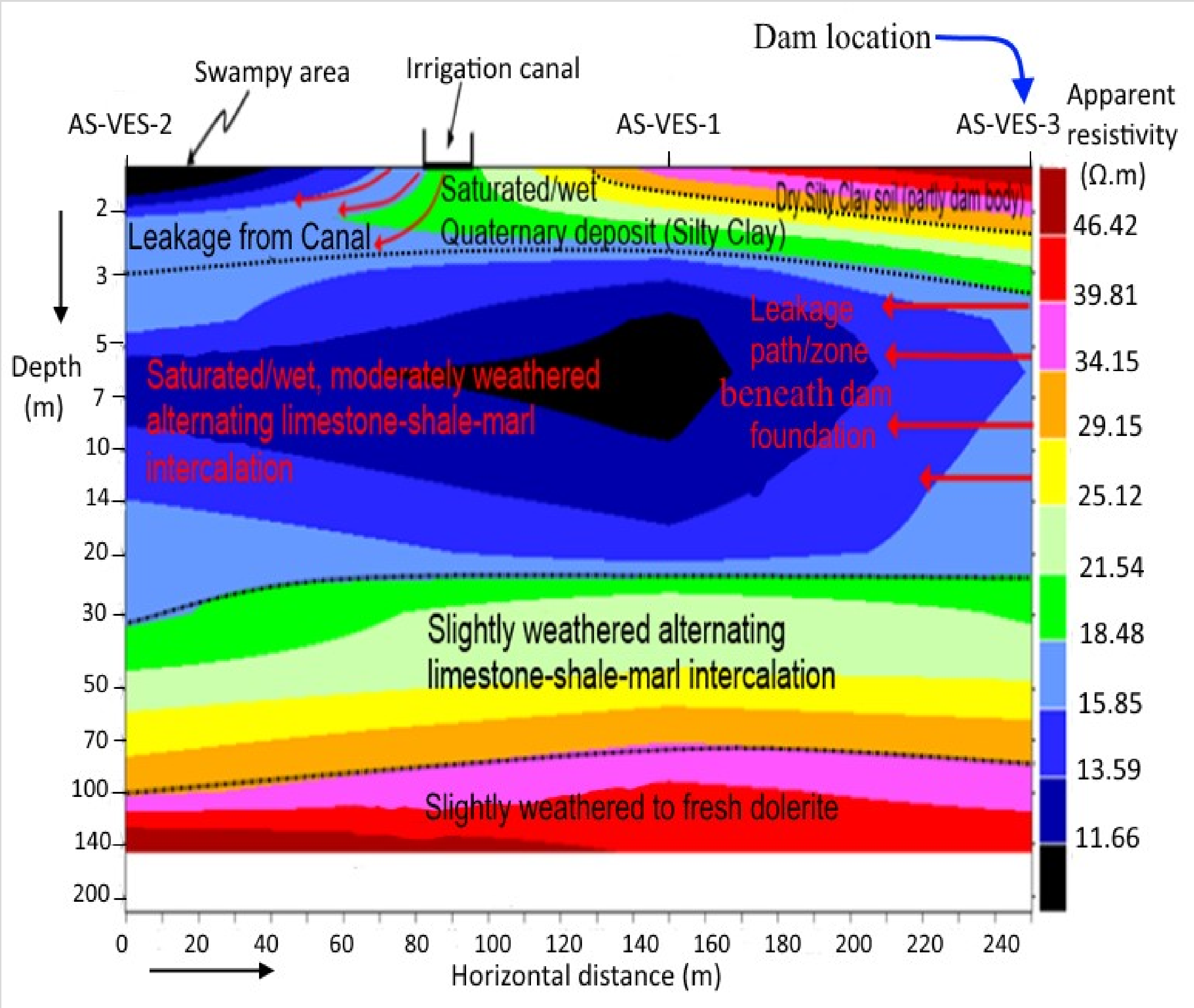


Figure 6.10. Geoelectrical cross-section along three VES from Adishuhu MDR (for location of VES see Fig. 6.4). Horizontal distance from AS-VES-2 to AS-VES-3 (at dam body). Location of dam is near AS-VES-3.

In the case of Adishuhu dam site, there is no significant geological structure and rocks are less disturbed, while in the case of Hizaetiwedicheber dam site, a major regional fault (Chelekot Fault) cross-cuts the area (Figs. 6.2 and 6.5). So, the spatial and vertical variations in orientation of the different resistivity layers are explained by the geological structures at the dam sites. Field observations confirmed the presence of minor faults and intensive fractures at Hizaetiwedicheber in deep exposures within the river banks (Fig. 6.3c).

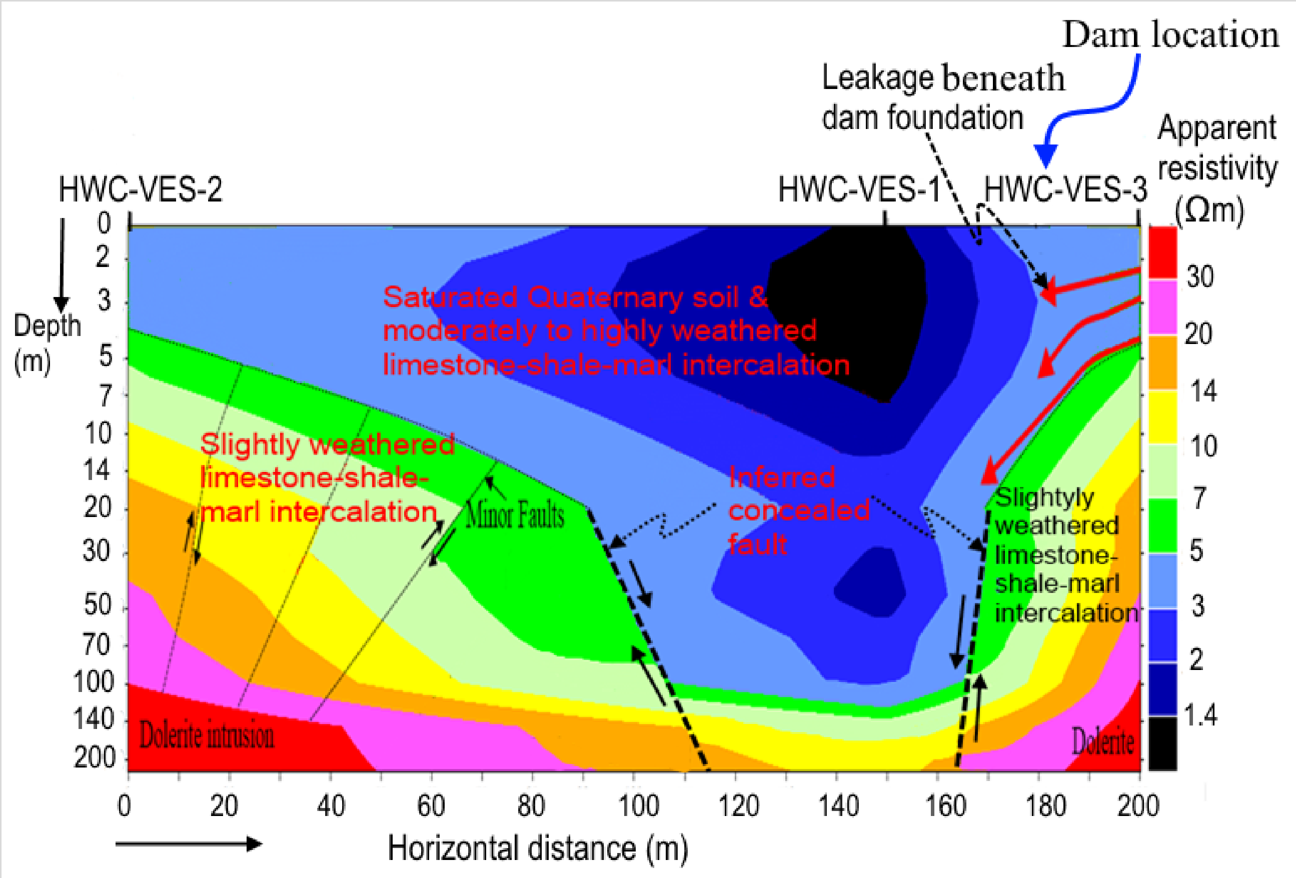


Figure 6.11. Interpreted geoelectric cross-section along three VES from Hizaetiwedicheber MDR (for locations of VES see Fig. 6.5. Horizontal distance from HWC-VES-2 to HWC-VES-3 (at reservoir). Location dam is between HWC-VES-1 and HWC-VES-3.

Unlike VES survey, the ERP survey was conducted for qualitative evaluation. In all profiles, except ASP5 and ASP6 (Fig. 6.8), the low resistivity or conductive zones were attributed to leakage or subsurface water flow and minor fractures. The low resistivity localities at ASP5 and ASP6 are explained by the likely presence of moisture in the periphery of the reservoir in the upstream side. The low resistivity zones correspond to the tributaries where moisture is relatively high in comparison to areas away from the tributaries or streams. At ASP2, the resistivity increases away from the downstream side of the dam, the immediate downstream of the dam being a conductive zone due to subsurface circulation of water from the reservoir. Another interesting pattern is shown at ASP4: the resistivity values along this profile were generally lower (more conductive) than the other profiles. This profile starts at the downstream toe of the dam, following the possible leakage path. The low resistivity portrayed by this profile is explained by fractured rocks and subsurface water from the reservoir. Field observations, including the presence of swampy ground, intermittent springs along the stream, flow of water along the stream, which appeared after the construction of the MDR, confirmed the results obtained from the geophysical survey.

Looking at profile plots of ASP1 and ASP3 on Fig. 6.8, the low values in apparent resistivity in both cases correspond to leakage zone (moist/marshy Quaternary soil and limestone-shale-marl intercalation unit) and the higher values are interpreted as dry limestone-shale-marl intercalation unit and localized dolerite unit at ASP1. The shale layer and minor fractures play important role for the slight variations in resistivity in the limestone-shale-marl intercalation unit.

The plots of the resistivity profiles taken at Hizaetiwedicheber MDR (HWCP1, HWCP2, HWCP3 and HWCP4) are presented in Fig. 6.9. Similarly, the axis of the minimum resistivity zone corresponds to the leakage zone or path for HWCP1, HWCP2 and HWCP4, while the low resistivity zone for HWCP3 is attributed to saturated/wet sediment accumulated within the reservoir (Fig. 6.5). The low resistivity values at this MDR are also influenced by the fault zone (Chelekot fault) and its impact on surrounding rocks. In general the leakage zone at this MDR corresponds with the alignment of the regional Chelekot fault. Along the fault water circulates via fractures most easily than in compact, less fractured rocks in the area. Some boreholes and hand dug wells were also observed to be productive along this fault and other joints. All field observations and the geophysical results suggest that the hydraulic conductivity of the geological materials along the Chelekot fault is higher than the surrounding.

The VES and the electrical resistivity profiling survey data collected and interpreted have shown similar trends with low resistivity values (anomalies) along the leakage zones/paths from the reservoir water in both MDRs. The maximum apparent resistivity value recorded at Hizaetiwedicheber is about 40 Ωm while at Adishuhu an apparent resistivity value up to 60 to

100 Ωm was recorded. This variation is explained by the presence of dolerite outcrops at Adishuhu MDR, raising the resistivity.

From the reported hydraulic conductivities for different formations, it can be concluded that the dolerite and shale layers are less pervious than the limestone. Hence, the limestone layers in the limestone-shale-marl intercalation unit must be responsible for the leakage of the MDRs. In addition, the weathered and fractured top part of all units was found to be pervious and liable to leakage.

Lugeon value or hydraulic conductivity of the leaky and non-leaky rocks was not determined specifically at the two MDRs. Hydraulic conductivity was estimated from discontinuity data at Hashenge MDRs (in the same region) for non-leaky dolerite unit to be about 2.06×10^{-6} cm/s and for leaky limestone-marl-shale intercalation unit about 4.19×10^{-1} cm/s. A Lugeon value ranging from 210 to 440 was obtained at the same site for the intercalation unit with higher joints and karastic features (chapter 3).

Field observations and local interviews at both MDRs confirmed that at higher water levels in the reservoirs, the leakage area is wide and extends towards abutments, while at low water levels the areal extent of leakage shrinks towards the toe of the MDRs, and the leakage at the toe of the MDRs also ceases when the reservoir runs dry. This cyclic phenomenon related to water level in the reservoir suggests a strong hydraulic connection between the reservoir and leakage zones downstream of the MDRs. Figure 6.12 shows a simplified delineation of the leakage zones for both MDRs. Most of the low resistivity zones or anomalies for the EP coincide with the leakage zones.

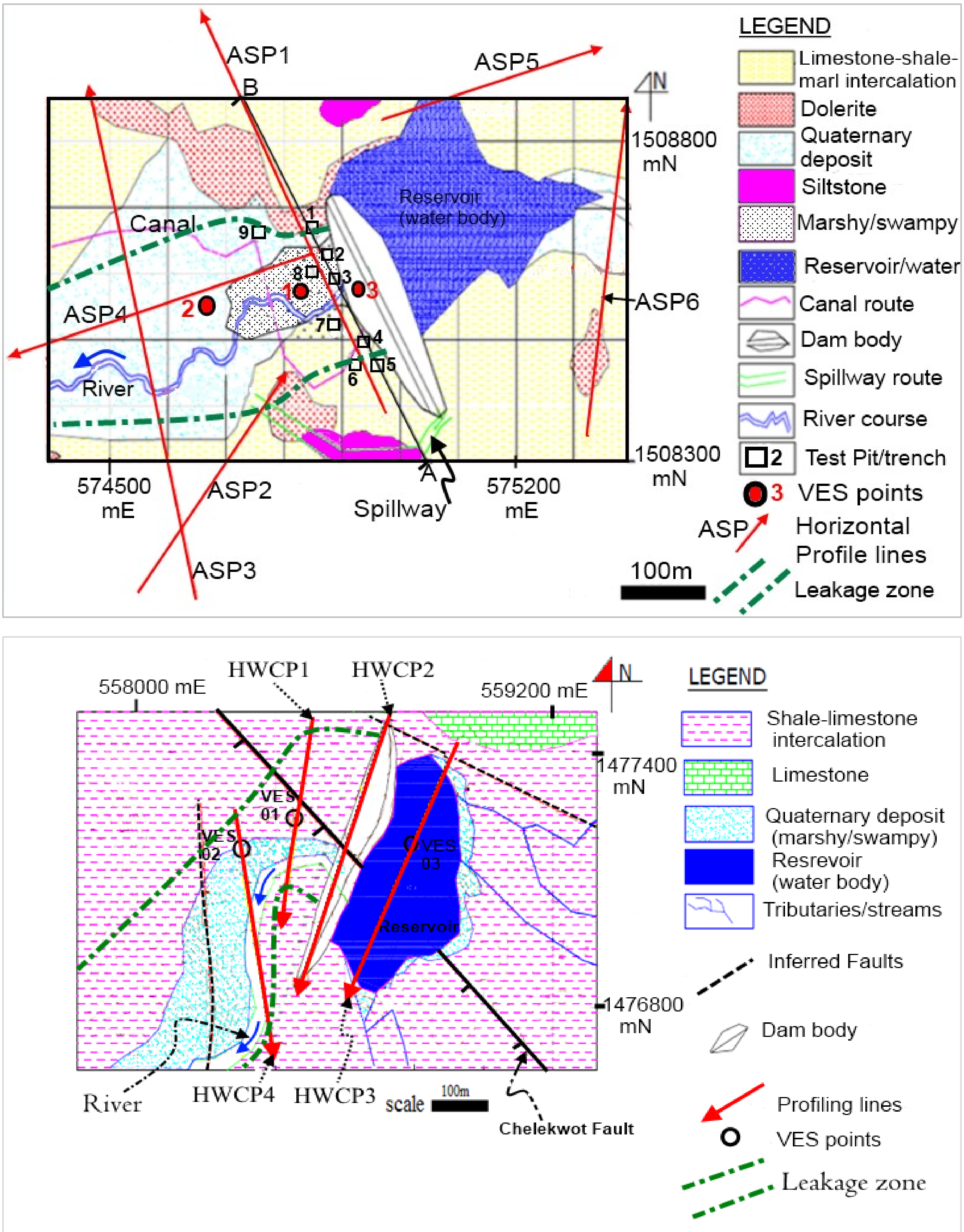


Figure 6.12. Leakage zone delimited based on geological, geophysical and hydrogeological information (top Adishuhu and bottom Hizaetiwedicheber).

CONCLUSION AND RECOMMENDATION

The regional and local geology and hydrogeology have played a major role in the planning, design, construction and performance of the MDRs. The MDRs (dam site and reservoir) are situated in an area underlain by Upper Jurassic Agula Formation, consisting of limestone, shale and marl and Quaternary soil deposits. In the case of Adishuhu MDR a dolerite sill underlies part of the right abutment. The dam axis intersects a fairly wide valley of cyclic limestone-shale-marl covering the abutment slopes and alluvial valley floor.

The observed joints, weathering and bedding planes, which form horizontal discontinuities at both MDRs and the fault at Hizaetiwedicheber MDR had play a major role in influencing rock mass hydraulic conductivity. The intrusion of dolerite into the limestone-shale-marl intercalation unit in Adishuhu MDR resulted in the development of fractures which increased the porosity and permeability of the formation. However, even in the absence of dolerite, leakage still occurs (as shown by Hizaetiwedicheber MDR). Water leakage through the foundation bedrock was detected by geo-electrical survey methods with the support of direct geological field data. Anomalous patterns in recorded data indicate potential leakage paths. Spatial distributions of the anomalies indicate a strong connection between the reservoirs and leakage areas in the downstream areas of the MDRs through pervious rocks.

It was concluded that the foundations of both MDRs, except the right abutment for Adishuhu (dolerite), are pervious due to the presence of thin bedding planes, joints, weathered materials and the fault at Hizaetiwedicheber MDR. The presence of water downstream at the toe of the MDRs, in depressions, and also in existing test pits and test pits excavated during the present study, which lie within the seepage zone demarcated during surface geological mapping, also confirms the electrical resistivity survey results.

Monitoring the reservoir levels using divers and the leakage flow downstream of the MDRs using current meter is highly recommended for better quantitative understanding of the problem. The result will help in providing best anti-leakage measures in the future. Regular follow up on the stability of the dam bodies using topographic surveying is highly recommended. Signs of cracks and settlements were observed on the dam bodies of both MDRs, but this is more serious at Hizaetiwedicheber MDR. This is just an early warning. Once leakage develops into preferential channeled flow, the potential for collapse become significant.

Considering the geology of the area shale and dolerite are more suitable as foundation and reservoir site for MDR from leakage point of view. The other rock units can be considered provided they are massive. A geophysical survey integrated with other techniques (test pits, drilling) is helpful in identification of water tight sites.

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Contribution of authors

Name of author	**Role of the author in this chapter**
Gebremedhin Berhane	*Was responsible for all the aspects of the study, data collection, VES & profiling layouts, interpreation and writing the article/chapter*
Mogos Amare	*Contributed for most of data collection in the field as part of his M.Sc. research together with and under the academic supervision of Gebremedhin Berhane*
Tesfamichael Gebreyohannes	*Provide logistical and technical support during fieldwork*
Kristine Walraevens	*Was the supervisor in the study, and critically reviewed and approved the article*

Partial view of Geba proposed dam site (from NNW to SSE direction) a trench on the left abutment is shown near the center of the photograph. The author has participated in this project as senior engineering geologist during drilling and pressure test operations ©2009 Gebremedhin Berhane.

CHAPTER 7

Geological challenges in constructing the proposed Geba dam site, northern Ethiopia

This chapter is based on Gebremedhin Berhane and Kristine Walraevens (2013). Geological challenges in constructing the proposed Geba dam site, northern Ethiopia. Bull Eng Geol Environ 72:339–352. DOI 10.1007/s10064-013-0480-9.

ABSTRACT

It is proposed to construct a dam across the Geba River, Ethiopia. The paper reports the engineering geological investigations undertaken, including mapping, discontinuity surveys, core drilling, water absorption testing and sampling for laboratory tests. The complexity of the site, with limestones and interbedded limestone-shale horizons, is indicated by the variability of the RQD and Lugeon values. Of the 63 tests undertaken, some two-thirds had Lugeon values implying grouting was necessary. Following removal and replacement of the alluvial deposits in the central area, a grout curtain including two to three rows of grouting holes was recommended to a depth of 100 m for the left abutment, 35 m for the central foundation and 60 m for the right abutment.

INTRODUCTION

One of the most important environmental issues faced by various countries is the lack of an adequate water supply. It has been estimated that nearly two-thirds of nations worldwide will experience water shortages by the year 2025 (United Nations Environment Programme, 2002). Koutsoyiannis (2011) has indicated that, due to the growth of population and average per capita water use, the amount of fresh water withdrawn globally each year has increased from 579 km^3 in 1900 to 3,973 km^3 in 2000 and demand is projected to rise further to 5,235 km^3 by 2025. He concluded that more dams are needed worldwide to meet increased water and food supply needs.

According to the United Nations Population Division (2002), by the year 2030, 56% of people in developing counties will reside in urban areas. In Ethiopia, some 17% of the population was residing in urban centres in 2010; this number is projected to reach 21% in 2025 (United Nations Population Division, 2010), presaging water shortages. Ten years ago, world population was growing by 1.24 per cent per year. Today, it is growing by 1.18 per cent per year, or approximately an additional 83 million people annually (United Nations, 2015). Africa has the highest rate of population growth, growing by 2.55 per cent annually in 2010-2015. Climate changes and the continuing trend of population migration to cities, mainly in developing countries, will aggravate the problem. In Eastern Africa, a 30% improvement in access to piped water sources over the last 30 years has been reported, more than half of which relates to urban areas (Lee and Schwab, 2005). However, many cities in this region are still suffering from a shortage of potable water and from water-borne diseases.

In Ethiopia efforts to alleviate the problem are being made by both the federal government and local administrative bodies, including the proposed Geba dam to be built across the Geba River, 25 km northwest of Mekelle city (Fig. 7.1). The dam will have a crest length of 1,000 m, a height of 80 m and a reservoir capacity of 350 million cubic meters. It is designed both to supply water to the city and surrounding populations and to regulate the flow of the river. Currently, Mekelle city is supplied with groundwater mainly from the Aynalem well field, some 5 km to the south east. In 1998, 11 wells were drilled and pump tested for 72 h. It was concluded that total output as some 220 l/s, with each well providing between 15 and 30 l/s. However, since 2002, the water level has declined continuously (Water Works Design and Supervision Enterprise, WWDSE, 2007).

Drought in Ethiopia is a frequently recurring phenomenon and its distribution and frequency have increased in recent years (Walraevens et al., 2009). In addition to excessive abstraction, climatic variability might be contributing to the decline in the water level in the well field.

Nothing better captures the enormity of the scarcity of water than the fact that water is only provided to residents for a limited number of days per week. Clearly, alternative ways to meet the rapidly growing water demand of the city must be found. In the last two decades the government has initiated the construction of micro-dam reservoirs and other water-harvesting structures for different purposes but the proposed Geba dam (Fig. 7.1) is a very important project.

Numerous dams, all over the world, are affected by leakage when filled (Mozafari *et al*., 2011). The hydraulic and mechanical properties of rock masses are the most important parameters in the design and construction of dams (Gurocak and Alemdag, 2011) and other water-harvesting and retaining structures. The permeability of rock masses in general and related to dam design and construction has been studied by numerous researchers (Bonacci and Roje-Bonacci, 2008; Foyo *et al*., 1997, 2005; Goodman *et al*., 1965; Heuer, 1995; Izharul and Hashmi, 1983; Kiraly, 1969, 1978; Ozsan and Karpuz, 1996; Snow, 1968; Uromeihy and Farrokhi, 2011; Yamaguchi *et al*., 1997). The Lugeon test (for details see chapter 3) is widely used to estimate the average hydraulic conductivity of rock masses (Quinones-Rozo, 2010) and is often considered both as the most important parameter in determining the critical permeability and as a criterion to determine the necessity of rock mass grouting (Sharghi *et al*., 2010).

The permeability of naturally occurring geological strata is important for foundation and underground construction, hydraulic structures and groundwater, oil and gas exploitation (Angulo *et al*., 2011; Morrow, 2000). In-situ permeability tests of soil and rock usually provide a more accurate determination of permeability than laboratory tests (Hamm *et al*., 2007; Mollah and Sayed, 1995). However, due to the heterogeneity of the hydrogeological characteristics of rock masses and the anisotropy arising from discontinuities, permeability values determined by in situ tests in a limited area may not reflect the real permeability of the rock mass at a project site scale. The Lugeon (packer) test is the most commonly used in situ test (Lugeon, 1933), but in situ tests in drill holes only provide information on the permeability of the strata immediately adjacent to the borehole (Gurocak and Alemdag, 2011). Detailed analysis and correlation with the geology of the site are necessary to complement the data from drill holes.

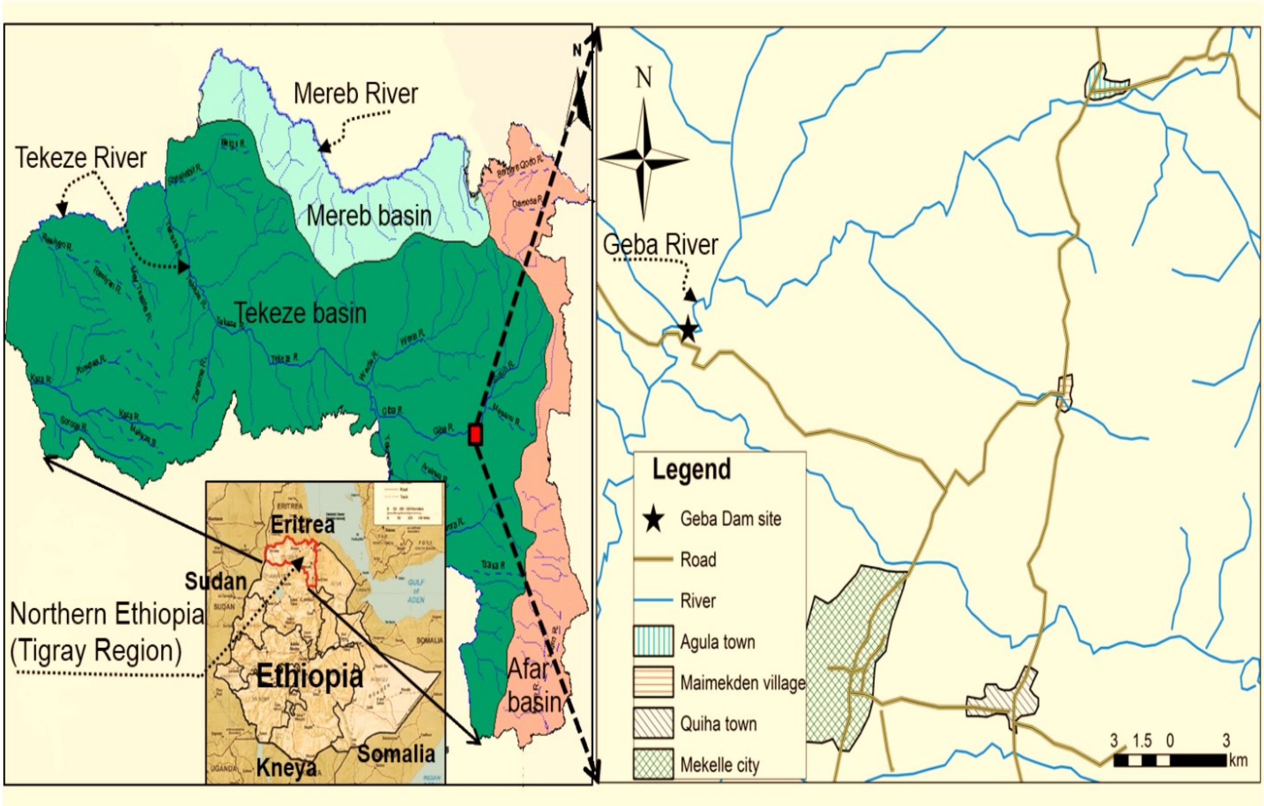

Figure 7.1. Location map of Geba dam site and its environs. Source for Tigray map modified from BoFED (2002).

The objective of this chapter is to evaluate and characterize the hydraulic conductivity of the rock masses at the site of the proposed Geba dam, and to check whether grouting is necessary and practical in the abutments and central foundation. Results were also compared with the conclusions and insights drawn in the previous chapters related to MDRs.

METHODOLOGY

The fieldwork included engineering geological mapping, discontinuity surveying, core drilling, Lugeon tests (details are given in chapter 3) and the acquisition of 38 soil and 10 rock samples from the site of the proposed dam. The mapping was undertaken along north–south lines at different intervals in order to intersect the different geological units and was complemented by air photograph interpretation. The discontinuity survey included not only slope face and scanline mapping but also information from the rock cores. The orientation data were analyzed using a computer program based on equal area stereographic projection (Rockworks15, Rockware, 2010), in the form of contoured pole and rose diagrams. Quantitative description of discontinuities including orientation, spacing, persistence, roughness, aperture and filling were determined in accordance with ISRM (1981a, b).

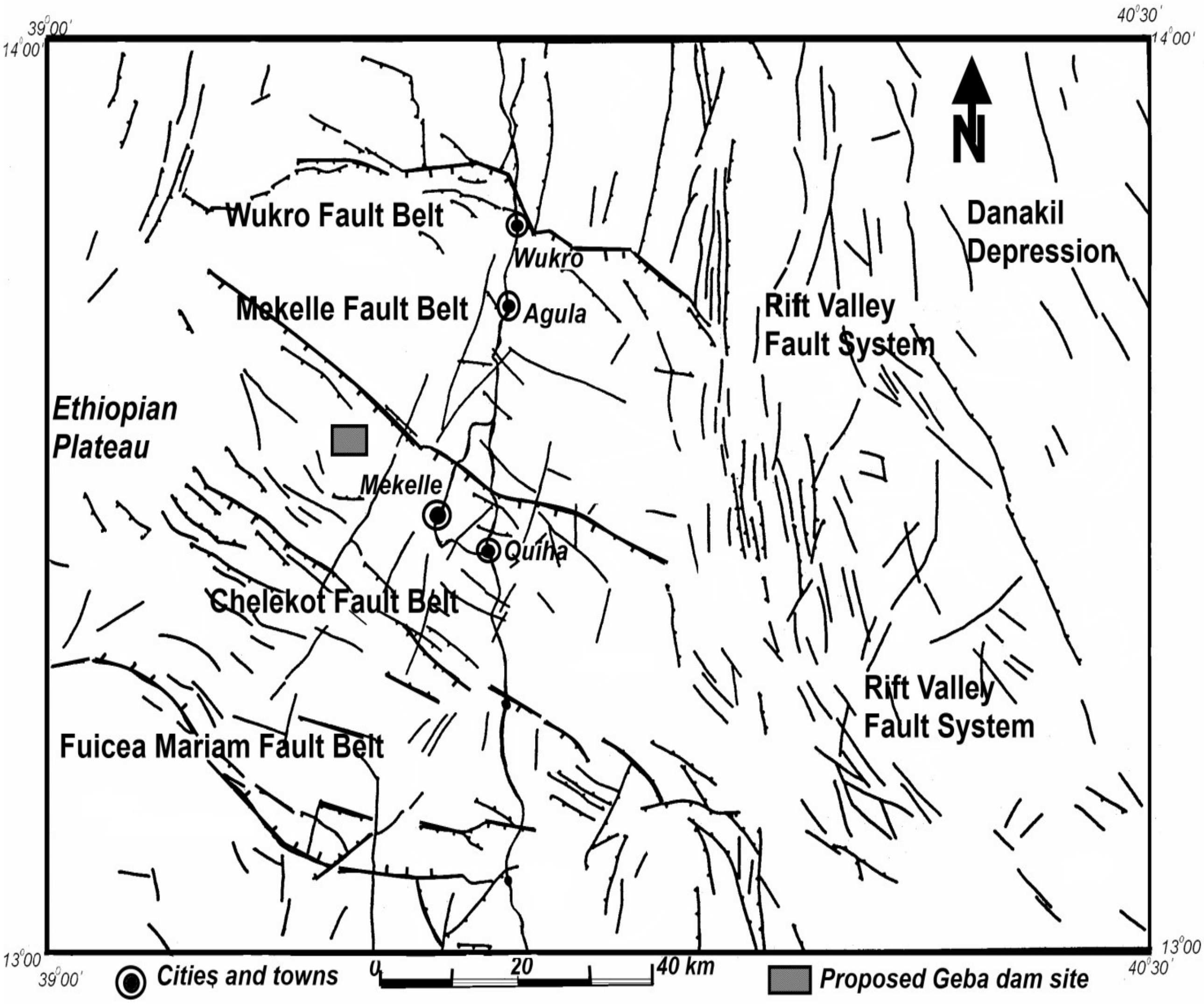

Figure 7.2 Fault map of Mekelle Outlier (modified after Levitte, 1970). Small rectangle shows location of Geba dam site.

After detailed geological and geomorphological fieldwork, a systematic geotechnical drilling campaign was planned and implemented with a wireline NQ type (75.7 mm diameter) diamond bit, along the dam axis and reservoir site. Twenty boreholes were drilled at dam site and reservoir to depths between 30 and 120 m, with a total core length (depth) of 1,253 m. Logging and rock quality designation (RQD) measurement was based on ISRM (1981a, b), care being taken to separate the artificial fractures created during the drilling. RQD was proposed by Deere (1964) as a measure of the quality of rock mass from drilled (borehole) core log. The RQD is defined as the ratio (in percentage) of the total length of sound core pieces that is 10 cm (4 inch) or longer to the length of the core run (equation 7.1). For RQD determination, the International Society for Rock Mechanics (ISRM) and ASTM (D6032) recommend a core size of at least NQ-size (core diameter 47.5mm) or NX-size (core diameter 54.7 mm) drilled with double-tube core barrel using a diamond bit. Artificial fractures can be identified by close fitting of cores and unstained surfaces. All the artificial fractures should be ignored while counting the core length for RQD (Zhang, 2016).

$$\mathrm{RQD} = \frac{\sum \text{Length of sound core pieces} \geq 10\text{cm}}{\text{Total core run length}} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots (7.1)$$

The relationship between RQD and the engineering quality of the rock mass as proposed by Deere (1968) is given in Table 7.1. RQD is a simple and inexpensive index, but when considered alone it is not sufficient to provide an adequate description of a rock mass, due to the reason that it doesn’t account joint orientation, joint condition, type of joint filling and stress condition.

Table 7.1. Correlation between RQD and rock mass quality (Deere, 1964, 1968; Deere and Deere, 1988, 1989).

RQD value	Rock quality description	General classification (Deere and, Deere, 1989)	Approximate equivalent fracture spacing (Deere, 1968)
0-25%	Ver poor	Crushed	Very close
25-50%	Poor	Shattered, very blocky and seamy	Close
50-75%	Fair	Blocky and Seamy	Moderately wide
75-90%	Good	Massive, moderately jointed	Wide
90-100%	Excellent	Intact	Very wide

Seventy-seven water pressure or Lugeon tests were carried out using expandable double packers. The test section length was varied from 1.5 to 5 m (with an average of 4 m) and the test pressure adjusted for each section to take account of the depth and the nature/type of rock to avoid hydraulic fracturing and jacking. The Lugeon values were calculated (for details see chapter 3) and the type of flow and behaviour were determined for each of the test sections. According to Houlsby (1976) and Quinones-Rozo (2010), laminar flow occurs when the Lugeon value of a rock mass is independent of the test pressure while turbulent flow is indicated by an inverse relationship between water pressure and Lugeon value. In the case of dilation, similar hydraulic conductivities are observed at low and medium pressures and much greater values at the maximum pressure. An increase in Lugeon value regardless of the changes in water pressure is an indication of washout, while a continuous decrease in Lugeon value regardless of the changes in water pressure suggests void filling. A total of 77 water pressure or Lugeon tests (63 on the dam site and 14 on the site of the reservoir) were performed in 18 boreholes (12 on the dam site and 6 on the site of the reservoir).

The unconfined compressive strength (UCS) test is commonly used as an easy and less sophisticated among all other compression test types where only the axial load (P_{ucs}) is applied to a cylindrical rock sample (core) and no lateral loads of any type are applied (equation 7.2). According to ASTM D2938-02 the length to diameter (L/D) ratio of grater than 2 (prefereably between 2 to 3) is recommended (ASTM, 2002).

$$\mathrm{UCS} = \frac{\mathrm{P_{ucs}}}{\mathrm{A}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.2)$$

where UCS is unconfined compressive strength (kN/m^2), P_{ucs} is maximum axial load applied (kN) and A is cros setional area (m^2) given by $A=(\pi D^2)/4$, where D is average specimen diameter (m). Descriptive terms used for intact rock based on UCS is shown in Table 7.2.

Table 7.2. Engineering classification of intact rock based on compressive strength as mentioned in ISRM (Brown, 1981).

Term	Strength MPa
Extremely weak rocks	0.25 – 1.0
Very weak rocks	1.0 – 5.0
Weak rocks	5.0 - 25.0
Medium strong rocks	25.0 – 50.0
Strong rocks	50.0 – 100.0
Very strong rocks	100.0 – 250.0
Extremely strong rocks	> 250.0

RESULTS AND DISCUSSION

Site geology

At the initial stage of the investigation the geology of the site was described in the field by conventional field techniques. The site is characterized by Mesozoic sedimentary sequences, typically limestone, limestone-shale intercalations, shale and travertine underlying unconsolidated colluvial and alluvial deposits (Fig. 7.3). Thick fractured limestone covers the left and right abutments of the dam site and extends toward the reservoir on the upstream side, forming steep cliffs. The uppermost part is dark grey to black in color, finely crystalline, compacted, and fractured with parallel horizontal bedding. Towards the foot of the cliff, thin beds of fossiliferous limestone were observed in the massive, dark brown rocks.

The limestone-shale intercalation unit is covered on both abutment slopes by colluvial deposits and in the central foundation by alluvial soils. This unit was exposed on the southeastern part of the dam site (Fig. 7.3) and extended both downstream and upstream. Its variable colour (light yellowish to greenish grey) and its fissility are typical features of this unit. The alternating beds form gentle slopes due to their low resistance to weathering and erosion compared with the thick limestones which form the cliffs.

The third rock unit is weak, yellowish, weathered, fissile shale, which is only exposed on the northwest side of the dam site. In places, thin beds of jointed limestone occur.

The travertine is whitish in color, generally porous, highly weathered and with some traces of bedding and lamination. In places, it shows some interconnected cavities which would lead to excessive leakage.

The central foundation (lower valley floor) is covered by up to 20 m of thick alluvial deposits (gravel-sand mixtures and clayey sandy soils). In places, the coarser river deposits are cemented by calcite while the fine soils form a flat topography, used as farm land. The distributions of these deposits are good indicators of morphological changes associated with past meanders of the Geba River.

Table 7.3 presents the results of unconfined compressive strength test of rocks from the dam site. Based on the descriptive terms in Table 7.2, 5 of the samples result to weak, 3 medium strong and only 2 fall to strong rock indicating that most of rock mass at abutments and foundation is weak. This situation as implication on groutability and stability of the rocks mass.

The liquid limit of the alluvial deposit varied from 0 or non-plastic to 66% with an average value of 26%; the plastic limit ranged from 0 or non-plastic to 45% with an average value of 13%. The dominant soil types are clayey/silty sand (SC, SM) and silty/clayey gravel (GM, GC). Of the 38 samples tested, some 37% were found to be non-plastic. The permeability varied between 10^{-5} and 10^{-3} cm/s, i.e. the material was of medium permeability. As a consequence, it was proposed that the alluvial deposit should be removed or cut-off before construction of the dam, to control leakage, prevent uplift pressures and instability of the dam and/or piping problems.

Discontinuity survey

Joints in outcrops of the abutment slope were studied based on slope face and scanline mapping. Figure 7.4 shows a plot of contoured pole concentrations and a rose diagram of 118 discontinuity measurements from both abutments. Measurements were taken systematically with special emphasis on joints with a favourable orientation for leakage with respect to the alignment of the dam axis and reservoir configuration. Discontinuity sets were identified visually in the field and from the rose diagram. Figure 7.4 shows three dominant sets of discontinuities characterize both abutments, NW–SE (J1), N–S (J2) and NE–SW (J3), which are mainly vertical to sub-vertical (tectonic joints); in addition, bedding plane, J4, is horizontal. The discontinuities are generally open, smoothly undulating and low to high persistent within the extent of the exposed surfaces, although most discontinuities extend beyond the exposure limits suggesting they are interconnected or intersect each other. The average spacing of the discontinuity sets ranges from 0.5 to 3 m with an average spacing of about 1.5 m (Table 7.4).

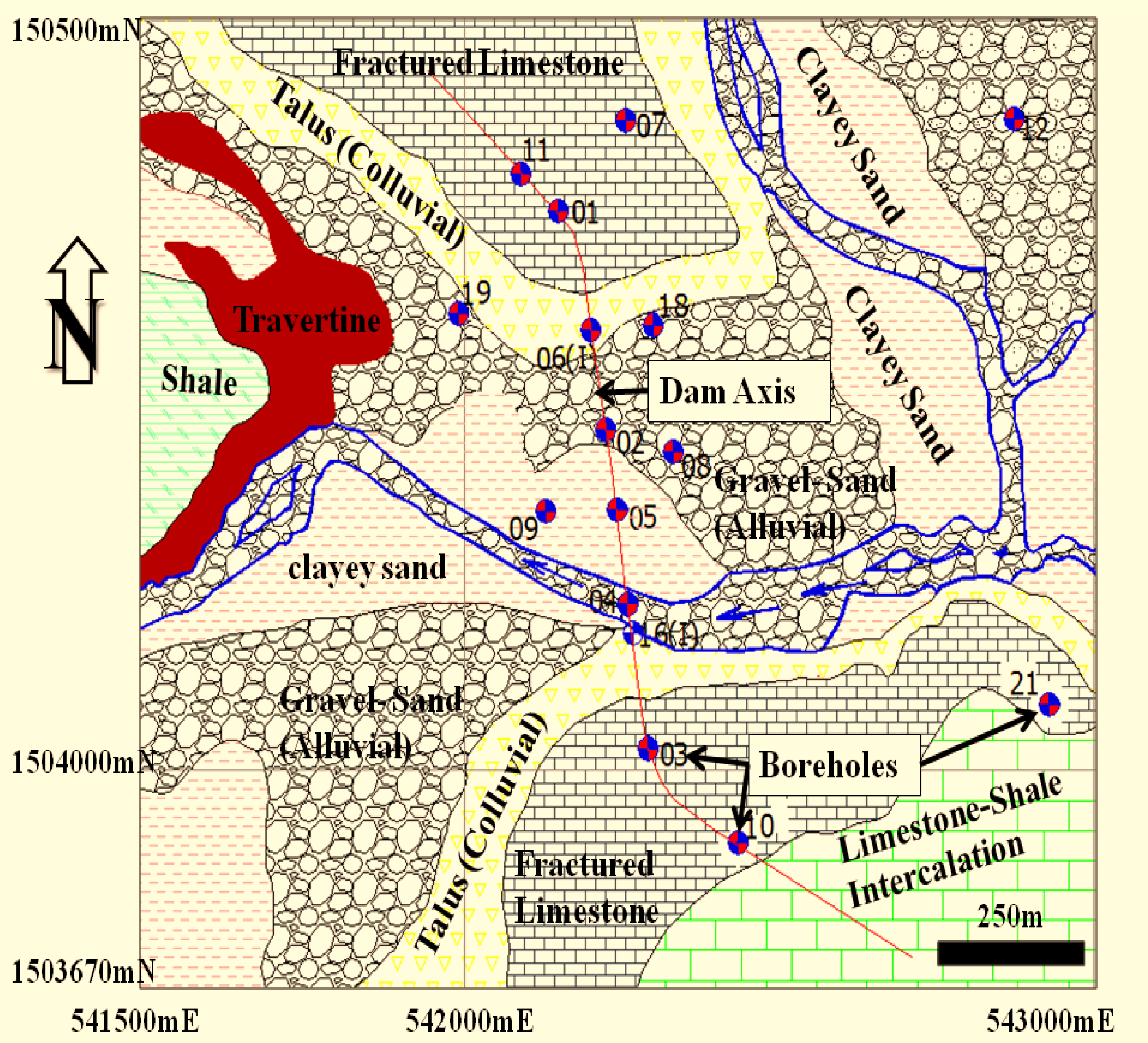

Figure 7.3. Simplified engineering geological map of Geba dam site. Boreholes and planned dam-axis are indicated. Boreholes on reservoir area are not indicated (see Annex for coordinates and locations). Coordinates of all the boreholes is included in Appendix C7 on CD.

Table 7.3. Unconfined compressive strength of rocks from Geba dam site.

Location	Depth interval (m)	Rock type	Unit weight (kg/m^3)	Unconfined compressive strength (MPa)	Descriptive terms (Brown, 1981)
Left Abutment (BH-03)	11.08-11.53	limestone	2730	22.9	Weak
	109.79-109.95	shale	2576	12.04	Weak
Central Foundation (BH-02)	25-25.16	Shale	2422	12	Weak
	70.83-71.16	gypsum	2759	25.4	Medium strong
	89.15-89.35	limestone	2855	51	Strong
Right Abutment (BH-01)	6.63-7.11	limestone	2854	26.5	Medium strong
	71.4-71.61	shale	2841	13.3	Weak
Right Abutment (BH-07)	64.83-65.11	limestone	2629	53.5	Strong
	70.72-70.96	shale	2454	14.4	Weak
	119-119.43	gypsum	3107	31.3	Medium strong

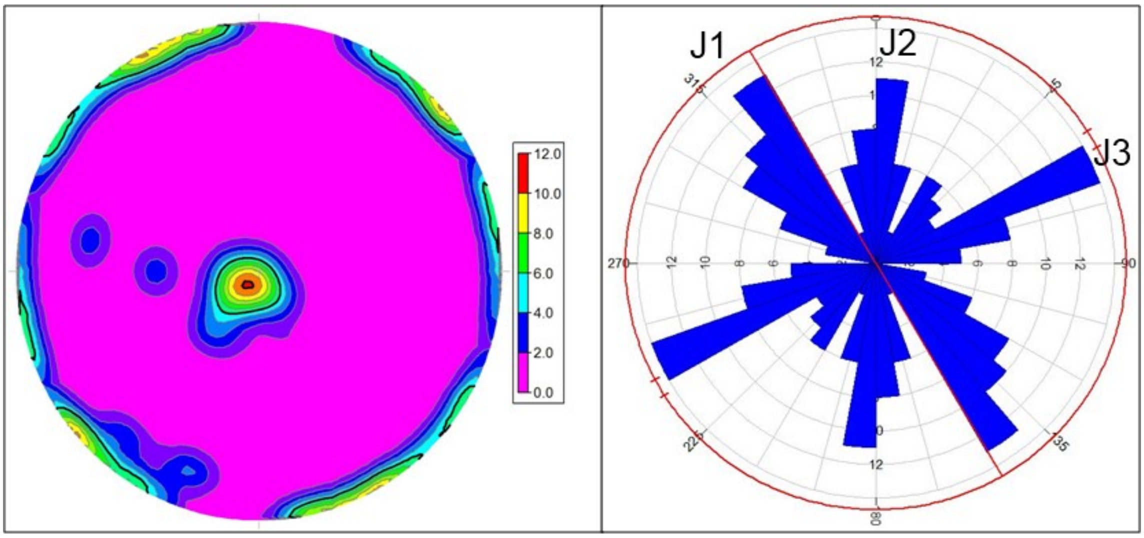

Figure 7.4. Stereographic projection contoured pole and rose diagram of discontinuity strikes from both abutments.

Borehole log results and interpretation

Careful visual observation and logging shows that the geological/geotechnical successions of the dam site and reservoir are very erratic attributed to complex sedimentation processes and subsequent tectonic and intrusive activities. The core samples studied provided a picture of the cyclic nature of the strata, the variation in fracture intensity, the thickness of the layers and the overall engineering properties of the material (e.g. strength and permeability).

The central river valley is covered by alluvial deposits (gravel-sand mixtures and clayey sand, Figs. 7.3, 7.5a, 7.6) with a thickness of up to 20 m, underlain by alternating fractured and bedded limestone-shale intercalations (Figs. 7.5b, 7.6). These are extremely variable in thickness and character and extend up to more than 120 m below ground level. The geological sequences of the left and right abutments are similar to those of the central foundation, except that there is no alluvial overburden in the central area although in places thin layers of colluvial deposits and thick limestone overlie the limestone-shale intercalation unit (Fig. 7.5).

Rock quality designation (RQD) index values and interpreation

The rock quality designation (RQD) value is defined as the sum of the core sticks in excess of 10 cm long, expressed as a percentage of the total length of core run (Deere, 1964). RQD has been used in many dam designs as a first rock mass quality assessment parameter (Ez Eldin *et a*l., 2007; Ghazifard *et al*., 2006; Ozsan and Akin, 2002). It is also considered as an index of rock quality (Deere and Deere, 1988) for preliminary assessment. Deere (1964) attempted to find a relationship between the numerical intensity of discontinuities to the rock mass quality and the significance of this and its effect on the deformability of the rock mass. He concluded that maintaining a consistent standard of drilling, the percentage of solid core recovered depends on the strength and number of discontinuities in the rock mass. Uromeihy and Farrokhi (2011) pointed out that RQD has some limitations for thinly layered rocks.

Table 7.4. Characteristics of major discontinuity sets.

Discontinuity set	Average spacing (m)	Average aperture (cm)	Persistence (m)	Roughness	Weathering degree
NW-SE (J1)	1.4	13.6	1.5	smooth, planar	slightly weathered
N-S (J2)	3.0	13.8	3.1	smooth, undulating	fresh to moderately
NE-SW (J3)	1.2	3.0	2.3	smooth, undulating	slightly weathered
Horizontal (J4)	0.5	4	14	smooth, planar	slightly weathered

Figure 7.5. Selected core from Geba dam site. a) Alluvial deposit with gravels and boulders (BH-2, depth interval: 0.00−4.00 m), b) limestone-shale intercalation (BH-02, depth interval: 3.50−8.30 m).

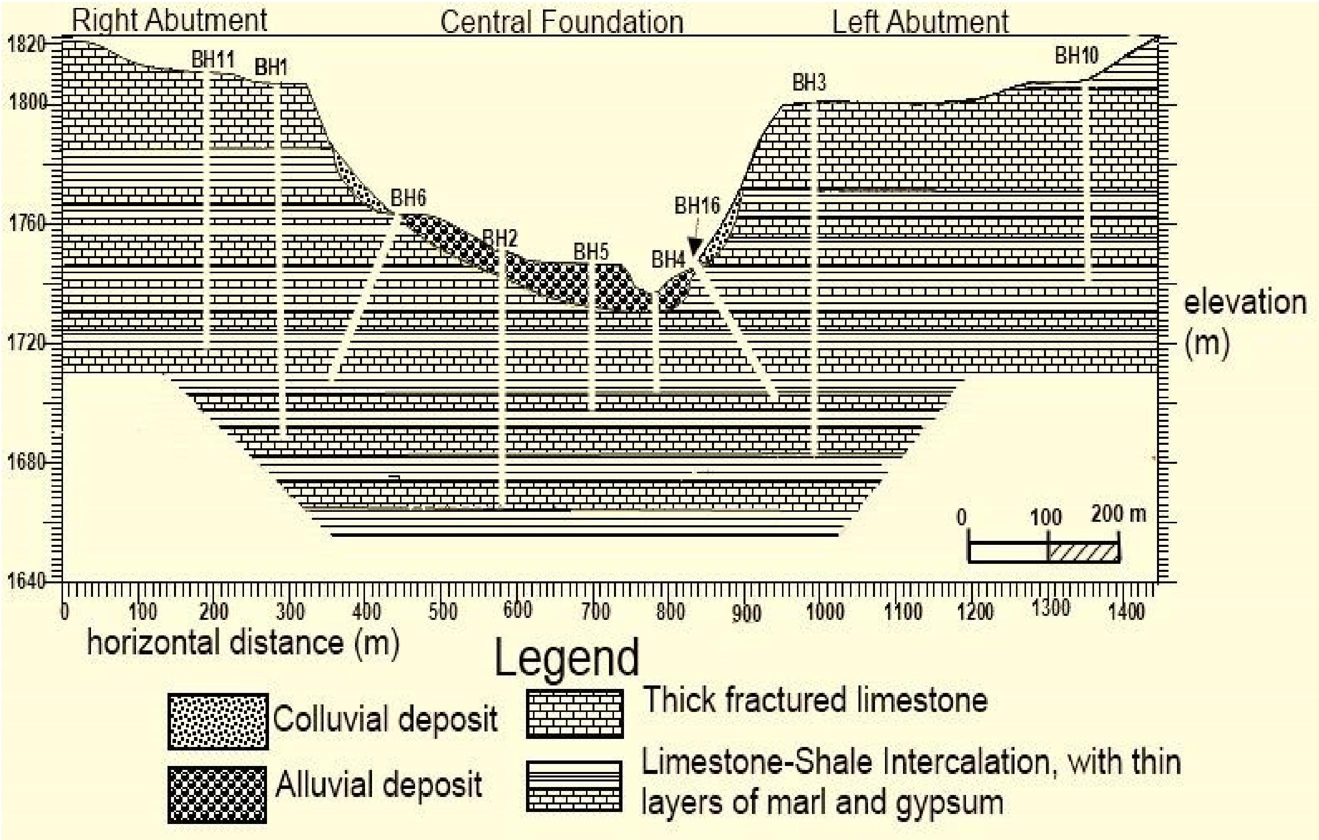

Figure 7.6. Simplified geological cross-section along Geba dam axis (facing upstream). BH6 and BH16 are oblique or inclined to check if vertical fractures and faults present.

Table 7.5. Statistical distribution of number of rock quality designation (RQD) values in the different rock quality classes.

RQD (%)	Rock Quality (Deere and Deere, 1988)	Left Abutment	Central foundation	Right abutment	Percentage distribution (%)
		BH- 03, 10 & 21	BH-02, 04, 05, 06, 08, 09, 16 & 18	BH-01, 07 11 & 19	
0-25	Very poor	82	34	21	35.6%
25-50	Poor	18	30	14	16.0%
50-75	Fair	18	48	22	22.9%
75-90	Good	7	42	15	16.6%
90-100	Excellent	9	21	4	8.8%

Table 7.6. Statistical distribution of number of Lugeon values in the different permeability classes for the pressure tests executed on the dam site.

Lugeon value range	Classification (Ghafoori et al., 2011)	Left abutment	Central foundation	Right abutment	Total number of tests	Percentage distribution (%)
		(BH-03,10 & 21)	(BH-02, 06, 08, 09, 16 & 18)	(BH-01, 07, 11 & 19)		
0-3	Impervious	6	12	6	**24**	38%
3-10	Low permeability	2	3	3	**8**	13%
10-30	Medium permeability	10	1	5	**16**	25%
30-60	High permeability	4	3	5	**12**	19%
>60	Very high permeability	0	1	2	**3**	5%
Total number of tests		**22**	**20**	**21**	**63**	

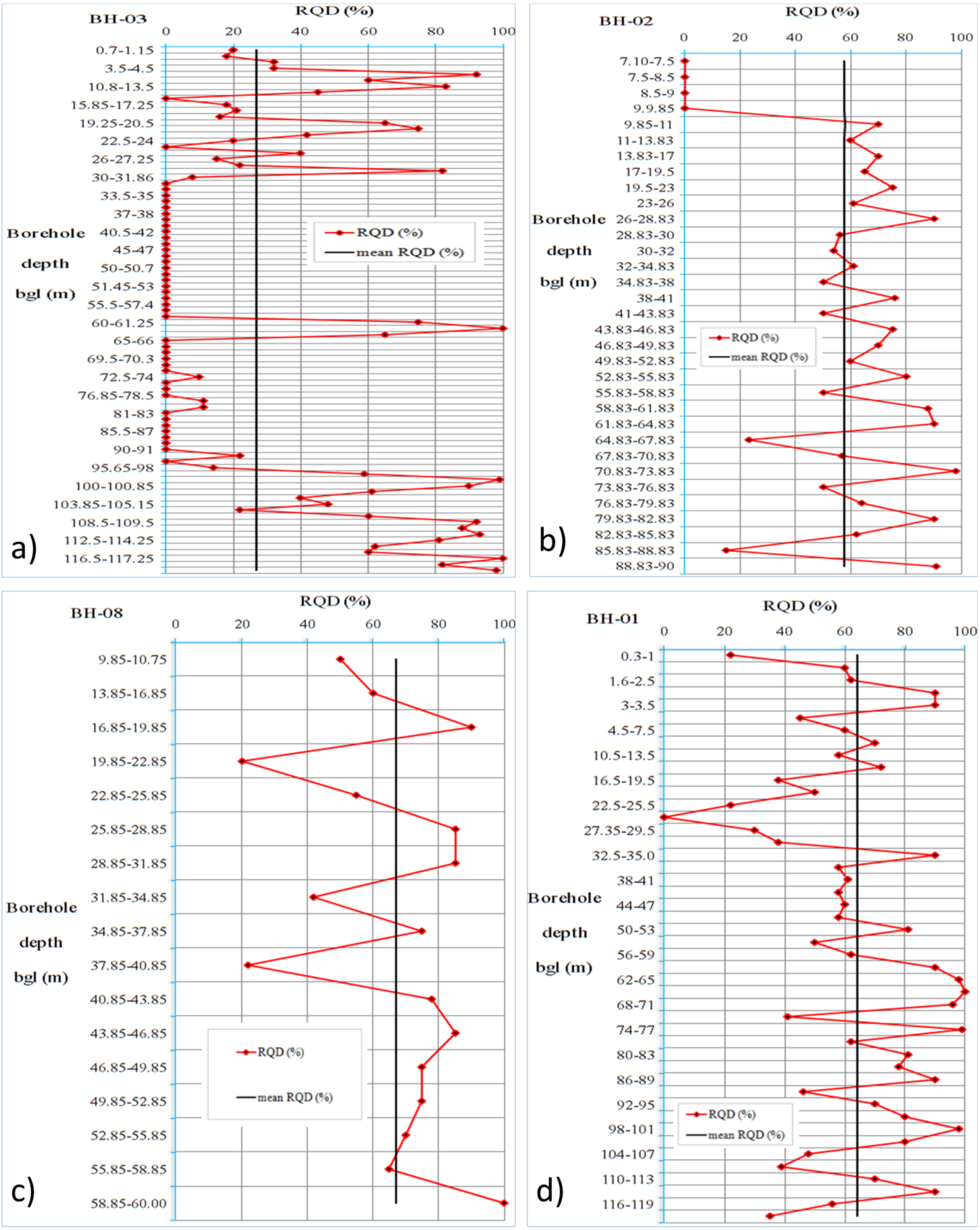

Figure 7.7. Values of RQD at different parts of the dam site: a left abutment; b, c central river valley and d right abutment.

Commonly, if the value of RQD is low, it would be assumed that the rock is highly fractured and with high fissure flows such that grouting would be required. However, in thinly bedded sedimentary rocks, such as shale, this is not true. The low RQD value for shale may be attributable to its inherent weakness and its tendency to lose strength when exposed to air and moisture. In general, as seen in Fig 7.7showing RQD of four selected boreholes, the shale and jointed limestone layers had lower RQD values. Basic statistical analysis of the samples in the dam site showed that 51% of RQD values would be classified as very poor to poor and 49% fair to excellent (Table 7.5).

Lugeon/pressure test results

The hydraulic conductivity of the rock mass at the dam site was evaluated by conducting a Lugeon test campaign using expandable double packers. The results are shown in Table 7.6 and Fig. 7.8 illustrates the results for four selected boreholes. As seen in Table 7.6, 62% of the Lugeon values were above 3, indicating grouting treatment is required (Houlsby 1976, 1990). The distribution of Lugeon values below 3 (impervious) is lower for both abutments than for the central foundation, probably due to the presence of thick fractured limestone in the abutments.

Many researchers reported that due to the overburden effect, hydraulic conductivity decreases with depth (Lee and Farmer, 1993; Nappi *et al*., 2005). Although a simple correlation between Lugeon values and depth for the dam site showed a general reduction in Lugeon value with increasing depth, there were many exceptions (Fig. 7.8). A study on fractured granite by Hamm *et al*. (2007) also showed an inconsistent relationship between hydraulic conductivity and depth. In addition, analysis of drilling data showed that there was no direct relationship between RQD value and Lugeon value (Figs. 7.7, 7.8). In such conditions, if the depths of sections for Lugeon tests are based on RQD or drilling log, they are unlikely to indicate the actual permeability of the rock mass as the RQD does not record the number, aperture or connectivity of discontinuities which significantly affect permeability. The problem is illustrated by a comparison of Figs. 7.7a and 7.8a. At a depth of 21.7–22.9 m, the limestone has a higher Lugeon value (53) and relatively higher RQD (50) than at 41.8–46.8 m where the alternating beds of limestone and shale have zero Lugeon and RQD values. Gunay and Milanovic (2005) reported hydraulic conductivities ranging from 0.0 to 50 Lugeons for limestone in southwest Turkey while Nonveiller (1989) reported a Lugeon value ranging from 0.0 to 180 for a reservoir constructed on karst limestone in Croatia.

Type of flow of water

The result of flow type analysis conducted for the different parts of the dam site and reservoir area are plotted in Fig. 7.9.

Of the 77 pressure tests undertaken, some 35% indicated turbulent flow, 22% laminar flow, 16% dilation, 12% washout and 4% void filling. Only 12% of the tests showed no flow record. Compared with the central foundation, the distribution of turbulent flow is high in both abutments, indicating fast flow in wide, open discontinuities or voids. In view of the geology of the area, this would suggest that mainly the limestone rock mass has open and large discontinuities or interconnected dissolution cavities not necessarily apparent at the surface.

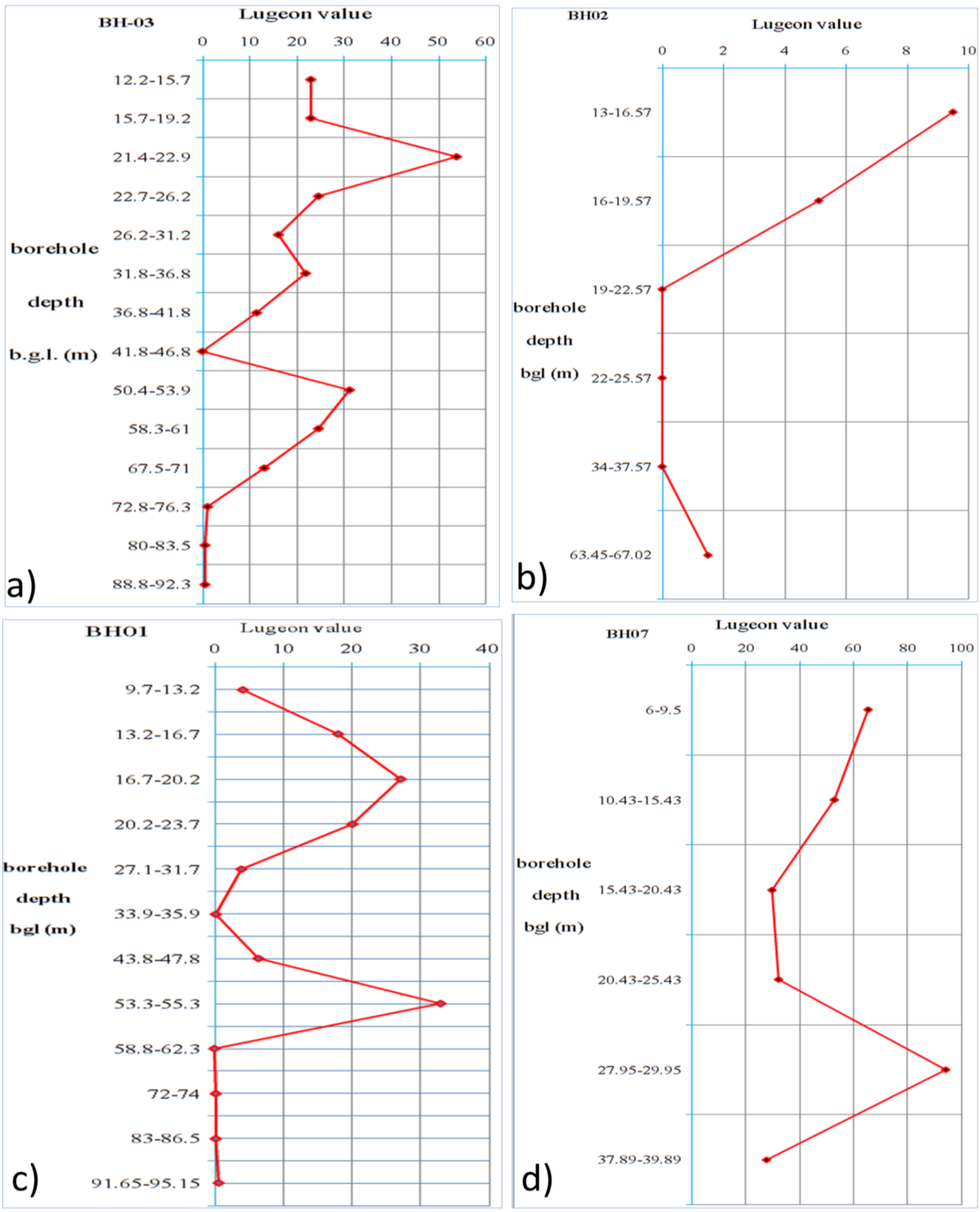

Figure 7.8. Plot of Lugeon values versus depth for selected boreholes: a left abutment; b central foundation; c, d right abutment.

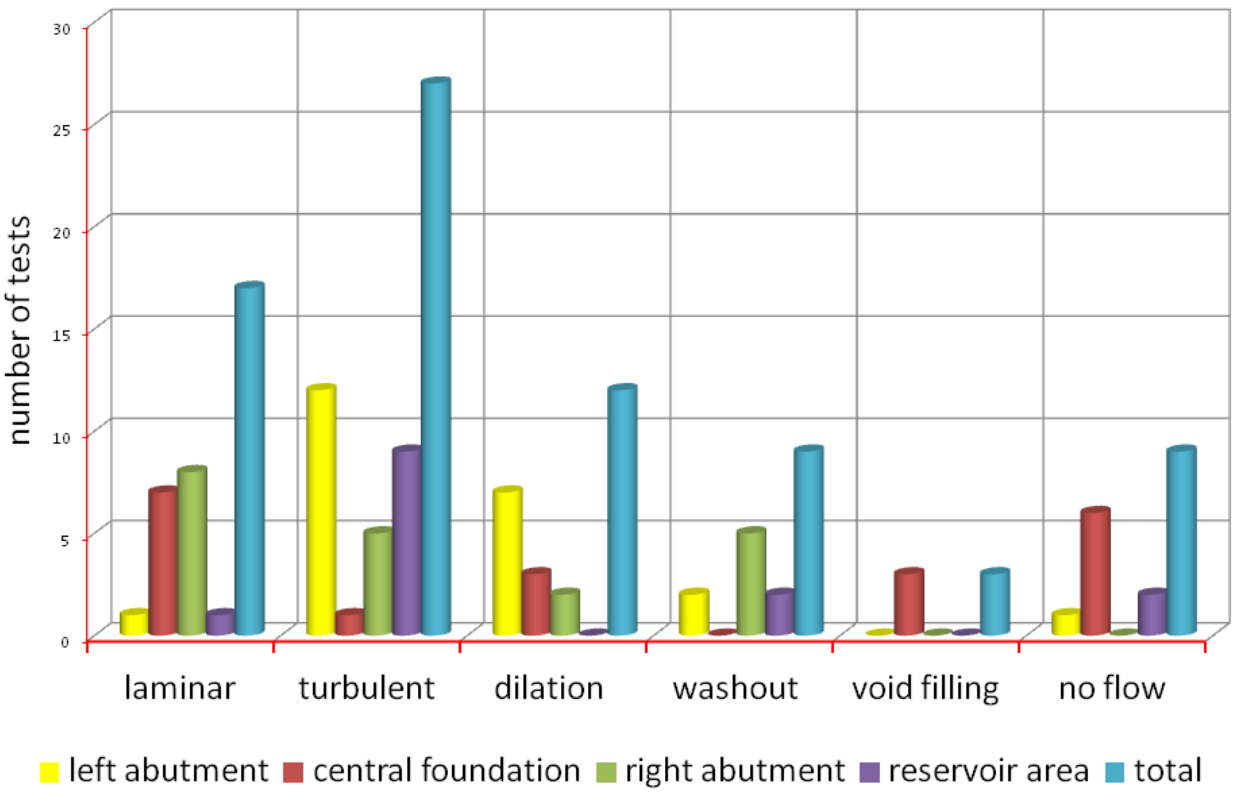

Figure 7.9. Dominant water flow type during pressure tests conducted at Geba dam site and reservoir.

Foundation treatment and groutability

Water leakage from a dam is always a problem, and particularly so where the preservation of water is essential in semi-dry areas such as northern Ethiopia. The geological investigation, including the discontinuity surveys, drilling (RQDs, borehole logs, etc.) and Lugeon tests, has indicated that treatment of the foundations will be necessary. In the central foundation, up to 20 m of alluvial deposits will need to be removed and replaced with compacted impervious clay material. Houlsby (1976, 1990) and Uromeihy and Farrokhi (2011) suggested that when the Lugeon values are between 3 and 10, a single row of grouting holes is required, while with values of over 10, a grout curtain should include three rows of grouting holes. The majority (62%) of the Lugeon values in the dam site were found to be higher than 3, and of these 79% were >10. The variation of Lugeon values with depth for both abutments and the central foundation is shown in Fig. 7.10. It can be seen that in general the Lugeon values decrease to less than 3 at a depth of about 100 m for the left abutment, 35 m for the central foundation and 60 m for the right abutment. As a consequence, a grout curtain including two to three rows of grouting holes was recommended to a depth of 100 m for the left abutment, 35 m for the central foundation and 60 m for the right abutment. Turbulent flow (Fig. 7.9) indicated big open discontinuities or dissolution cavities. This suggested that a coarse grout is essential. In addition, as the rock mass quality was generally poor, injection at holes should be carried out in stages, using an up-down method in 3–5 m sections. The analysis of the core logs showed a cyclic limestone-shale sequence in all the boreholes, hence the determination of the grouting sections must be based on the geological units, bearing in mind that the shale units will not take grout.

CONCLUSIONS AND RECOMMENDATIONS

This study assessed the engineering geological characteristics of the proposed Geba dam site with particular emphasis on the hydraulic conductivity and groutability of the materials. The rock mass at the dam site was a sequence of cyclic limestone-shale intercalations of variable thicknesses and degrees of fracturing and was characterized by both bedding and tectonic discontinuities. The RQD and Lugeon values did not show any clear relationship, but as many of the rocks with low RQDs had low Lugeon values, the use of RQD as a parameter for the selection of Lugeon test sections, is not applicable.

Water flow during the Lugeon tests was found to be dominantly of turbulent type suggesting interconnected and open discontinuity conditions at the dam site. About 62% of Lugeon values were found to be greater than 3, and of these, 79% had values greater than 10, indicating excessive leakage through the rock foundations should be expected.

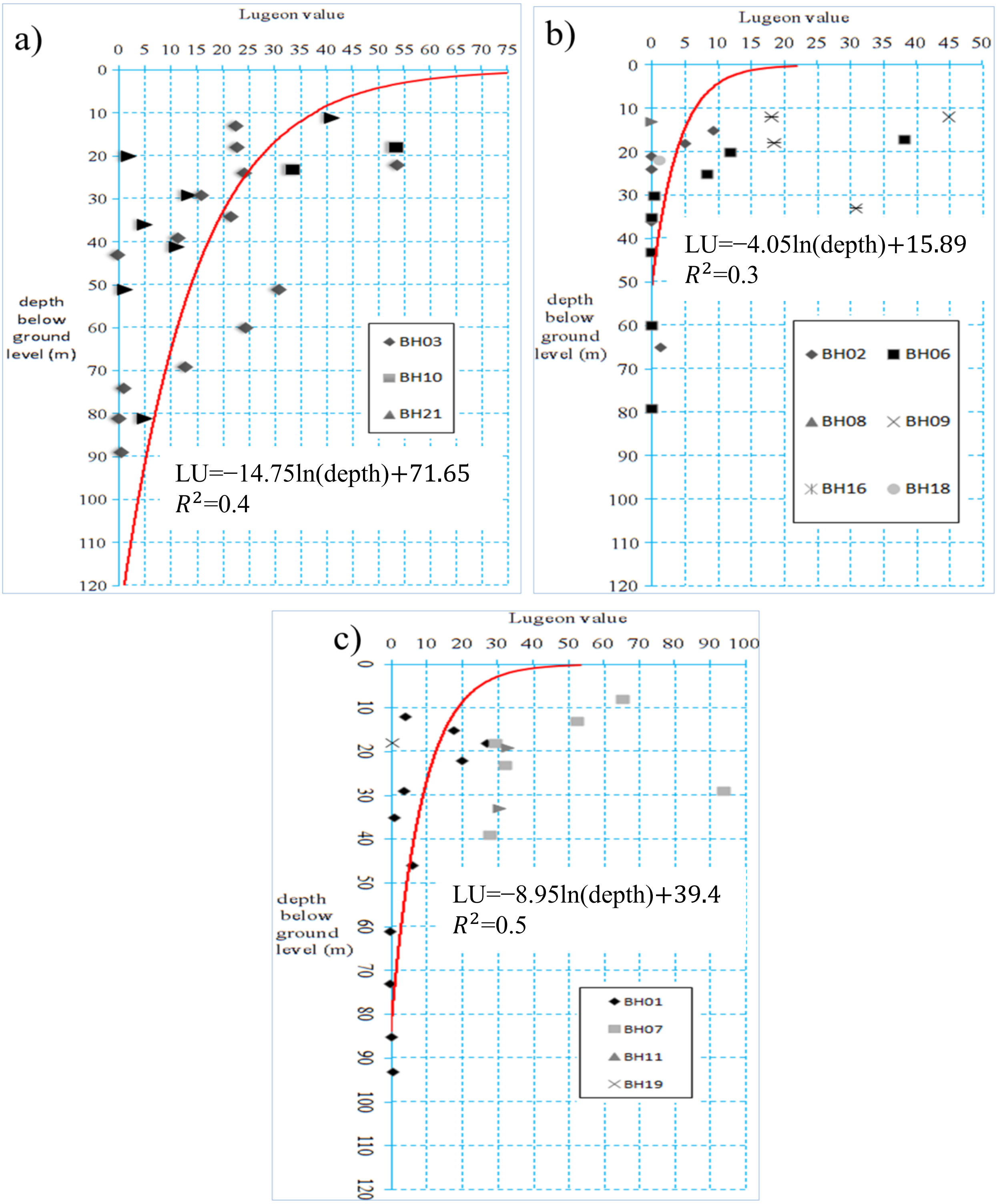

Figure 7.10. Variability of Lugeon values (LU) with depth at various boreholes: a left abutment, b central foundation and c right abutment.

The results of the discontinuity surveys, Lugeon tests and drilling showed that the dam site was complex and needs close consideration throughout the detailed design and construction phases. A grout curtain with two to three rows of grouting holes was recommended to a depth of 100 m for the left abutment, 35 m for the central foundation and 60 m for the right abutment. In addition, coarse grout should be injected in stages, using an up-down method at 3–5 m sections. It was recommended that the design and layout of the grouting should be reviewed as more information becomes available during design and construction phases.

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Contribution of authors

Name of author	**Role of the author in this chpater**
Gebremedhin Berhane	*Was responsible for all the aspects of the study, data collection, BH logs, RQD determination, field test execution, interpreation and writing the article/chapter*
Kristine Walraevens	*Was the supervisor in the study and critically reviewed and approved the article*

Geotechnical drilling operation at Hashenge MDR (at left abutment). Delta 250 Drilling Rig
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CHAPTER 8

Synthesis and outlook

GENERAL

MDRs are very common throughout the world, but their establishment in large numbers in Ethiopia in general and in Tigray in particular is a recent practice. No work has been done to investigate their leakage problem in connection with their geological, engineering geological and hydrogeological settings. This doctoral research is related to this particular problem.

In this chapter the findings obtained in the six chapters (chapters 2 to 7) and their implications are discussed and summarized. Moreover, based on the results obtained, the engineering geological and hydrogeological characteristics of the different rock units in the study area are briefly presented. Site investigation strategy for future implementation of MDRs is also suggested to help stakeholders and decision makers in the sector.

RESULTS AND CONCLUSION

To understand the problems of MDRs in Tigray and to verify the mechanisms and causes of leakage problems, different methods were used in this study by focusing on four selected case study MDRs and one proposed large scale dam site. Despite the different site specific geological and hydrogeological settings, the MDRs have a common leakage problem.

The main results and conclusions related to the overall MDRs in Tigray are summarized below.

- Out of the existing 92 MDRs in Tigray, statistical analysis showed that 61% of them are found to have siltation problems, 53% suffer from leakage, 22% from insufficient inflow, 25% have structural damages or failures and 21% have spillway erosion problems. Furthermore, nearly 70% of the MDRs are founded on carbonate dominant sedimentary terrain with intrusions of dolerite sills and dykes.

- The regional and local geology and hydrogeology have played a major role in the planning, design, construction and performance of the MDRs. The MDRs (dam site and reservoir) are situated in an area underlain by metamorphic, sedimentary, igneous and Quaternary soil deposits.
- The main problems highlighted, siltation and leakage, are found to be highly linked to geological conditions. These problems are found to be very high in MDRs located in sedimentary rocks. Siltation is found to be more significant in areas where shale is the dominant rock type; on the other hand, leakage is more common in areas where limestone predominates.
- This study clearly demonstrates the crucial role of geology related to the MDR problems. In-depth geological investigation of an area targeted for MDR construction, is an indispensable condition for reducing the problems with MDRs in the future.

Specific results related to the four selected detail studied MDRs (Hashenge, Arato, Adishuhu and Hizaetiwedicheber) are summarized below.

- This research has been able to show that the sedimentary sequence found on the left abutment of both Arato and Hashenge MDRs and below the central foundation in Arato MDR is a pervious unit and hence a leakage zone. On the other hand, the dolerite that underlies the right abutment of the two MDRs and the central foundation of Hashenge MDR is found to be semi-pervious to impervious and no leakage was observed along these localities. Yet, the dolerite unit has an impact on the hydraulic conductivity of the limestone-shale-marl intercalation unit and other rock units along its contact due to the baking effect during the time of eruption. This is an important feature that should be taken into account during site investigation for any water harvesting structures and groundwater exploration in the area and other regions with similar geological settings.

- It is also shown that the discontinuity data from slope face mapping/measurement, vertical electrical sounding results, drilling information and observational geological description at Hashenge MDR were in close agreement and able to identify the leakage path. The discontinuity spacing and aperture were found to be important factors, highly affecting the hydraulic conductivity of the rock mass.
- The packer test result and analysis of discontinuity data at Hashenge MDR were also found in good agreement. The hydraulic conductivity value from packer test falls within the minimum and maximum values obtained from discontinuity data analysis for the limestone-shale-marl unit.
- Arato MDR is dominantly covered with three lithological units: Quaternary soil deposits, dolerite and limestone-shale-marl intercalation unit. The geological, hydrogeological, hydrogeophysical and hydrochemical data analysis reveals that there is a hydraulic connection between the impounded reservoir and the downstream leakage discharge zone. The limestone-shale-marl intercalation unit of Agula Shale is found to be the leaky formation and responsible for the inefficient performance of the project in terms of water loss via leakage.
- The relatively low resistivity data recorded up to a depth of 16 m to 20 m in the downstream side of Arato MDR were inferred to be generally due to highly conductive material, likely the water saturated and pervious limestone-shale-marl intercalation unit

and Quaternary soil deposits, and partly due to deep weathering of the dolerite unit**.** The highly resistive materials in the area were found to be massive dolerite and dry limestone dominated intercalation unit (Agula Shale). Hydrochemical data from Arato reservoir water, from downstream shallow hand dug well and stream water confirmed these waters to be of the same origin, such that the source for the subsurface and stream water is from the impounded reservoir.

- The available hydrogeological information concerning the limestone-shale-marl intercalation unit confirms it to be the main water bearing formation in the area in the form of a multi-layer aquifer system.
- The groundwater recharge for Arato MDR catchment was estimated using different approaches. The natural recharge was estimated at 104 mm, 92.8 mm and 100 mm using SMB, CMB and WTF methods, corresponding to some 1.41×10^6 m^3. The recharge estimated using SMB can be considered as annual assuming negligible recharge during the rest of the year. Similarly the recharge from CMB is annual by its nature, but the recharge from WTF method represents only for 44 days.
- The runoff was estimated using the SCS-CN and water balance approaches. The result from SCS-CN was about 0.71×10^6 m^3, while from the water balance approach based on diver data logger, it was about 0.64×10^6 m^3. It was possible to estimate the leakage from the reservoir using the water balance model approach for the observed first part of the dry period; it corresponds to 13.2 mm/day or 112,300 m^3 for the 83 days observed dry period (1353 m^3/day).

- With the same water balance model and using the runoff (RO) estimated by CN method, the leakage loss during the wet period was found to be 4602 m^3 per day (0.24×10^6 m^3 in 53 days) which corresponds to 57.5 mm/day.
- The leakage in the area has an indirect and unintended positive impact on local farmers, improving their livelihoods by introducing small-scale irrigation from shallow hand dug wells and diverting streams emanating from reservoir leakage in all the three MDRs except at Hashenge MDR.
- The observed joints, weathering and bedding planes, which form horizontal discontinuities at Adishuhu and Hizaetiwedicheber MDRs, and the fault at Hizaetiwedicheber MDR, have major influence on the rock mass' hydraulic conductivity. The intrusion of dolerite into the limestone-shale-marl intercalation unit at Adishuhu MDR resulted in the development of fractures which increase the porosity, and permeability of the formation. However, even in the absence of dolerite, leakage still occurs (as shown at Hizaetiwedicheber MDR). Water leakage through the foundation bedrock at both sites was detected by geo-electrical survey methods with the support of direct geological field data. Anomalous patterns in recorded resistivity data indicate potential leakage paths. Spatial distribution of the anomalies indicates a strong connection between the reservoirs and leakage areas downstream of the two MDRs through the pervious limestone-shale-marl intercalation unit.

This study also assessed the engineering geological characteristics of the proposed Geba dam site with particular emphasis on the hydraulic conductivity and groutability of the materials in view of potential leakage problems. Detailed results and conclusions related to the proposed Geba dam are presented below.

- The rock mass at the dam site is a sequence of cyclic limestone-shale-marl intercalations of variable thicknesses and degrees of fracturing and is characterized by both bedding and tectonic discontinuities. The RQD and Lugeon values did not show a clear relationship, but as many of the rocks with low RQDs had low Lugeon values, the use of RQD as a parameter for the selection of Lugeon test sections, is not found applicable.
- Water flow during the Lugeon tests was found to be dominantly of turbulent type suggesting interconnected and open discontinuity conditions at the dam site. About 62% of Lugeon values were found to be greater than 3, and of these, 79% had values greater than 10, indicating excessive leakage through the rock foundations should be expected.
- The results of the discontinuity surveys, Lugeon tests and drilling data showed that the dam site is complex and needs close consideration throughout the detailed design and construction phases. A grout curtain with two to three rows of grouting holes was recommended to a depth of 100 m for the left abutment, 35 m for the central foundation and 60 m for the right abutment. In addition, coarse grout should be injected in stages, using an up-down method at 3–5 m sections. It was recommended that the design and layout of the grouting should be reviewed as more information becomes available during design and construction phases.
- The results obtained from detailed site investigation of Geba dam site confirm the conclusions drawn with limited subsurface investigation results for the four MDRs in relation to the limestone-shale-marl unit, which is found pervious in all case study sites. This gives confidence in the methods or approaches used in the MDR case studies, at least for the limestone and limestone-shale-marl units as it is confirmed by detailed in-situ tests and drilling data at the proposed Geba dam site.

These results are considered highly important for future new MDR site selection in the region and other regions with a similar geological environment, as well as to propose and implement anti-leakage measures. Table 8.1. presents a summary of engineering and hydrogeological characterisitcs for the common rock units in the study sites.

Table 8.1. Summary of engineering and hydrogeological properties for the main lithologic units.

Parameter		Quaternary Deposit	Dolerite	Limestone-shale-marl	Limestone
Common minerals and presence of fossils		various	Plagioclase, pyroxene, Fe-oxide, biotite	Calcite, clay minerals, Fe-oxide, plagioclase, fossils	Calcite, clay minerals, Fe-oxide, plagioclase, fossils
Typical features		Stream deposit	Dyke and sill	Cyclic nature (bedding)	Bedding
Hydraulic conductivity (cm/s)	Pumping test			1.42×10^{-2} (12.3 m/day)	2.15 to 6.66×10^{-2} (18.6 to 57.5 (m/day)
	Discontinuity		2.06×10^{-6}	4.19×10^{-1}	
	Lugeon test			4.225×10^{-3} (0-440 Lu)	
Transmissivity (m^2/day)				186	336 to 403
Strength (MPa)				12-14.4 (shale)	22.9-53.5
Unit Weight (kg/m^3)				2,422-2,841 (shale)	2,629-2,855

RECOMMENDATIONS AND FUTURE RESEARCH

This study brings concrete issues to the forefront for policy and technical considerations giving special emphasis to the role of geological, engineering geological and hydrogeological inputs for sustainable and technically sound implementation of projects in the sector in general and to MDRs in particular. In this light, some recommendations are drawn, which need policy consideration and technical implementation:

- An appropriate project concept prior to planning followed by in-depth geotechnical and geo-hydrological studies can significantly reduce the risks or at least minimize water losses or leakage, siltation and other problems to acceptable levels. The decision to construct a MDR should not be based on poor geological understanding and without respect of or adaptation to the findings of geological conditions.

- Any mitigation strategies should take the geo-hydrological and engineering geological condition of the MDR into account.
- Installation of a cut-off wall at the upstream toe of the MDRs or providing an impermeable cover (blanket) on the pervious reservoir could be considered as possible solution to minimize the leakage problem underneath the dam foundations, reservoir floor and abutments. As an alternative, proper utilization of the water from shallow wells from the leakage zone downstream of the MDRs may be also conceived as a target without incurring additional costs of maintenance (e.g. Adishuhu, Arato & Hizaetiwedicheber MDRs).
- Future planning, design and construction of MDRs in the area shall be based on sound understanding of the geomorphology/topography, geology, geo-hydrology and engineering geology of the site.
- Evaluation and research of the MDRs in terms of cost and benefit in comparison to other water harvesting technologies/systems (e.g. large dams, ponds, groundwater recharge, etc.) is recommended.
- Further monitoring of the leakage rate and reservoir and groundwater levels is recommended by manual or automatic sensors. These long-term data could be used to validate the study over a longer period.
- The hydraulic conductivity of the Mesozoic sedimentary rocks and dolerite in the study area are not well documented spatially and with depth in light of the proportions of limestone, shale, marl and impact of dolerite. Systematic research considering the

lithological variability, tectonic impacts like faults and discontinuities, and weathering processes may help largely towards future hydrogeological prospection, water harvesting and other infrastructural developments in the area and in other areas with similar geological set up.

- It is commonly acknowledged that most of the impacts from climate change will relate to water, hence research on the role of the MDRs towards fighting or minimizing the impacts from climate change could be an important future research area.
- Site investigation for major hydraulic structures (e.g. dams, MDRs, etc.) requires field and laboratory equipment as well as monitoring tools (e.g. geophysical tools, water level sensors, drilling tools, laboratory facilities, etc.). These are among the main bottlenecks for researchers and practitioners in the area. Some of these tools are available in few governmental and other non-governmental organizations and sometimes they are not used at all. To break the bottleneck, decision makers, researchers and practitioners shall work together toward providing the unavailable tools, and make use of the existing ones and make them accessible for users in the region. This approach can at least minimize problems that may exist in projects due to the lack of necessary investigation tools and lead to optimal utilization of available resources.

One of the principal uncertainties in geotechnical engineering is the risk of encountering unexpected geological conditions during construction; if not detected and solutions provided, this can lead to problems during the life span of the project (e.g. MDR). This is the result of geological complexities attributed to genetic, epigenetic and weathering processes.

During the planning, design and construction of the MDRs in Tigray there was no as such specific site investigation procedure one should follow and the site investigation itself was very limited in terms of procedures, techniques, depth, etc. In general only surface observations and hand dug test pits up to a maximum depth of 6 m were used during the design phase and no geological or engineering geological follow up was made during construction.

Looking at these drawbacks and lack of site investigation procedure for MDRs, it is found important to windup this dissertation by suggesting site investigation procedures that suite the geological settings in most parts of Ethiopia in general and in Tigray in particular, and that are practical.

The total engineering geology approach (Fookes *et al*., 2000) with modifications to suit for MDR is proposed. The total engineering geology approach consists of understanding the geological and geomorphological history of the construction site at the early stage of the project and adopting site investigation strategies and monitoring programs accordingly (Ngan-Tillard *et al*., 2010). Taking geology and geomorphology into account for planning subsequent investigations accordingly, minimizes investigation costs and geotechnical/engineering geological problems that may be encountered during construction and life time of the MDR. The proposed pragmatic approach (Fig. 8.1) is a kind of "*learn as you go*" process, meaning that it can be modified or updated based on actual practical results from MDR projects.

Since, there is no unique recipe to follow during planning and implementation of the MDRs in the region, the proposed approach can be used as a starting scheme with frequent evaluation and update from actual results. This approach allows broad understanding of the anticipated conditions of the site from the geology and geomorphology during the desk study or preliminary site investigation stage.

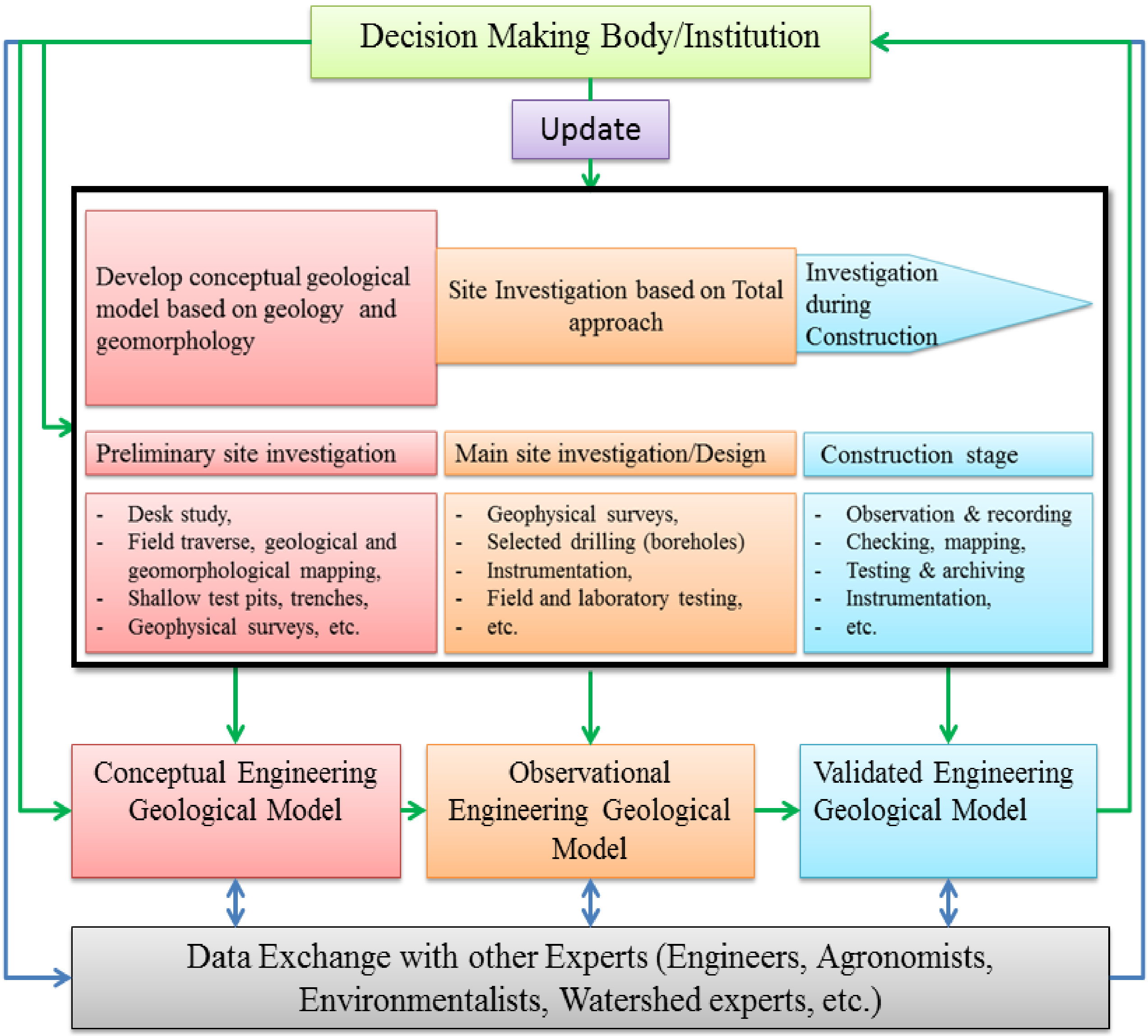

Figure 8.1. Proposed investigation approach for MDRs.

The proposed approach also gives an opportunity to review and for prioritizing different sites at preliminary stage before proceeding to more expensive subsurface investigation techniques during the main investigation stage. This departs from a linear vision of development and paves the way towards more technically sound, cost effective and sustainable water harvesting development and it helps policy makers reach an information based decision.

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APPENDICES (on CD)