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Enhancing conjunctive management of surface and groundwater resources in selected trans-boundary aquifers : Mount Elgon Aquifer Modelling Final Report B

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Document Sheet

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Executive Summary

Objectives; The project objective was to enhance knowledge and capacity for sustainable use and management of trans-boundary aquifers and aquifers of regional significance in the Nile Basin. The assignment involved the development of water balance models with quantified: recharge, outflows and withdrawals for Mt Elgon aquifer shared between Kenya and Uganda in the Nile Basin.

Methodology; The study involved a review of the SADA report of the Mt. Elgon aquifer and development of a groundwater conceptual model. A groundwater flow model code (GMS 10.6.3) and GIS platform (ArcGIS 10.8) were used to develop a numerical model that was run both under steady state and transient conditions for water balance reporting. Scenario analyses of numerical model runs were made under varying climate change stress and population use pressure up to 2050. Recharge estimates for historical, recent and future scenarios were based on changes in precipitation and controlled abstraction. A training manual integrating all the model materials and approaches was summarised.

Conceptual and numerical groundwater models;

- Mt. Elgon aquifer is a transboundary system shared between Uganda and Kenya, spanning three lake basins and several administrative units, covering an area from about 4,900 km^2 modelled over an area of nearly 8,500km^2;
- Drainage over the slopes of Mt. Elgon is largely radial towards streams on the foot slopes joining to form larger river that drain into Lakes Kyoga, Turkana or Victoria, a similar pattern largely followed by the groundwater flow directions;
- A bimodal annual rainfall (MAM and SON) also controls a temporal pattern of groundwater recharge in the region;
- Average aquifer drilled depths is 60 mbgl with the regional aquifer system having largely varying degrees of confinement (semi-confinement/leakiness);
- Recharge is regionally indicated to be very low to medium, with values that vary between 0 to 400 mm/ annum and discharge is through baseflow to join streams and springs;
- Hydraulic properties include mean *T* values of 9.7 m^2/d values and *S* values of 0.0027 derived from deep weathering and fractures, thick palaeosoils, and gas bubbles within lava flows, shallow groundwater sources and spring discharge;
- Mt. Elgon aquifer system depicts recharge in the higher caldera areas, with slopes dominated by runoff and springs, that flow and infiltrate into the low-relief region underlain by deeply weathered and fractured crystalline rocks, and discharge through alluvial and lacustrine sediments, and wetlands;
- National indicative hydrologic budget zones indicate for Ugandan side of the Mt. Elgon aquifer, main inflows as recharge (82%) and fluxes (18%) from adjacent hydrogeological units; whereas outflows include groundwater surface drainage (80%), fluxes (12%) to adjacent hydrogeological units, and abstraction wells (9%). For the Kenyan side main inflows are recharge (89%) and fluxes (11%) from adjacent hydrogeological units; whereas outflows include surface drainage (79%), fluxes (17%) to adjacent hydrogeological units, and groundwater abstraction wells (4%). For the volcanic region main inflows as recharge (85%) and fluxes (15%) from adjacent hydrogeological units; whereas outflows include fluxes (71%) to adjacent hydrogeological units, surface drainage (25%), and groundwater abstraction wells (4%).

Numerical models projecting different socioeconomic and climate scenarios from present to the year 2050 in the horizon for selected SSPs, and range of climate change scenarios was used to identify strategic recommendations for sustainable management and utilization of Mt Elgon aquifer;

- For the impact of increased/unsustainable withdrawals from Recent to 2050 on water balance the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by each of the three projected scenarios, however, there is a total drawdown of about 14 m.
- For the impact of climate change projections from Recent to 2050 on water balance, again, the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by each of the two projected scenarios, however, there is a total fall in water level of about 26 m.
- Impacts of projected climate change and increased demand from Recent to 2050 on water balance, again, the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by the scenario, however, there is a total fall in water level of about 10 m.
- Impacts of climate change (increased recharge) and increased demand on groundwater levels indicate drawdowns of up to 50m in selected urban growth centres in the region;

Groundwater suitability regions; five classes of the groundwater potential are identified including excellent (17%); high (39%); moderate (19%); low (15%); very low (9%);

Training materials; Groundwater Modelling System (GMS) Training Manual for the Mt. Elgon Aquifer System;

Recommendations for sustainable conjunctive groundwater – surface water use;

- Conjunctive development and management of surface and ground waters in the Mt. Elgon aquifer region is critical where the water balance shows a significant portion of surface water fluxes.
- Transboundary shared aquifer management policies and frameworks to include data sharing protocols across the region to support initiatives that generate and require to equip/run water budget accounting tools and models over temporal, spatial and projected frameworks.
- Dedicated groundwater level and quality monitoring proximate to surface water and climate observatories is critical for the development and management of groundwater and its interaction with surface water resources in the Mt. Elgon aquifer region.
- Alternative approaches (e.g. use of chemical isotopes and tracers) to provide complementary information on groundwater dynamics and interactions with surface water in a region with a dearth of datasets.
- Harnessing of relevant remote sensing approaches (e.g. gravity, infrared and altimetry methods) to support limited collection of in situ datasets from inaccessible terrains in the region for both surface water and groundwater systems.

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Acronyms

AWMZ	Albert Water Management Zone
BMZ	The Federal Ministry for Economic Cooperation and Development
CAAC	Catchment Area Advisory Committee
CAO	Chief Administrative Officers
CBO	Community Based Organization
CBWRM	Catchment Based Water Resources Management
CCD	Climate Change Department
C-DLB	Chairperson District Land Board
CDO	Community Development Officers
CFA	Community Forest Association
CIDP	County Integrated Development Plan
Client	Nile-SEC
CMC	Catchment Management Committee
CMO	Catchment Management Organisations
CMP	Catchment Management Plan
CMS	Catchment Management Secretariat
COVID-19	Corona Virus Disease - 2019
CSF	Catchment Stakeholder Forum
CSO	Civil Society Organisation
CTC	Catchment Technical Committee
D&DP	Donor and Development Partners
DAIMWfAP	Department of Agricultural Infrastructure, Mechanisation, and Water for Agricultural Production
DCDO	District Community Development Officer
DDP	District Development Plan
DEA	Directorate of Environmental Affairs
DEA-RWO	DEA Regional Wetlands Office
DEdO	District Education Officer
DEO	District Environment Officers
DESS	Department of Environmental Support Services
DFO	District Forest Officer
DGSM	Directorate of Geological Survey and Mines
DHD	District Health Department
DLG	District Local government
DNRO	District Natural Resources Officer
DPO	District Production Officer
DPP	Directorate of Physical Planning
D-PP	District Physical Planner
DRC	Democratic Republic of Congo
DWD	Uganda Directorate of Water Development
DWO	District Water Officers
DWRM	Uganda Directorate of Water Resources Management
DWSSC	District Water and Sanitation Coordination Committee
ECOTRUST	The Environmental Conservation Trust of Uganda
EMCA	Environmental Management and Co-ordination Act
ENRM	Environmental Natural Resources Management
ENSAPT	Eastern Nile Subsidiary Action Programme Team
EU	European Union
FAO	Food and Agricultural Organization
FBO	Faith Based Organization
FGD	Focus Group Discussions
FSSD	Forestry Sector Support Department
GDS	Government Deconcentrated Structures

GEF	Global Environment Facility
GFS	Gravity flow scheme
GIS	Geographical Information System
GMS	Groundwater Modelling System
GOK	Government of Kenya
GRACE	Gravity Recovery and Climate
GW/SW	Groundwater/Surface water
IC	International Consultant
ICRAF	International Council for Research in Agroforestry
IGAD	Intergovernmental Authority for Development
IGRAC	International Groundwater Resources Assessment Centre
ITWAD	International Transboundary Water Affairs Department
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
KADILAC	Kapchorwa District Landcare Chapter (KADILAC)
KFS	Kenya Forest Service
KNBS	Kenya National Bureau of Statistics
KfW	Kreditanstalt für Wiederaufbau
KWMZ	Kyoga Water Management Zone
L.sum	Lumpsum
LC5	Local Council 5
LG-S	Local Government Structures
MAAIF	Ministry of Agriculture Animal Industry and Fisheries
masl	metres above sea level
mbgl	metres below ground level
MDAs	Ministries, Departments and Agencies
MEMD	Ministry of Energy and Mineral Development
MFPED	Ministry of Finance, Planning and Economic Development
MIS	Management Information System
MLG	Ministry of Local Government
MODFLOW	finite-difference groundwater model
MOH	Ministry of Health
MoLHUD	Ministry of Lands, Housing and Urban development
MoTIC	Ministry of Trade, Industry and Cooperatives
MoTWA	Ministry of Tourism, Wildlife and Antiquities
MWE	Ministry of Water and Environment, Uganda
MWI	Kenya Ministry of Water and Irrrigation
NAADS	National Agricultural Advisory Services
NaFORRI	National Forestry Resources Research Institute
NARO	Uganda National Agricultural Research Organisation
NBI	Nile Basin Initiative
NELSAP	Nile Equatorial Lakes Subsidiary Action Program
NELSAP CU	Nile Equatorial Lakes Subsidiary Action Program Coordination Unit
NEMA	National Environment Management Authority
NEMA-RO	NEMA Regional Office
NFA	Uganda National Forestry Authority
NFA-SO	NFA Sector Office
NGO	Non-governmental Organization
Nile basin	Countries include Rwanda, Burundi, DRC, Uganda, Kenya, Tanzania, South Susan, Ethiopia, Sudan, Eritrea, and Egypt
Nile-COM	Nile Council of Ministers
Nile-SEC	Nile Basin Initiative Secretariat
Nile-TAC	Nile Basin Technical Advisory Committee

NRD	Natural Resources Departments
NRM	Natural Resources Management
NWRA	National Water Resources Assessment
NWSC	National Water and Sewerage Corporation
O&M	Operation & Maintenance
OPM	Office of the Prime Minister, Uganda
PIBID	Presidential Initiative on Banana Industrial Development
PRA	Participatory Rural Appraisal
PS	Physical Sciences Consultant
PSFU	Private Sector Foundation of Uganda
RAIN	RAIN-Uganda
RDC	Resident District Commissioners
RED	Renewable Energy Department
RWRC3	Rural Water Regional Center -3
RWSSD	Rural Water Supply and Sanitation Department
RWTSUs	Regional Wetlands Technical Support Units
SADA	Shared Aquifer Diagnostic Analysis
SAP	Strategic Action Program
SAS	Senior Assistant Secretary
SC	Social Sciences Consultant
SDG	Sustainable Development Goals
SEP	Stakeholder Engagement Plan
SVIP	Sironko Valley Integrated Projects (SVIP)
TBA	Trans-boundary aquifers
ToR	Terms of Reference
TSU	Technical Support Units
UBOS	Uganda Bureau of Statistics
UFA	Uganda Forestry Authority
UIA	Uganda Investment Authority
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNMA	Uganda National Meteorological Authority
UNWMZ	Upper Nile Water Management Zone
UO	Umbrella Organisations
UWA	Uganda Wildlife Authority
UWASNET	Uganda Water and Sanitation NGO Network
UWS-E	Umbrella of Water and Sanitation East
UWSSD	Urban Water Supply and Sewerage Services Department
VWMZ	Victoria Water Management Zone
WB	World Bank
WfP	Water for Production
WfPD	Water for Production Department
WfPRC-E	Water for Production Regional Centre East
WMD	Wetlands Management Department
WMZ	Water Management Zone
WQMD	Water Quality Management Department
WRA	Water Resources Assessment
WRA	Kenya Water Resources Authority
WRMAD	Water Resources Monitoring & Assessment
WRPRD	Water Resources Planning & Regulation
WRUA	Water Resource Users Association
WSDF	Water Supply Development Facilities
WSDF-E	Water and Sanitation Development Facility East
WSDF	Water Supply Development Facilities
WSGS	Water and Sanitation Gender Strategy

WSRB	Water Services Regulatory Board
WUC	Water User Committees
ZARDI	Zonal Agricultural Research and Development Institute

1. INTRODUCTION

1.1 Background and rationale

Groundwater resources may not be strictly non-renewable, however, in certain cases, the residence time is extremely long spanning thousands of years, which is ideally longer than the normal human activities and water resources planning initiatives. In such cases, there is definitely a need for sufficient knowledge that can ensure adequate management and planning strategy. Within the Nile Basin, there has been a steady increase in groundwater resilience due to increasing water abstraction. However, over-abstraction is quickly depleting the available groundwater resources. Further, natural recharge is under threat due to high climate variability and land use/land cover changes that lead to declined surface water/ground water interactions. The threats on transboundary aquifers are much more severe due to lack of unified groundwater governance and management mechanisms. It is therefore critical to increase our understanding of the unique groundwater properties through detailed investigations, mapping and assessment.

The Nile Basin Initiative (NBI) is a cooperative arrangement initiated and led by the Nile riparian countries to promote joint development, protection and management of the common Nile Basin water resources. One of the key result areas NBI Secretariat (Nile-SEC) implemented Basin Wide Program focuses on is trans-boundary groundwater aquifers. With the financial support of the Global Environment Facility (GEF) through United Nations Development Program (UNDP), the Nile-SEC will implement its first groundwater study project with the objective of enhancing knowledge and capacity for sustainable use and management of transboundary aquifers and aquifers of regional significance in the Nile Basin. This project has five components aiming at strengthening the overall water resources management nationally and basin-wide.

Along the Nile basin countries, reliance on groundwater is rapidly increasing due to the increased demand over water supply. There is ample evidence that groundwater recharge in the Nile basin is under threat. This is partly attributed to climate change, high rainfall variability, and land use/land cover changes leading to declining amount of surface/ground water interaction in different areas. The interaction between groundwater and surface water systems (rivers, wetlands, lakes) has not been adequately considered within the Nile basin. The threats on trans-boundary aquifers are more severe because of lack of common groundwater governance and management mechanisms. Therefore, it is of vital importance to build and expand on the understanding of groundwater resources characteristics through detailed investigation, mapping and assessment of the Nile basin aquifer systems. This project will also enhance the understanding of the implications of impacts of potential climate change scenarios on the overall basin surface and groundwater resources in the Nile. The socioeconomic context is also an important issue in groundwater management for sustainable use and protection that needs to be properly addressed through stakeholder's engagement in a participatory approach for adequate groundwater management systems. Because across the Nile basin groundwater has been inadequately studied, this assignment shall improve the understanding of the characteristics of the transboundary Mt. Elgon Aquifer.

1.2 Programme objectives

The project objective was to enhance knowledge and capacity for sustainable use and management of trans-boundary aquifers and aquifers of regional significance in the Nile Basin. Specific objectives included to:

- Improve knowledge and understanding of groundwater resources in the Nile Basin;
- Strengthen overall water resources management nationally and basin-wide;
- Respond to climate change impacts through effective risk-reduction adaptation measures - e.g. conjunctive use and management of surface water and groundwater;
- Ensure a healthy ecosystem and strengthened livelihood.

The project comprises the following five (5) components with the current study focusing on Component 1:

- **Component 1: Furthering knowledge and understanding about availability of groundwater resources in the selected aquifers underlying watersheds in the sub-basins of the Eastern Nile and the Nile Equatorial lakes**;
- Component 2: Development of action plans on groundwater resources governance, management, and protection for inclusion in national, sub-basin frameworks: – also including consideration of surface water/groundwater resources conjunctive use;
- Component 3: Targeted pilot projects to explore conjunctive use of surface and ground waters, and links to biodiversity conservation and climate change adaptation;
- Component 4: Further strengthening capacity to address groundwater issues at the national and regional levels;
- Component 5: Communications and awareness raising;

Three aquifer areas were chosen for the current intervention, namely The Kagera aquifer shared among Burundi, Rwanda, Tanzania and Uganda; The Mt. Elgon aquifer shared between Kenya and Uganda; and the Gedaref-Adigrat aquifer shared between Ethiopia and Sudan. The aquifers are located in diverse ecological zones ranging between arid, semi-arid and tropical. This assignment aimed at fostering current mutual understanding for the groundwater flow regime and mechanism of recharge, policies, management systems, community engagement and sustainable development plans for effective utilization and protection from over abstraction, depletion and pollution.

1.3 Assignment objectives and outputs

The main objective of the modelling assignment was to generate water balance modelling scenarios under various stress conditions including climate change for the Mt. Elgon aquifer with quantified: recharge, outflows (base flow, deep percolation, etc.) and withdrawals from 2021 to 2050 applying different management parameters.

The assignment outputs include:

1) Development of conceptual and numerical groundwater models at a transboundary scale
2) Development of numerical models projecting different socio economic and climate scenarios from present to the year 2050 in the horizon for selected SSPs (Shared Socioeconomic Pathways), and range of climate change scenarios to identify strategic recommendations for sustainable management and utilization of Mt Elgon aquifer.
3) Identification of key threats to sustainability of shared groundwater aquifers (climate change scenarios, increased/unsustainable withdrawals, land use/change).

4) Generated historical, recent and future scenarios for different trends in aquifer recharge as a result of changes in precipitation or land use/cover will be quantified and documented
5) Training materials on transboundary groundwater modelling for the aquifer system
6) Recommendations for sustainable conjunctive groundwater – surface water use covering technical aspects.

1.4 Report structure

The study involves Mr. Robert Naguyo, the groundwater modeller on the Ugandan side; Mr. Sospeter Simiyu Wekesa, the groundwater modeller on the Kenyan side; and, Dr. Michael Owor, the international modelling consultant for the Mt. Elgon aquifer.

This Mount Elgon Aquifer Modelling Report B report integrates the contributions from the national groundwater modelling reports B of Kenya and Uganda. The report summarizes the background and rationale for the study, shared aquifer characteristics, materials and methods, model conceptualisation, numerical flow model generation, and model projections under increasing demand and climate change.

2. SHARED AQUIFER CHARACTERISTICS

2.1 Policy, governance and institutional frameworks

The details of the policy, legal and institutional frameworks relevant to water resources management is reviewed in the Mt. Elgon aquifer final SADA report (2023).

2.1.1 Policies

Kenya

In Kenya national policies and legislation include The Constitution 2010; Water Act 2016; National Water Resources Management Strategy; The Water Services Regulations 2021 (Legal Notice No. 168 of 2021); The Water Harvesting and Storage Regulations 2021 (Legal Notice No. 169 of 2021); The Water Resources Regulations 2021 (Legal Notice No. 170 of 2021); The Irrigation Act 2019; The Climate Change Act, 2016; The Environmental Management and Co-ordination Act (EMCA) 1999 (amended 2015); The Agriculture Act 2012; National Water Master Plan 2030;

Kenyan related policies and plans include The Sessional Paper No.1 of 2021 on National Water Policy; National Land Policy; Policy on Environment and Development; Policy on Climate Change; Rainwater Harvesting and Storage Strategy (2019); The Environmental Management and Co-ordination Act 2015 (EMCA); Public Health Act Chapter 242; National Policy on Gender and Development, 2020; Other Legal Instruments includes Land laws; Environmental Impact Assessment Guidelines; Cultural Heritage laws; National Labour and employment Laws; National Child Protection Laws; National Laws on Vulnerable and Marginalized groups;

At the county level Busia County has developed the Water and Sewerage Services Act 2015, Bungoma County has developed a Draft Water Policy 2020 while Trans-Nzoia County is yet to develop a Policy or an Act; Bungoma County Water Policy (Draft, 2021); Busia County Water and Sewerage Act, 2015;

Uganda

In Uganda national policies and regulation include The Constitution of the Republic of Uganda (1995); National Water Policy (1999); National Policy for the Conservation and Management of Wetland Resources (1995); Uganda National Land Policy; National Forestry Policy; The Renewable Energy Policy for Uganda; Water Act Cap 152 (1997); National Environment Act (1995); National Climate Change Policy (2015).

Regional

At a regional level policies geared towards the protection, conservation and use of water resources in the Nile River Basin include the NBI Environmental and Social Policy June 2013; NBI Wetland Management Strategy June 2013; NBI Communication and Stakeholder Engagement Strategy 2018-2023; NBI Information Disclosure Policy; NBI Climate Change Strategy June 2013; National Gender Policies of project countries; NBI Gender Mainstreaming Policy and Strategy July 2012; NBI Strategy for Management of Environmental Flows; East African Community policies; International policies and procedures related to the ESMF; Indigenous/Vulnerable People Policies.

Uganda is party to the Protocol for Sustainable Development of Lake Victoria Basin and Nile Basin Initiative; 2.1.5 Legal Framework for the Sustainable Management of the Nile Waters (e.g. Agreed Curve for the Lake Victoria Release; Nile Basin Cooperative Framework Agreement; The Lake Victoria Basin Commission);

International
International conventions include the Ramsar Convention (1971); UN Framework Convention on Climate Change (UNFCCC) and related Kyoto Protocol; UN Convention on Biological Diversity; International conventions for shared water resources; UN SDG 6: Clean Water and Sanitation; Helsinki Declaration on the protection of the ozone layer (1989).

2.1.2 Governance frameworks

Kenya
Groundwater governance is included within frameworks of Groundwater management instruments; Catchment areas and catchment management strategies; Groundwater development and allocation; Groundwater conservation areas (GCAs); Water rights and water permits; Regulating the construction of wells and boreholes; Wastewater licensing; Controls on development in recharge/discharge zones and pollution;

Uganda
Integrated Water Resources Management (IWRM) includes the Policy Committee on Environment; The Water Policy Committee; The IWRM Working group, The Water and Environment Sector Working Group (WESWG); The Inter-Ministerial Technical Committee regarding Water for Production; The Wetlands Advisory Group (WAG); Water Net;

At regional levels are Water Management Zones (WMZ; Water and Sanitation Development Facility (WSDF); Technical Support Units (TSU); Umbrella Organizations (UO); Water Supply and Sanitation Boards (WSSBs);

At catchment levels are Catchment Management Organisations (CMOs); The Catchment Stakeholder Forum (CSF); The Catchment Management Committee (CMC); Catchment Managemen Plans (CMP); The Catchment Management Secretariat (CMS); The Catchment Technical Committee (CTC);

2.1.3 Institutional arrangements

Kenya
Ministry of Water and Irrigation (MoWI) is responsible for Water Resource Management (e.g. Water Resources Authority, WRA; Basin Water Resource Committee, BWRC; Water Resource User Associations, WRUAs); Water Supply and Sewerage Services (e.g. Water Services Regulatory Board, WASREB; Water Works Development Agencies, WWDAs; Water Services Providers, WSPs); Other relevant institutions (e.g. Water Tribunal; Water Sector Trust Fund; National Water Storage Authority; Water Service Regulatory Board, WSRB; National Water Conservation and Pipeline Corporation);

Uganda

Ministry of Water and Environment (MWE) has three directorates: Directorate of Water Resource Management, DWRM comprises of four departments namely Water Resources Monitoring and Assessment Department, Water Resources Planning and Regulation Department, Water Quality Management Department and the International Transboundary and Water Affairs Department; the Directorate of Water Development, DWD has the departments of Rural Water Supply and Sanitation, Urban Water Supply and Sewerage Services, Water Utility Regulation and Water for Production; and the Directorate of Environmental Affairs, DEA comprises of three departments of Environmental Support Services, Forestry Sector Support Department and Wetlands Management Department; MWE further works closely with four semi-autonomous entities namely: the National Environment Management Authority (NEMA); the National Water and Sewerage Corporation (NWSC); the National Forest Authority (NFA); and the Uganda National Meteorological Authority (UNMA); Other national entities significantly impacted by technical water management issues are the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF); Ministry of Tourism, Wildlife and Antiquities (MoTWA) including Uganda Wildlife Authority (UWA); Ministry of Energy and Mineral Development (MEMD). The Ministry of Education and Sports (MoES); Ministry of Health (MOH); Ministry of Local Government (MLG); Uganda Water and Sanitation NGO Network (UWASNET); Office of the Prime Minister, Uganda (OPM);

At the District level, the District Natural Resources Department (including the District Environment Office, District Forestry Office, and District Wetlands Office), District Works or Engineering Department under which the District Water Office falls, District Production Department with the District Agricultural Office, District Veterinary Office and District Fisheries Office, District Planning Department, Department of Community Based Services, District Information Department, and District Health Department are key in the implementation of the CMP.

Regional level

At the regional level, the institutions responsible for protection, management and promoting equitable access and use of Nile water resources, including shared aquifers includes the Nile Council of Ministers (Nile-COM); The Nile Technical Advisory Committee (Nile-TAC); The NBI Secretariat (Nile-SEC); NELSAP CU; Eastern Nile Council of Ministers (ENCOM); and Eastern Nile Subsidiary Action Programme Team (ENSAPT).

2.2 Shared aquifer extent

Mt. Elgon aquifer is a trans-boundary aquifer (TBA) shared between Kenya and Uganda (Fig. 2.1), with an initial estimated area of about 4,900 km^2 (IGRAC, 2021), and ~85% lying within the Nile Basin. The boundaries of the aquifer system were delineated during the IAEA Project No. AF39, covering the middle to upper sections of Mount Elgon and excluding its foot slopes (IGAD, 2011). The aquifer extends from Mt. Elgon which is a solitary extinct volcano straddling the Kenya-Uganda border. On the Ugandan side, the aquifer region is conceptualised to lie within the Lakes Kyoga and Turkana basins and underlies at least nine (9) districts of Kapchorwa and Kween (fully within the aquifer region), others including Amudat, Bududa, Bukwo, Bulambuli, Nakapiripirit, Namisindwa and Sironko, which span largely two (2) catchments of Awoja and Mpologoma. Sub-catchments that are wholly within the aquifer region include Sipi, Muyembe, Simu-Sisi, Lwakhakha and Upper Manafwa. The sub-catchments that are partially within the aquifer region include, Muchilmakat, Chebonet-Atari, Kelim, Sironko, Taboki, Lake Okolitorom, Namatala, and

Middle Manafwa. On the Kenyan side the aquifer region is within the Lakes Victoria and Turkana basins and spans four (4) Counties; West Pokot, Busia, Trans-Nzoia (sub-counties of Endebes and Saboti) and Bungoma (sub-counties of Mt. Elgon, Sirisia, Kimilili and Kabuchai). The greater modelled region includes Trans Nzoia, Busia, West Pokot, and Bungoma Counties. It covers the areas of Kacheliba, Kapenguria, Endebes, Kitale, Saboti, Kiminini, Kaptama, Kapsokwany, Kimilili, Chwele, Webuye, Sirisia, Lwakhaha, Malaba, and Bungoma.

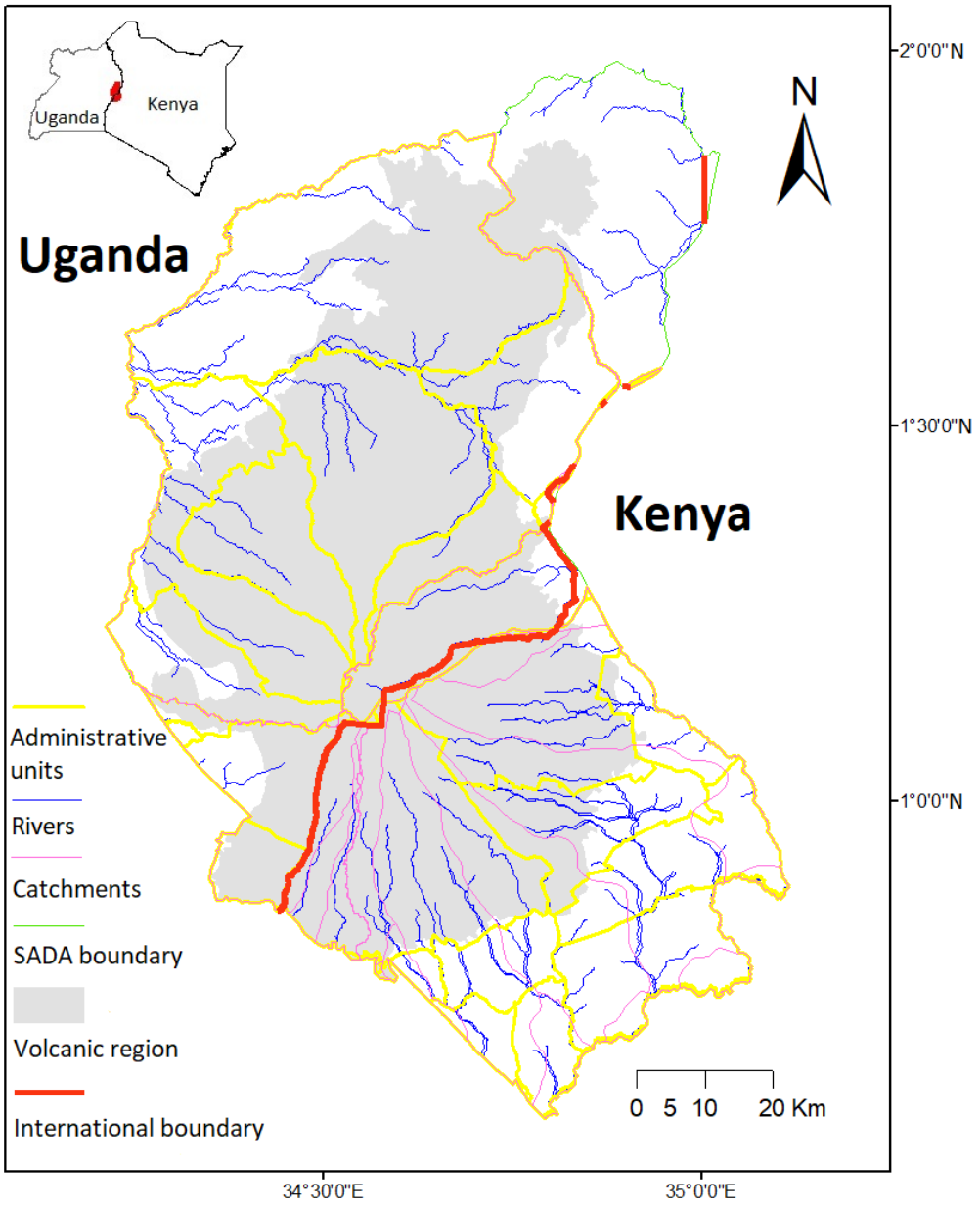


***Figure 2.1**: Map of extent of the Mount Elgon SADA beyond the volcanic region within the drainage basins and administrative districts of Uganda and counties of Kenya (Inset: maps of Uganda and Kenya).*

2.3 Physiography and drainage

Mt. Elgon is a solitary extinct Pliocene shield volcano with one of the largest craters in the world, about 8 km in width, located in the western part of Kenya, in Trans Nzoia County and bisected by the Kenya Uganda border. A digital terrain model was generated from the ALOS PALSAR High-Resolution DEM with a resolution of 12.5m that is radiometric terrain corrected (ASF, 2022) (Figs. 2.2 a and b). The southern edge of the aquifer extent is marked by Mount Elgon at the border between Uganda and Kenya. Mount Elgon with its craters, deep valleys and ridges rise to the highest peak in the area forming an undulating topography. Mount Kadam lies within the northern extreme portion of the aquifer boundary between Amudat and Nakapiripirit districts. The altitude of the region ranges from less than 1,040 m above sea level (masl) to over 4,321 masl at the peak of Wagagai. Much of the aquifer area lies at an altitude ranging from 1042 to 4279 masl. The rest of the area in between the two mountain ranges, lies between 938 and 1156 masl (Awoja CMP, 2017; Mpologoma CMP, 2017). Cross sections drawn north to south and east to west of the physiography of the Mount Elgon aquifer region derived from Google Earth Pro show that the terrain to the north and east is lower lying and more rugged than the terrain to the east and south which is higher and slopes more gently away from the volcanic massif.

Drainage over the slopes of Mt. Elgon is largely radial towards streams on the foot slopes joining to form larger rivers that drain into Lakes Kyoga, Turkana or Victoria. Rivers on the Kenyan side include Kuywa, Sosio, Kibisi, Sio-Malaba/Malakisi, Ewaso-Rongai Noigamaget and Sabwani (Fig. 2.2c). These rivers are the major tributaries of River Nzoia which drains into Lake Victoria. The water from the rivers is utilized for domestic consumption, small scale irrigation and also have potential for hydroelectric power generation to support rural electrification, industrialization and fisheries. These activities could be a mitigation towards floods in the county. River Nzoia catchments and its tributaries are however threatened by encroachment, agriculture and other human activities. In the Kitale Plain, the principal river is the Koitoboss which rises from the foot of the Koitoboss peak. The other major river in the area is River Suam which originates from the Mt. Elgon slopes. River Nzoia originates from the Mount Elgon area and flows southwards to Lake Victoria while River Sipi originates from the northeastern part of Mt. Elgon and flows towards the central Nile Basin (Rannveig and Bernardas, 2012).

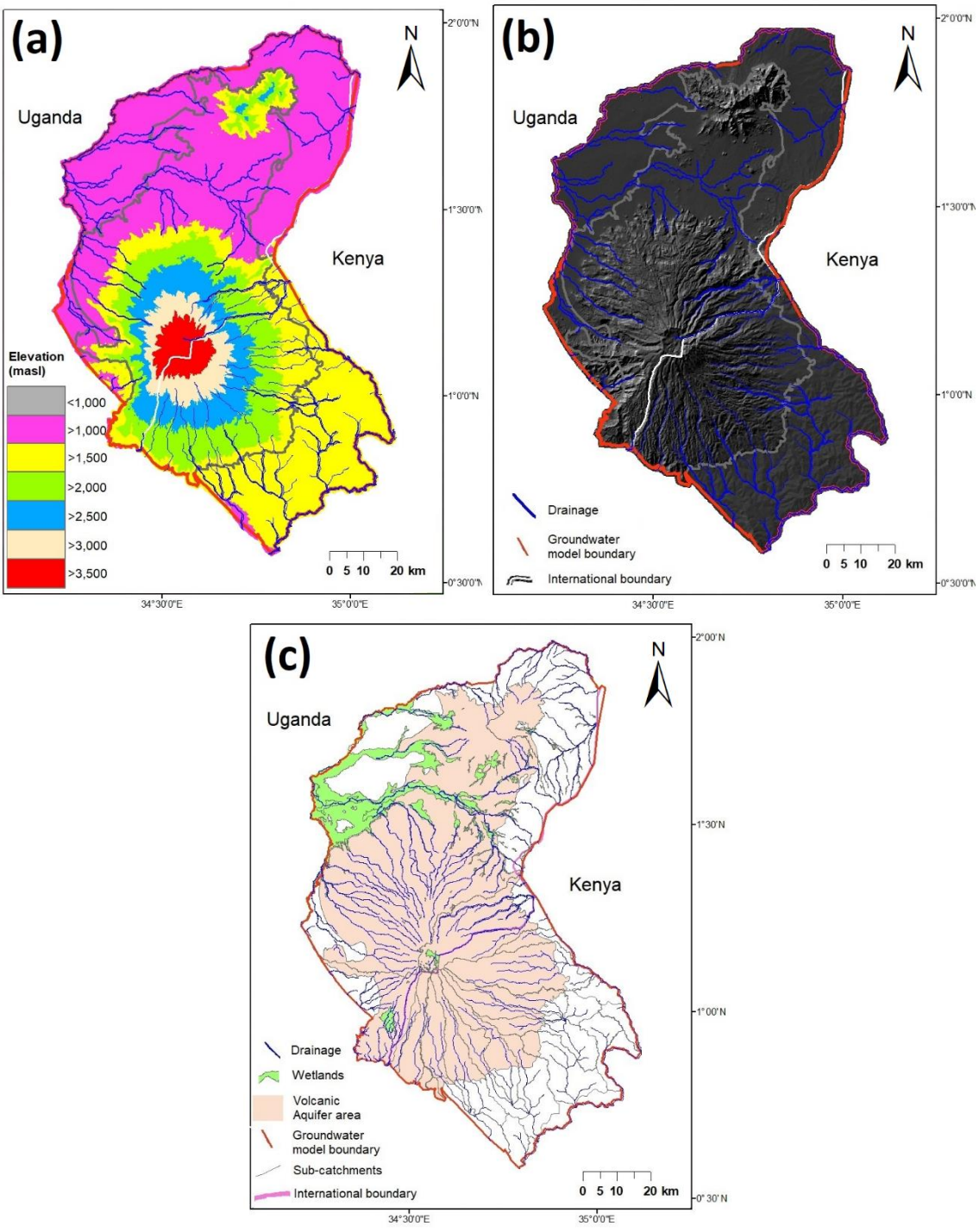


***Figure 2.2**: Maps of the Mt. Elgon aquifer region shared between Uganda and Kenya showing (a) digital terrain model derived from the 12.5m resolution ALOS PALSAR DEM (ASF, 2022); (b) topographic hill shade relief with main drainage; (c) main drainage and sub-catchments.*

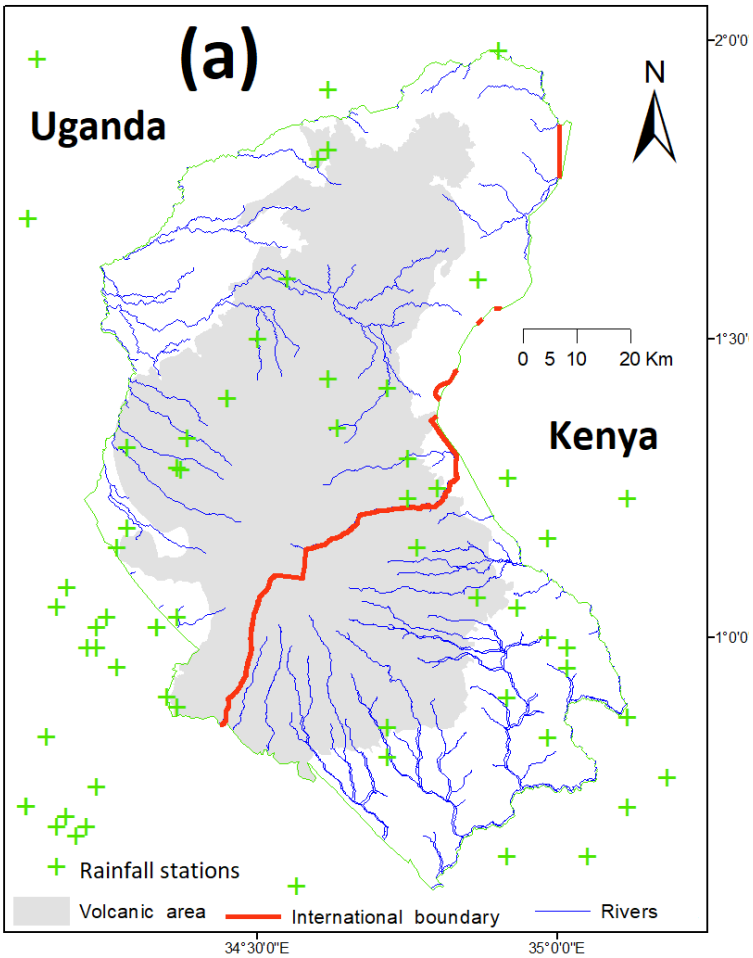
2.4 Climate

The area being within the Inter Tropical Climatic Zone (ITCZ) experiences four seasons annually (Fig. 2.3a). The first (heavier) rain seasons normally stretch from March to May and the second (lighter) rains from October to November. Dry seasons occur in the months of January to February and June to September. There is more rainfall in the foothill zones of Mount Elgon, with an average of 1,270 mm the minimum recorded being 1,016 mm and the maximum 1,549 mm. This region lies largely within the highland climatic zone having an average annual rainfall of 1500 mm. The climate of the region is highland equatorial with an annual rainfall of 700 to 1,800 mm. Despite being just 2^{o} from the Equator, the altitude results in the area having a relatively mild climate, with annual patterns dominated with rainfall rather than radiation. Much of the area is well-watered with the exception of Amudat and Nakapiripirit districts in Uganda and can support rain-fed agriculture, although seasonality varies across the southern and the northern parts of the aquifer region where seasonal droughts are a common feature. The aquifer area around Mt. Elgon experiences high bimodal annual rainfall of between 1500 and 2000 mm. At the Mt. Elgon foothills and slopes, rainfall decreases from south to north with the northern slopes falling within the rain shadow of the mountain. The northern part of the area in Amudat and Nakapiripirit districts of the Karamoja sub-region, generally experience erratic rainfall whose annual mean is 745 mm which is not conducive for crop production. Stations in eastern Uganda show mean annual rainfall (1991-2020) from 727 mm in Kotido to the north to 2126 mm in Buginyana within the Mt. Elgon aquifer region (Figs. 2.3b). Figures 2.3c illustrates 44 rainfall stations located on the Kenyan side with daily records from 1931-2004. Mean monthyl rainfall ranges from 17.5 to 63.8 mm with a mean values of 39.1 mm. On the Kenyan side rain falls throughout the year in the region. The month with the most rains April, with an average rainfall of 180 mm. The month with the least rain is January, with an average rainfall of 33 mm. A wet day is one with at least 1 mm of liquid or liquid-equivalent precipitation. The chance of wet days varies very significantly throughout the year. The wetter season lasts 7.9 months, from March to November, with a greater than 43% chance of a given day being a wet day. The month with the most wet days in Bungoma is August, with an average of 21.4 days. The drier season lasts 4 months, from November March. The month with the fewest wet days is January. Annual rainfall amount increases in the direction of the great lakes region. The high rainfall amount and the distribution over the area give an indication of the potential of groundwater recharge in the area. Across the Mt. Elgon aquifer region, mean annual precipitation over a period of 2010 – 2020 using 0.05° resolution satellite imagery and rain gauge observations (CHIRPS, 2021) ranges from 687 to 2,544 mm per annum with higher precipitation received on the southern parts of the region (Fig. 2.4a).

The mean monthly temperatures in the southern part of the aquifer area, range between 15 °C and 27 °C while those at the northern extreme part, may go up to 32^{o}C. The forests of the Mt. Elgon National Park are the main potential groundwater recharge areas within the aquifer region. The annual temperature recorded on the Kenyan side varies between 0°C and 32°C due to different levels of altitude, with the highest peak of Mt. Elgon recording slightly less than 0°C. The average wind speed is 6.1 km/hr. In the last decade, the region experienced increasing variability in rainfall and temperature patterns that have influenced changes in agricultural seasons. Stations in eastern Uganda show mean monthly (1991-2020) minimum temperatures ranging from 13.9 ^{o}C in Buginyana to mean monthly (1991-2020) maximum temperatures of 30.5 ^{o}C in Soroti. On the Kenyan side February is the warmest month of the year. The temperature in February averages 22.2 °C. The lowest average temperatures in the year occur in July, when it is around 18.7 °C. The

hot season lasts for 2.2 months, from January 14 to March 21, with an average daily high temperature above 28°C. The hottest month of the year is in February, with an average high of 29°C and low of 16°C. The cool season lasts for 4.2 months, from May to September, with an average daily high temperature below 26°C. The coldest month of the year in the region is August, with an average low of 14°C and high of 25°C.

Data on evapotranspiration was extracted at a 100m resolution from WAPOR (2021) - The FAO portal to monitor water productivity through open access of remotely sensed derived data. The actual evapotranspiration and interception (*ETIa*) is the sum of the soil evaporation (*E*), canopy transpiration (*T*), and evaporation from rainfall intercepted by leaves (*I*). The value of each pixel represents the *ETIa* in a given year (2015-2020). Mean annual actual evapotranspiration and interception varies between 460 and 1800 mm (Fig. 2.4b). The mountain tops have the lowest water loss through evapotranspiration partly due to lack of vegetation with the humid cropped region to the south having the highest losses.



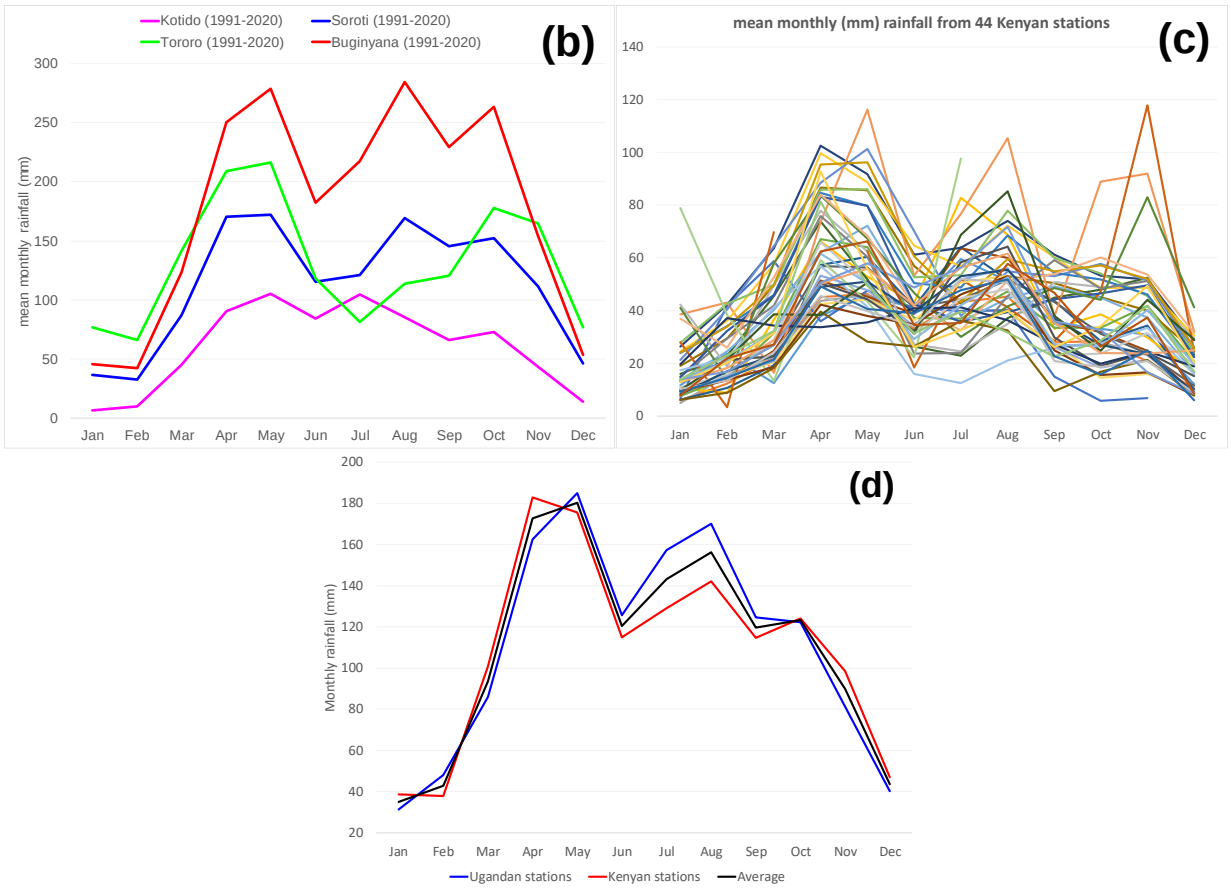


***Figure 2.3**: a) Locations of historical and current rainfall stations in the Mt. Elgon aquifer region; (b) mean monthly rainfall of Eastern Uganda during 1991-2020 (middle left); (c) Kenyan 44 stations mean monthly rainfall of 1931-2004 bottom (middle right); (d) Mean monthly rainfall for stations in the Mt. Elgon aquifer region.*

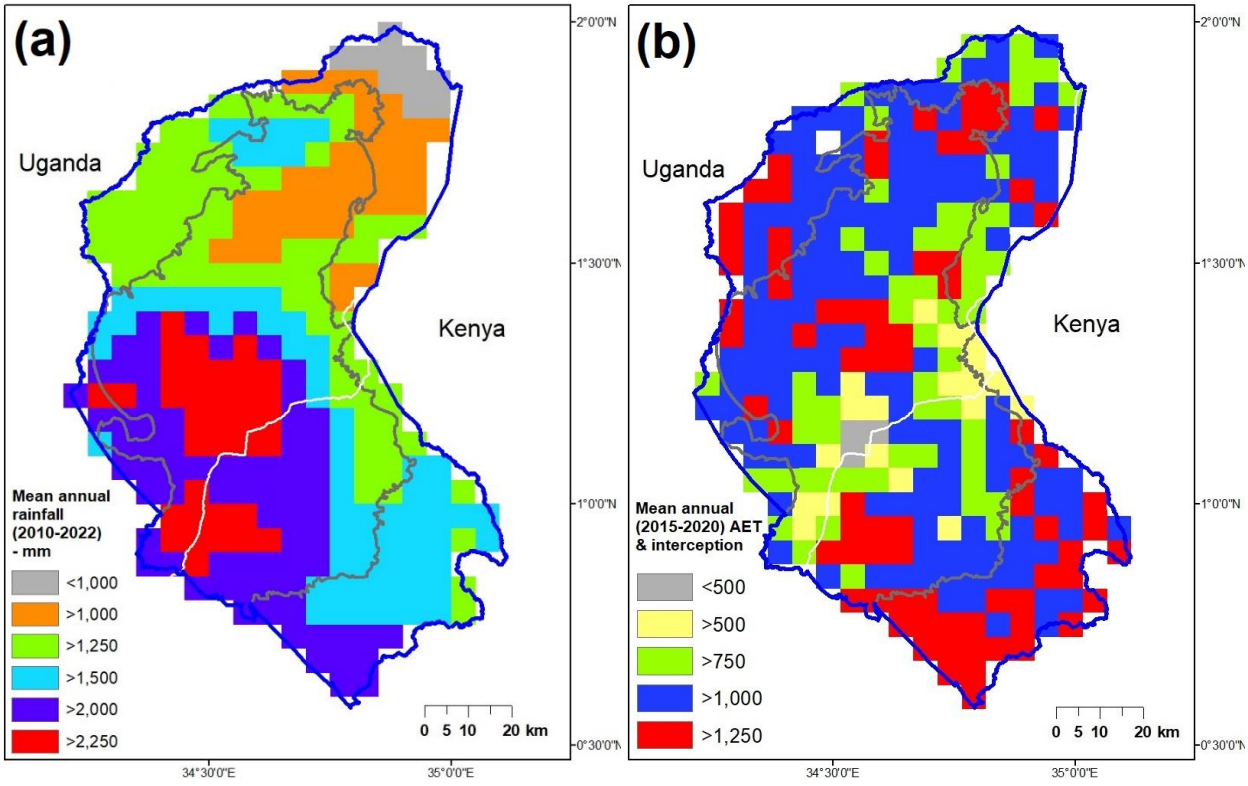


Figure 2.4*: Maps of the Mt. Elgon aquifer region shared between Uganda and Kenya showing (a) gridded mean annual rainfall (2010-2020) adapted from CHIRPS (2021) (left); (b) gridded mean annual (2015-2020) actual evapotranspiration and interception adapted from WaPOR (2021) (right).*

2.5 Regional hydrology

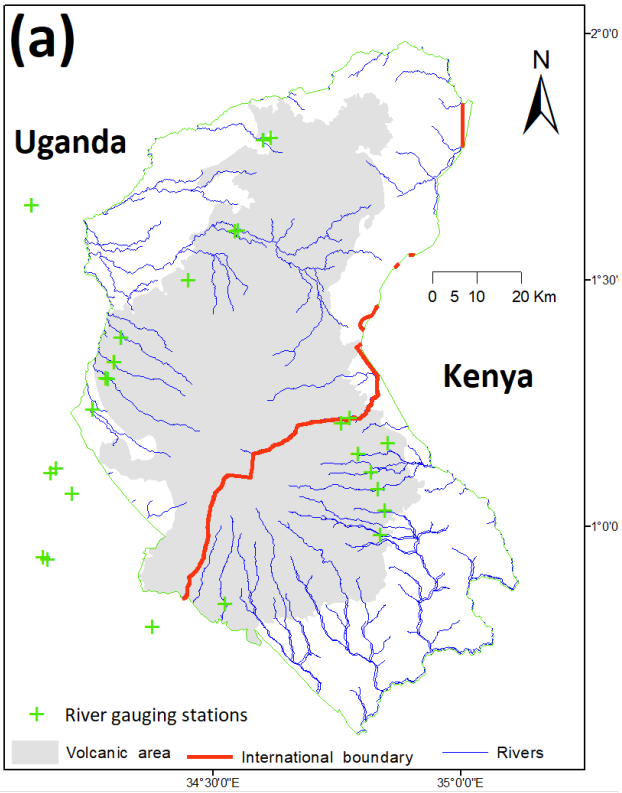
2.5.1 Wetlands and streams

The Mt. Elgon ecosystem support critical terrestrial and wetland habitats in addition to the much-needed ecosystem functions. For example, Nzoia River drains to Lake Victoria through a system of swampy valleys in Bungoma, Uasin Gishu and Trans-Nzoia. These wetlands are also considered to interact and be supported by groundwater systems especially in the Lake Kyoga basin of Uganda (Fig. 2.2c). The different habitats support important biodiversity including birds, mammals, reptiles and amphibians, plants biodiversity. The wetlands in the area are mainly characterized by rivers, springs, swamps and dams. The wetlands range from various sizes and are also under different management systems. The management of these wetlands range from communal, private and government to open access wetlands consequently exhibiting varying levels of threats and biodiversity importance.

2.5.2 River discharge

Most rivers emanating from the slopes of Mt. Elgon are gauged; however, the data is not consistent. The mean monthly river discharge varies with areas of the catchments contributing to the flow at the gauge locations. Major peak flow events occur between March to May (MAM) and June to

September (JAS). During these months, river discharges build up due to surface and subsurface runoff and the rivers recharge groundwater systems. Conversely, the months of December to February is generally dry and the river flows are sustained by groundwater baseflow. The mean monthly river discharge (m3/s) from 1947 to 2000 of 35 stations located on the Kenyan side (Fig. 2.5a) is displayed in Fig. 2.5b. The mean discharge ranges from 3.4 to 8.9 m^3/s with an average value of 9.9 m^3/s. On the Ugandan side daily time series of discharge and level of the main Rivers Manafwa, Namalu, Namatala, Simu, Sipi and Sironko captures large seasonal variations (Fig. 2.5c).



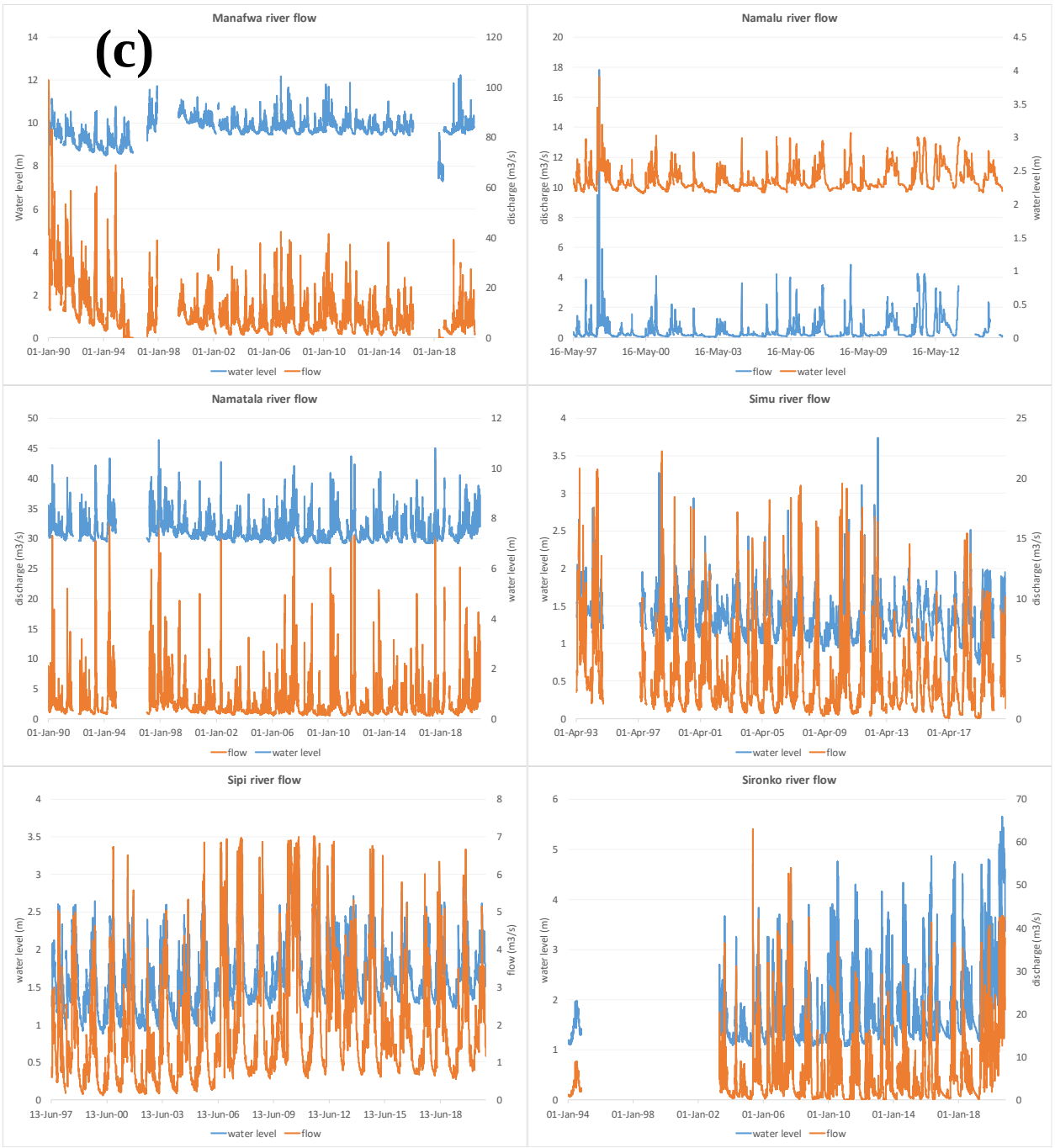


Figure 2.5*: (a) Location of river gauging stations in the Mt. Elgon aquifer region; (b) the mean monthly river discharge (m^3/s) from 1947 to 2000 of 35 stations on the Kenyan side (middle); (c) Daily time series of Rivers Manafwa, Namalu, Namatala, Simu, Sipi and Sironko in Uganda (bottom).*

2.6 Land use land cover

Regionally, the land use and land cover of the Mt. Elgon aquifer region is mapped from the ESA Sentinel-2 imagery at 10m resolution. It is a composite of LULC predictions for 10 classes throughout the year in order to generate a representative snapshot of 2020. The classes broadly include water, trees, shrub, grass, flooded vegetation (wetlands and swamps), crops, built areas, bare land, snow/ice and cloud cover (Fig. 2.6). The southern parts of the Mt. Elgon aquifer region is highy cropped and built up. Around Mt. Elgon is a thick tree cover with shrubs towards its peak. The low-lying northern parts of the region is largely covered by shrub and grasslands.

The area on the Kenyan side has only one gazetted forest, the Mt. Elgon Forest Reserve, which covers an area of 618 km^2, and Mt. Elgon National Park, which occupies 51 km^2. Mt. Elgon area has variable vegetation ranging from grass savanna on the lowlands to montane forest and bamboo on Mt. Elgon slopes. Land use on the lower slopes of Mt. Elgon is intensive with cultivation of maize as the dominant crop. Adjacent to the Mt. Elgon forest are smallholder farmers who largely practice mixed farming but also depend on the forest for their livelihood. The practice of agro-forestry is common with trees like Sesbania (*Sesbania grandiflora*), Calliandra (*Caloundra calothyrsus*) and certain timber and fruit trees are planted together with crops or along the farm borders. However, continued pressure from human activities significantly affects the forest cover. The forests are critical to the climatic conditions of the territorial boundaries of the region and beyond as they are the water catchments for Lakes Turkana and Victoria.

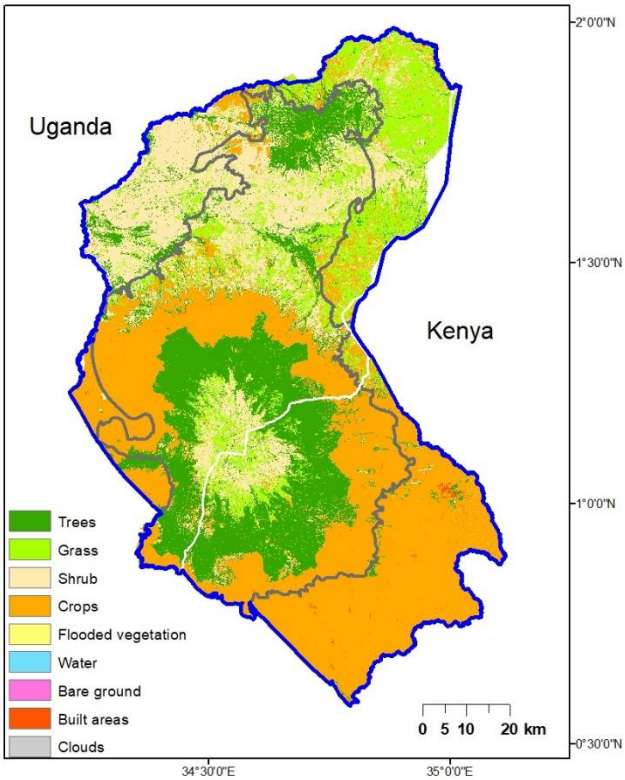


***Figure 2.6**: Land cover and land use around the Mt. Elgon aquifer region of Uganda and Kenya derived from Sentinel-2 of 10-m resolution (adapted from Karra et al., 2021).*

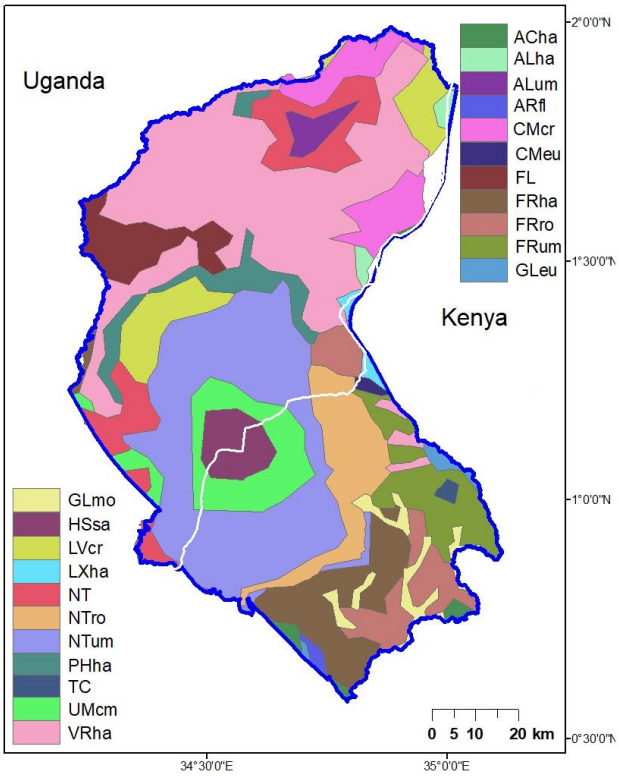
2.7 Regional geology

2.7.1 Soils

The dominant soil type in the Kenyan side of the area is mainly clay. Generally, the soils are well drained, very deep, and red to dark red. This coverage describes both the soil physical and chemical properties of Kenyan soils. It was done by Kenya soil survey (KSS) in 1982 and revised in 1997. The soil cover is reddish brown to grey in colour and supports farming of maize and coffee and other natural and planted trees. There is a close relationship between ferralsols and cambisols which are formed from disintegration of granitic rocks. The granites give rise to coarse light brown, sandy, soils more subject to soil erosion than the more clayey varieties, while the diorites, syenodiorites and syenites, having a greater proportion of mafic minerals, give darker red brown, more clayey, type. The calcareous are moderately sodic and the deeper soils are saline. Nitosols are found at the transition between the MMB rocks and the volcanic. These soils are well drained, deep and dark red.

Most soils in Amudat and Nakapiripirit districts of Uganda are of moderate to high productivity whereas others are categorised to be moderate to low productivity. In this part of the aquifer area, the key issues in relation to land degradation are soil erosion and decreasing soil fertility. Bukwo, Kapchorwa and Kween have soils that can be categorised into three zones which include Mount Elgon high farmlands, farm-forest and short grass plains. The soils in the Mount Elgon high farmlands of Bukwo, Kapchorwa and Kween, are derived almost entirely from volcanic parent materials and are typically red-clay loams, well-drained, highly leached, often acidic, but high in nutrients thus making them highly productive. The forest zone of these districts is characterised by reddish-brown loam soils over deep clay loam subsoils. Clayey soils with often vertic properties characterise the short grass plains of these districts. The Sebei flat plains are in addition characterised by calcareous soils. This zone extends up to the lower steps or terraces of Mount Elgon where the clay loam soils are more often acidic. The rocks on the slopes are deeply weathered; the dominant soils are vertisols, regionally known as “black cotton soils”. The area is highly influenced by past volcanic activities and the soil is very variable. The impermeable nature of most of the rocks makes the adjacent areas of Mt. Elgon vulnerable to landslides during wet seasons. Topsoils are shallow especially around the Mt. Elgon National Park. Generally, the soils in the highlands are clays, while those in the midlands and the lowlands are clay loams or sandy.

Regionally soil data was derived from the European Soil Data Centre (ESDAC, 2014). More than 50% of the Mt. Elgon aquifer region is underlain by haplic vertisols (Fig. 2.7). Other key soil types include haplic ferralsols, eutric gleysols, albic plinthosols, rhodic ferralsols, haplic acrisols, plinthic acrisols, eutric fluvisols, chromic and cambisols.



ACha - Haplic Acrisols; ALha - Haplic Alisols; Alum - Umbric Alisols; ARfl - Ferralic Arenosols; CMcr - Chromic Cambisols; CMeu - Eutric Cambisols; FL - Undifferentiated Fluvisols; FRha - Haplic Ferralsols; FRro - Rhodic Ferralsols; FRum - Umbric Ferralsols; GLeu - Eutric Gleysols; GLmo - Mollic Gleysols; HSsa - Sapric Histosols; LVcr - Chromic Luvisols; LXha - Haplic Lixisols; NT - Undifferentiated Nitisols; NTro - Rhodic Nitisols; NTum - Umbric Nitisols; PHha - Haplic Phaeozems; TC - Undifferentiated Technosols; UMcm - Cambic Umbrisols; VRha - Haplic Vertisols;

***Figure 2.7**: Maps of the Mt. Elgon aquifer region shared between Uganda and Kenya showing categories of the main regional soil types.*

2.7.2 Regional geology and structures

Mount Elgon is located to the west of the Gregory Rift and with an Early Miocene age, is one of the oldest volcanoes in the region. The volcanism is related to the pre-rift stage of the East African Rift System (EARS) which included the initial development of the Kenya-Tanzanian Dome. Doming and volcanism related to a deep-seated magma plume spread southward from the Ethiopian segment of the EARS at approximately 30 Ma. The location of Mt. Elgon is significant because as rifting developed to the half-graben and full graben stages, volcanism in the Gregory Rift shifted both southward and eastward. An unusual feature of the Elgon volcano is that it is built directly upon Basement terranes, as determined by the earliest mapping (Davies, 1952), (Fig. 2.8a). In comparison, most volcanic cones associated with the Gregory Rift are constructed on earlier generations of rift-related volcanic rocks. The western sector of Elgon overlies granite-gneiss of the Central African Craton, part of a more-or-less contiguous Archaean terrane between western Kenya and the Albertine Rift in western Uganda. The eastern sector is located on the metasediments of the Mozambique Belt (Neoproterozoic). Magma may have been fed through a central conduit that exploited a structural weakness on the edge of the craton. The region around Mount Elgon includes a number of pre-Elgon intrusive bodies, including, for example, the Budeda

Hill carbonatite (King et al., 1972; Woolley, 2001). There are also basins dominated by Miocene age sedimentary rocks. A unique cache of Miocene fossils, including mammals, aquatic reptiles, birds, and crabs, has been discovered in a basin near Butwa on the northeastern slopes of Mt. Elgon (Bishop et al., 1969). The Mt. Elgon volcanism is dominated by nephelinitic tephra and agglomerates (Davies, 1952), typical of a group of magmas defined by Baker (1987) as characterising the pre-rift activity of the Gregory Rift. Agglomerates, which can be readily observed on the higher slopes, include clasts which are typically10 cm in size. Locally blocks of nephelinite and phonolite up to 1 m in size occur. Well-bedded tuffs are a subordinate feature (Fig. 2.8b). Lavas (nephelinite and minor phonolite and trachyte) are estimated to contribute less than one per cent by volume of the volcanic pile. The dominance of tephra is consistent with a high explosive index, typical of much of the pre-rift volcanism of the Gregory Rift.

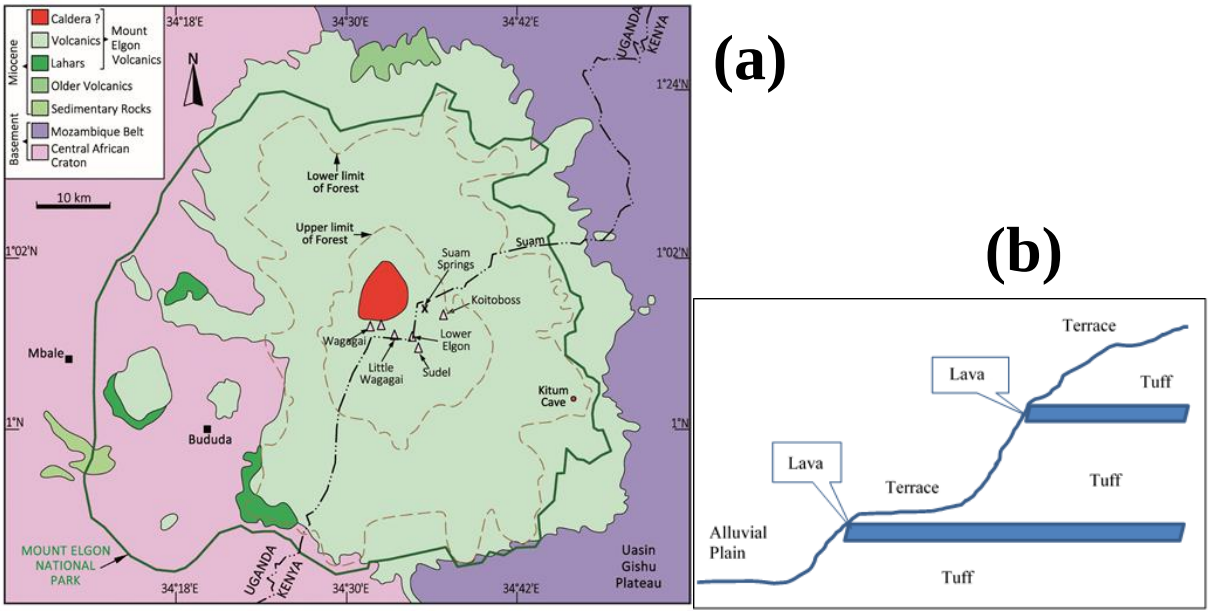


***Figure 2.8**: (a) The geology of the Mt. Elgon simplified from various sources (after Geotraveller 30, 2017); (b) Schematic diagram of Mt. Elgon stratigraphic units on the Ugandan side.*

The region consists of Mozambique Belt (MMB) rocks as the oldest unconformably overlain by Neogene volcanics and Pleistocene to Recent soils as the youngest units (Gibson, 1950; Searle, 1952; Miller, 1956). The MMB rocks consist mainly of quartzite and schist derived from argillaceous and arenaceous sediments which were transformed by metamorphism and recrystallization into quartz and feldspar-rich rocks with much muscovite, biotite, and hornblende minerals. These rocks are fossiliferous and considered to be from the Precambrian. The main members of this unit are conglomerates, mudstone and grits while pebbly grits and sandy mudstones make up the subordinate with different sequence of deposition. The Mt. Elgon Neogene lavas comprise a great mass of agglomerate, breccias and tuff with intercalated bands of lava, the hole having been ejected from a vent during Neogene period. The boulders of lava in the agglomerate are composed of nephelinites that contained minerals such as olivine, augite, magnetite, ilmenite and perovskite similar to the lava flows themselves. Surrounding the caldera produced round the vent are lavas and breccias of phonolitic-nephelenites in which aegirine-augite

and orthoclase appear. The floor of the caldera, lying over 300 meters below the caldera rim and beyond, is composed of volcanic ash, the last eruptive material ejected from the volcano.

The detailed lithology of the main geological formations is summarised as follows;
Mobile Mozambique Belt (MMB) rocks; the rocks in the study area consist of metamorphic rocks that resulted mainly as the effect of pressure, and consequent rise in temperature. These rocks are mainly pelitic schists and gneisses, metamorphosed semi pelitic sediments. Main minerals include quartz, feldspar, muscovite, biotite, and hornblende.

Pelitic schists and gneisses; these rocks include muscovite-quartzite, mica schist and hornblende schists. Biotite-schists were closely associated with the asbestos deposits in some areas forming an outer rim to the zoned bodies. The schists occur within the metamorphic succession, but showed considerable distortion. Inclusions within the muscovite include rutile, zircon and apatite. Chlorite-schists are rare in the area. The outcrops are fine grained, dense, glistening black rocks which outcropped only over narrow widths, suggesting dyke-like forms.

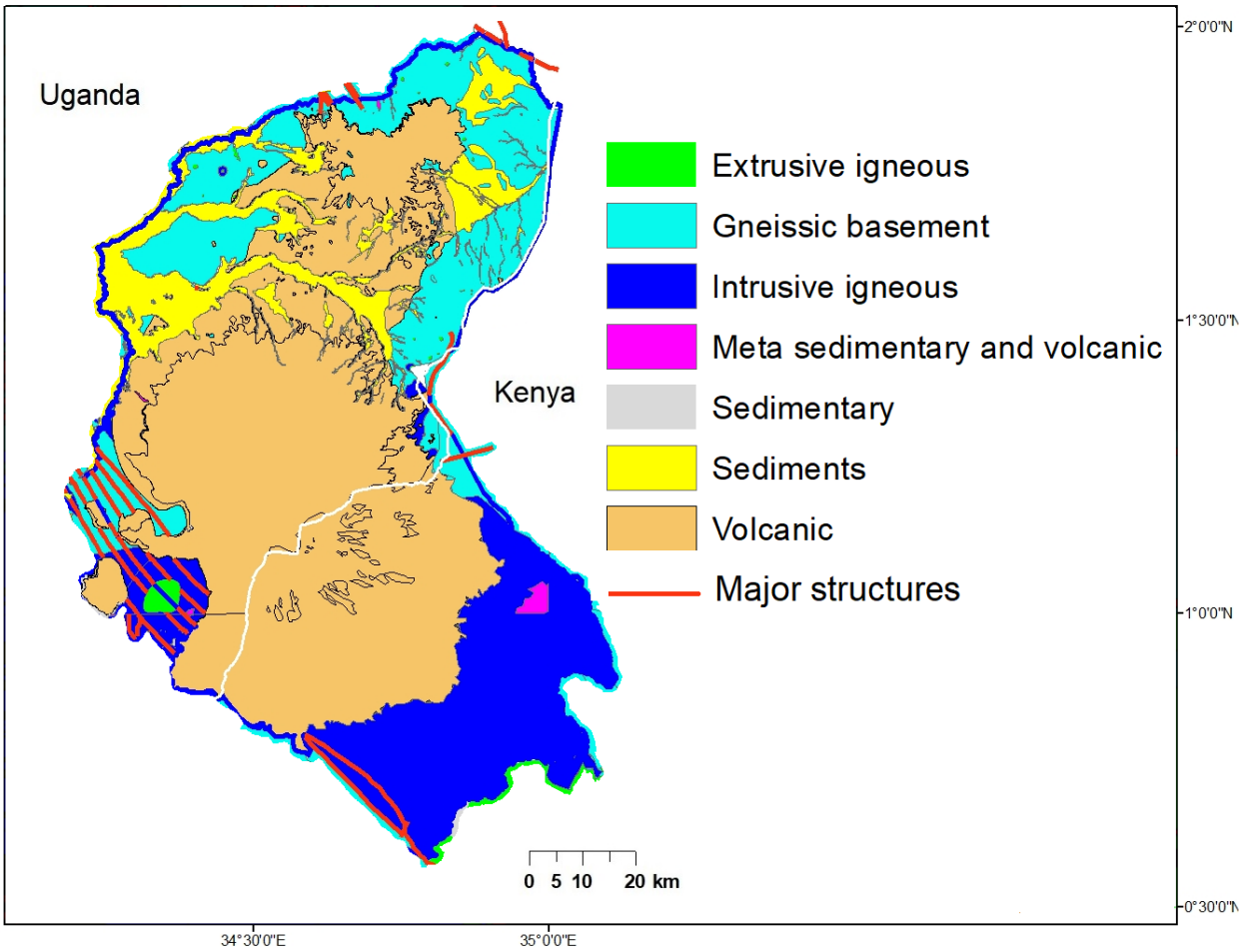
Metamorphosed semi-pelitic sediments; these gneisses are formed by the metamorphism of sandy shales and argillaceous sandstones and are represented in the area by biotite gneisses, feldspar-porphyroblast gneisses and the banded microcline augen gneisses. The semi-pelitic sediments are good indicators of groundwater occurrence and flow due to their porosity and permeability within their individual grains and foliation planes.

Neogene volcanic rocks of Mt Elgon; huge boulders of agglomerates and phonolites occur around Mt. Elgon National Park. Neogene lavas of Mt Elgon are largely composed of the huge mass of agglomerates, breccia and tuffs with intercalated bands of lava, the hole having been ejected from a vent during Neogene times. The boulders of lava in the agglomerates are composed of nephelinites that contain mafic material such as olivine, augite and magnetite. Surrounding the caldera are lavas and breccias of phonolitic-nephelinites in which aegirine augite and orthoclase appear around the vent. The floor of the caldera, lying over 300 metres below the caldera rim, is volcanic ash that mark the last eruptive material ejected from the volcano. Isolated occurrences of nephelinite are found capping hills in the Suk plains. Although the vents through which these lavas were extruded have not been discovered, a volcano plug has been found at Sagat Hill containing agglomerates with associated nepheline-syenite-porphyry intrusions and dykes.

Most geological formations originate from the Precambrian supereon. Large sections of the aquifer are dominated by alkali volcanics including areas around Mount Elgon (one of the oldest volcanoes in East Africa) and Mount Kadam. The portion of Amudat District that lies within the aquifer boundaries is partially Aruan series and partly Quaternary sediments. The lithologies are dominated by volcanic rocks and associated sediments. In the portion of Amudat district within the aquifer boundary, alluvium (sand, silt and gravel) are observed while the central section of the aquifer is overlain by superficial alluvium with associated swamps. (Awoja Catchment Management Plan, 2017). The geology in the Mt. Elgon region comprises of mainly Precambrian and Cainozoic rock formations including volcanics, granites, and sediments. The top of the mountain is characterized by scarps of agglomerates in linear pattern.

The main structural domain is oriented northwest-southeast with a secondary domain in the northeast-southwest (Fig. 2.9). The Aswa shear join forms a southwesterly boundary with the volcanic region rock region in Uganda. It is also evident that the shear zone runs beneath the volcanic region into Kenya.

The most dominant geological units were categorised into seven main hydrogeological formations including extrusive igneous rocks, gneissic basement, intrusive igneous rocks, meta sedimentary and volcanic rocks, sedimentary rocks, sediments and volcanic rocks (Fig. 2.9). The hydrogeological formations with the most borehole sites include extrusive igneous rocks, gneissic basement, intrusive igneous rocks, sediments and volcanic rocks.



Volcanic rocks (e.g., volcanic lava, tuff, agglomerates, mudflow and nephelinite); Sediments (e.g., alluvial and lacustrine sediments, outwash debris and laterite); Gneissic basement (e.g., gneiss, granulite, migmatite, charnokite and basement); Intrusive igneous rocks (e.g., granite, gabro, diorite, granodiorite, granitoid, pegmatite, fenite and ijolite); Extrusive igneous rocks (e.g., carbonatite, phonolite, nephelinite, basalt, rhyolite, marble and metasomatic rocks); Meta sedimentary and volcanic rocks (e.g., amphibolite, schist, quartzite and metavolcanic rocks); Sedimentary rocks (e.g., sandstone, mudstone, arkose, conglomerate and grit).

***Figure 2.9**: Generalised regional geology and structures of the Mt. Elgon aquifer across Uganda and Kenya.*

2.8 Regional hydrogeology

2.8.1 Shared aquifer architecture

(i) Extent of aquifer

The region around the volcanic massif is considered to form the recharge area which discharges to the outlying catchment areas. The aquifer occupies a solitary extinct Pliocene shield volcano with one of the largest craters in the world, measuring about 8 km in width, located in the western part of Kenya, in Trans Nzoia County and bisected by the Kenya-Uganda border. The Mount Elgon aquifer is considered a multi-layered hydraulically connected, largely confined aquifer whose lithology is predominantly basaltic crystalline rocks, with some parts unconfined. The average depth to the water table is 18 mbgl within Uganda. The average depth to the top of the aquifer is 30 mbgl while data is not available on the average thickness of the aquifer system (TWAP Groundwater, 2015). Previous studies on the Kenyan side indicated a shallow unconfined aquifer occurs from ca. 15 mbgl, while for the deeper confined aquifers, there are two layers up to 100 mbgl beneath which are either volcanic rock sequences at higher altitudes, or metamorphic rocks at lower altitudes (e.g., Olago, 2018). The porosity of fractured consolidated rock materials within the aquifer system varies between 0.05 and 0.15 from an empirical list of variation in porosity for both consolidated (rocks) and unconsolidated formations. The aquifer on the Ugandan side is dominated by the fractured crystalline basalt that unconformably overlies the banded granite gneiss and migmatites of the basement complex. In some sections of the aquifer especially in the highland areas, the agglomerate lava is an aquitard offering the aquifer, semi-confined/ leaky conditions.

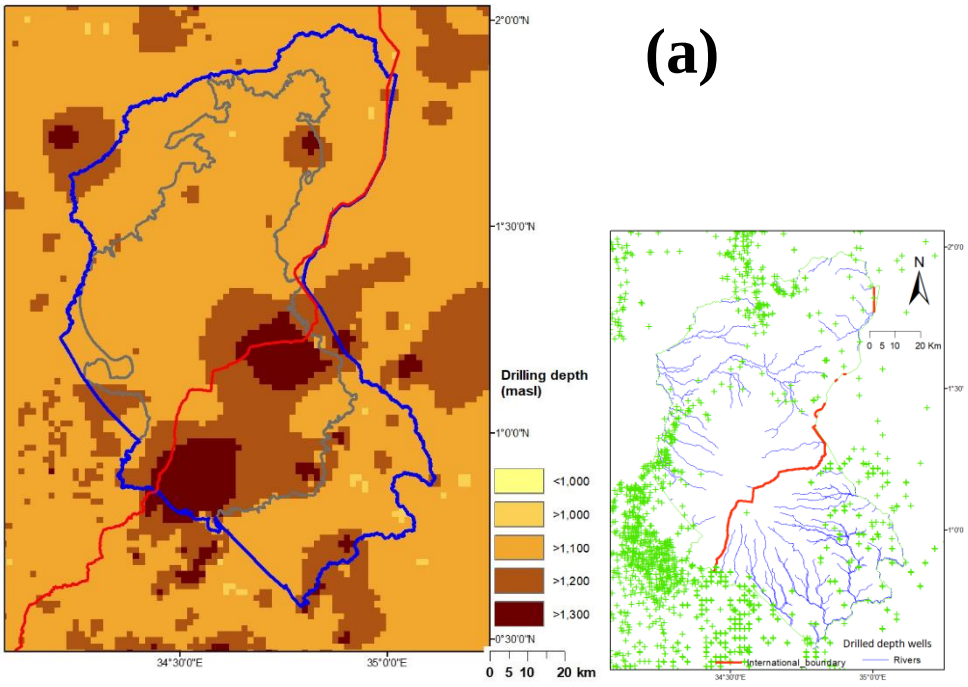
(ii) Thickness of aquifer

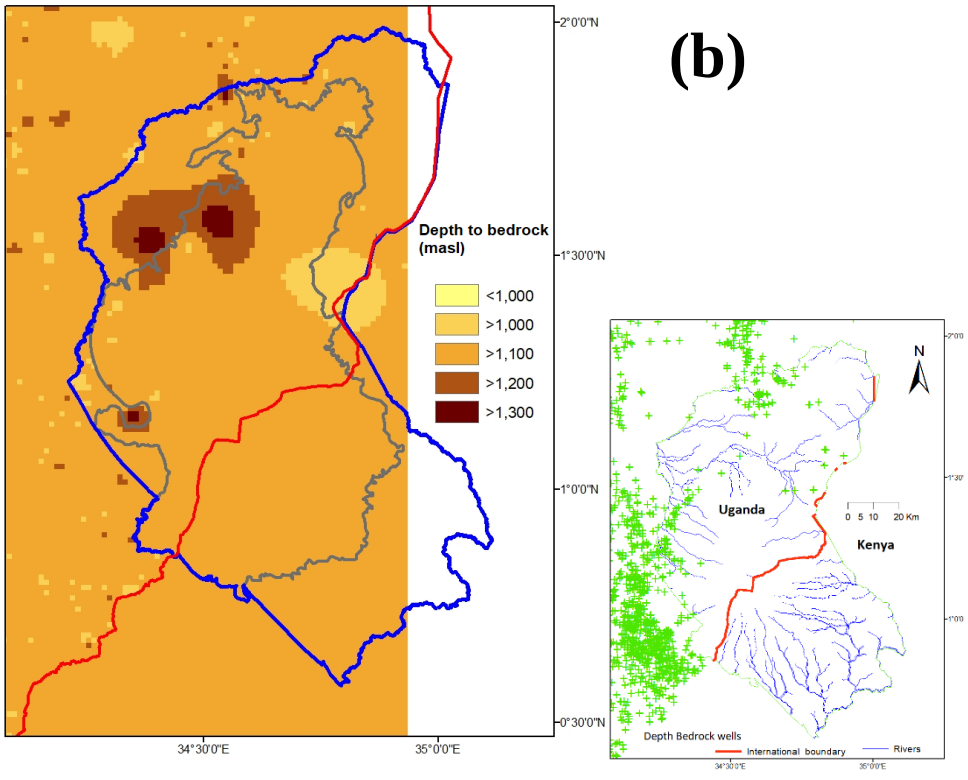
Most of the existing groundwater boreholes are outside the region underlain by the volcanic hydrogeological formation. Interpolation of the physical properties of the groundwater environment is thus indicative and assumes a homogeneous, interconnected hydraulically aquifer sytem. The depth to the bottom of the aquifer is inferred from the total drilled depth (Fig. 2.10a) of the aquifer and in some cases depth to bedock (Fig. 2.10b). This drilled depth goes up to 300 mbgl, with mean and median values of 60.5 and 55.6 mbgl, respectively. The drilled depth varies between 10 to 200 mbgl on the Kenyan side. However, for a large part of the aquifer the depth to the bottom of the aquifer formation is below 100 mbgl derived from the maximum depth for several drilled boreholes of 100 mbgl except for the few exceptional areas. The top of the aquifer is inferred is inferred from the depth to first water strike (Fig. 2.10c). The vertical thickness of the aquifer was inferred from the difference between the water strike level and total drilled depth of the existing boreholes. Regionally, the difference between drilled depth and first water strike ranged up to 144 m, with mean and median values of 29.9 and 28.0 m, respectively. The aquifer thickness further varies from <20 m to 133.2 m on the Kenyan side.

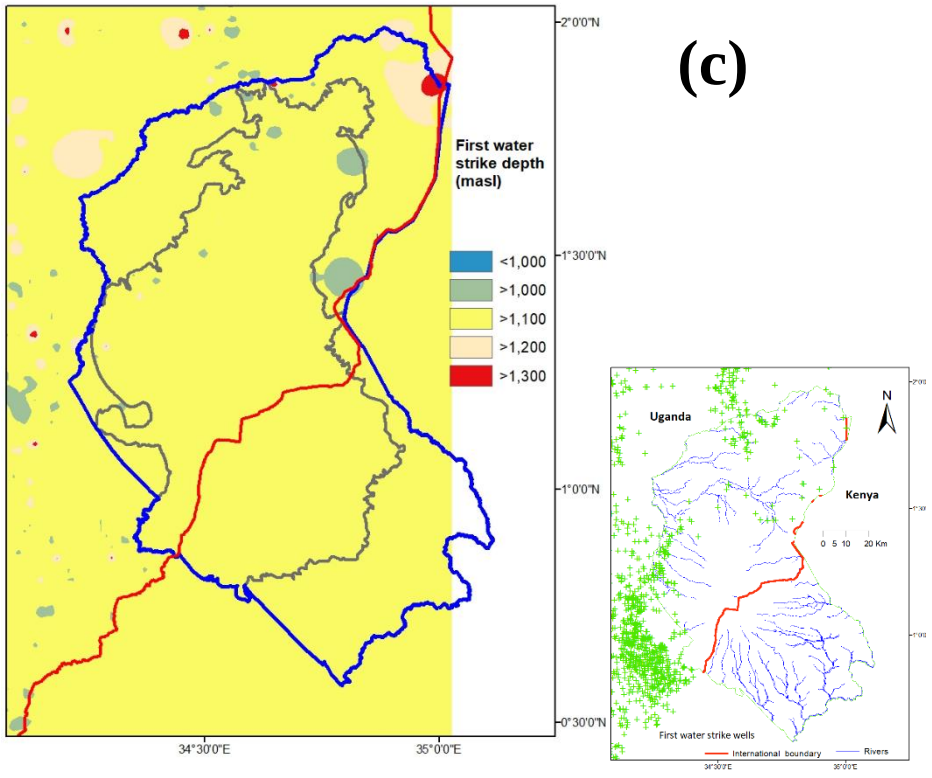
(iii) Degree of aquifer confinement

The depth to water table was inferred from the static/rest water level on well completion ranging from ground level to 90 mbgl, with mean and median values of 9.4 and 7 mbgl, respectively. It varies between 2 and 24 mbgl on the Kenyan side. The degree of aquifer confinement is inferred from the difference between the first water strike level and the static groundwater level (Fig. 2.10d). The difference ranged up to 65.8 m, with mean and median values of 20.4 and 21.0 m, respectively. This information suggests that the regional aquifer system has largely varying

degrees of confinement (semi-confinement/leakiness). However, there are are also numerous shallow wells in the area whose water levels fluctuates seasonally indicating the presence of shallow a phreatic aquifer system. Thus, the region can be considered as a multi-layered aquifer system with an aquitard separating the lower confined layer from the upper unconfined layer. The presence of springs whose discharge fluctuates seasonally is also an indication of a shallow unconfined aquifer system in the region. The extent of fracturing of the confining layer is not well known.




(b)
Depth to bedrock (masl)
<1,000
>1,000
>1,100
>1,200
>1,300
2°0'0"N
1°30'0"N
1°0'0"N
0°30'0"N
34°30'0"E
35°0'0"E
N
Uganda
Kenya
0 5 10 20 Km
Depth Bedrock wells
International boundary
Rivers


(c)
First water strike depth (masl)
<1,000
>1,000
>1,100
>1,200
>1,300
2°0'0"N
1°30'0"N
1°0'0"N
0°30'0"N
34°30'0"E
35°0'0"E
N
Uganda
Kenya
0 5 10 20 Km
First water strike wells
International boundary
Rivers

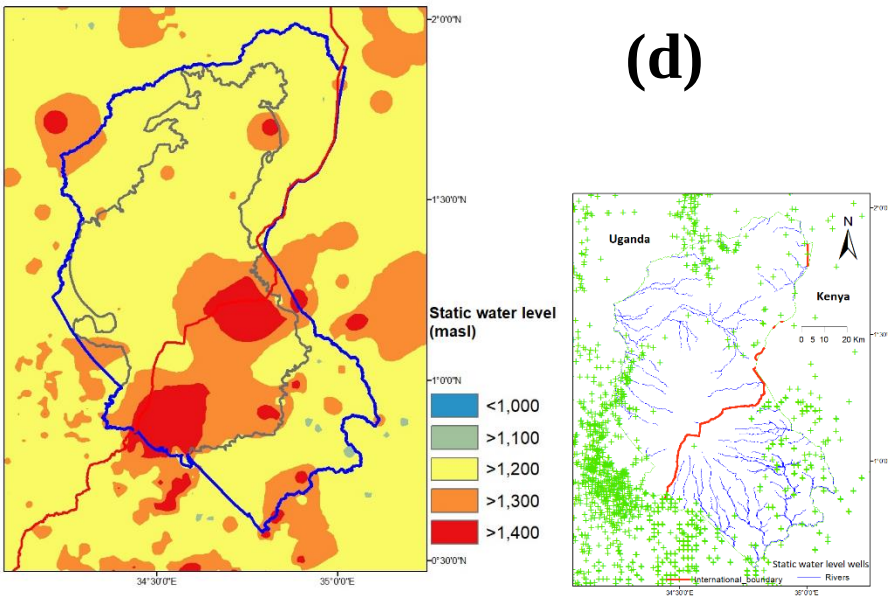


***Figure 2.10**: Aquifer architecture inferred from indicative and data density maps of (a) drilling depth, (b) depth to bedrock, (c) first water strike level, (d) and static waterlevel of the Mt. Elgon aquifer across Uganda and Kenya.*

2.8.2 Recharge and discharge characteristics

Groundwater recharge is expected to be largely focused through preferential pathways, e.g. fracture domains. Diffuse recharge could also conceptually occur through one of three main mechanisms, (i) rainfall percolating through the soil horizon inexcess of soil moisture field capacity; (ii) indirectly from flooding of rivers/lakes/wetlands during the wet seasons, and (iii) lateral movement through shallow aquifers from higher elevation areas to the low-relief regions. Regionally, groundwater recharge depends heavily on the intensity of individual rainfall events rather than total annual rainfall. However, intensive rainfall events will also induce high surface runoff. The traditional bi-modal rainy seasons of March-May and September-November is expected to generate recharge following lag periods of weeks to months. Locally, recharge estimates from several approaches (e.g., soil moisture balance, Cl mass balance, water balance models, water level function methods, tracers) indicate very low to medium, with values that vary between 0 to 400 mm/ annum. However, infiltration rates of up to 600 mm/ annum have been estimated in the area covered by the Mount Elgon National Park.

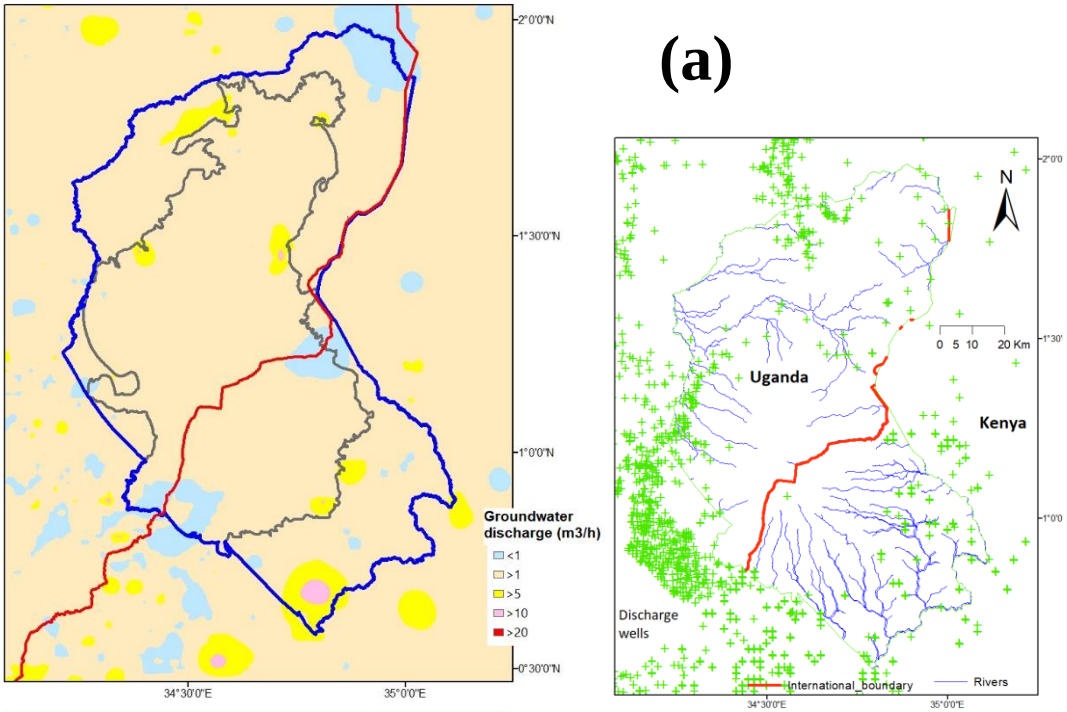
Regionally across Africa, MacDonald et al. (2021) estimate for the period 1970–2019 from 134 ground-based estimates and upscaled statistically, long-term average distributed groundwater recharge rates. Recharge volume for Kenya and Uganda is 230 and 240 km^3/decade, respectively; depth for Kenya and Uganda is 400 and 960 mm/decade, respectively. Groundwater storage for Kenya and Uganda is 8,800 and 960 km^3, respectively. Groundwater annual recharge per capita for Kenya and Uganda is 430 and 530 m^3, respectively. Groundwater storage per capita for Kenya and Uganda is 160 and 7.4 x 1000 m^3, respectively.

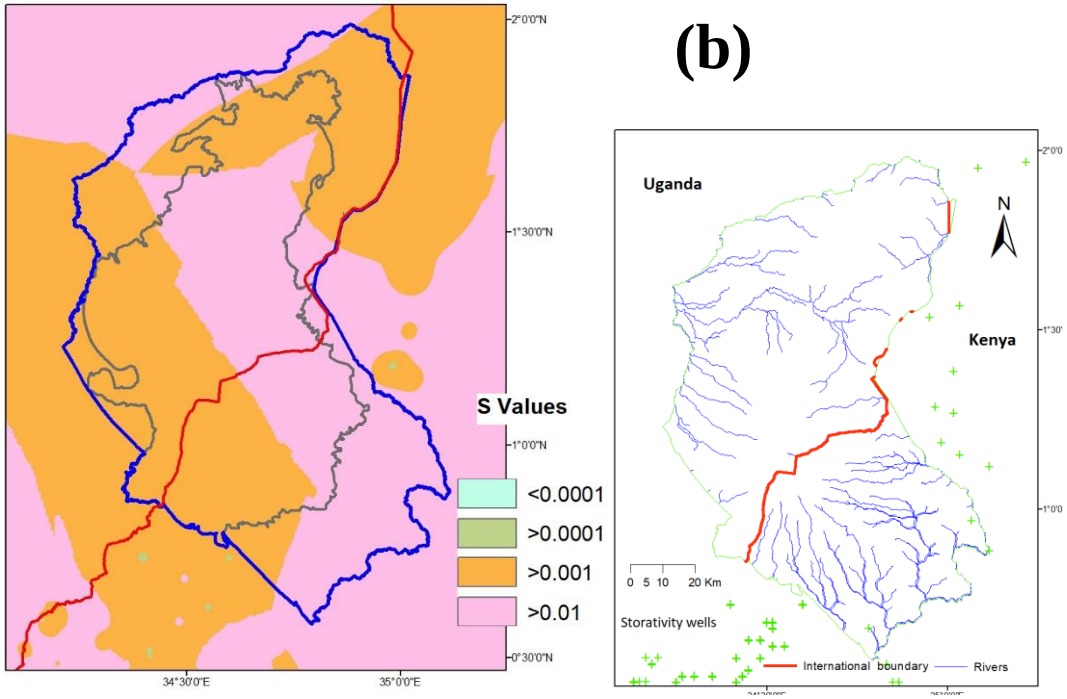
Discharge in the region is mainly through natural springs and stream flows especially on the mountain slopes. In the low-lying areas, the main mechanism of discharge is abstraction through boreholes and shallow wells.

2.8.3 Hydraulic properties and storage

Transmissivity describes the ability of the aquifer to transmit groundwater throughout its entire saturated thickness. A part of the secondary datasets included already analysed transmissivity and storativity values. However, most of the primary datasets were obtained from test pumping after well completion of new groundwater sources. These records were scanned and transcribed to create a digital dataset. The pumping test duration was for at least two to three hours under constant rate using a low yielding electric pump; recovery data was recorded for 60-180 minutes and was often incomplete; the pumping phase itself was also often less than 2 hours; and only manual dip measurements were made. The BGSPT^{TM} approach was used (Barker 1985; Barker and MacDonald, 2000). The method assumes the groundwater flow being modelled is through homogeneous and porous media. Despite this, the method is illustrated to be capable of analysing fractured aquifers to a sufficient degree of accuracy provided that the borehole penetrates a representative sample of the aquifer, flow is laminar and the travel time taken for water to move from the matrix to the borehole is short (Barker and Black 1983; Black 1985). BGSPT^{TM} is a code designed to simulate and analyse pumping test data accounting for well storage. Input data (time in days, drawdown in metres and discharge in m^3/d^{-1}) from the test pumping records is run by an executable file to produce an output file. The model used is relevant for the datasets derived from weathered hydrogeological formations, assumes a semi-confined aquifer of infinite extent, overlain by an unconfined aquitard, with horizontal flow in the aquifer and vertical flow in the aquitard through Darcy's Law allowing for well losses. Model parameters included transmissivity (T) (constrained by 0.1 - 100 m^2/d^{-1}), well radius (constrained by 0.03 – 0.08 m), aquifer (constrained by 0.002 - 0.01 m^{-2}/d^1) and well losses (constrained by 0.002 - 0.001 m^{-5}/d^2). The BGSPT model attempts to minimize R^2 (the sum of squares of residuals - differences between observed and calculated drawdowns). The BGSPT^{TM} was preferred as it provides a reliable transmissivity estimate.

Regionally, the yield of groundwater boreholes ranged up to 43.3 m^3/hr, with mean and median values of 2.6 and 1.5 m^3/hr, respectively (Fig. 2.11a). Transmissivity of the Mt. Elgon aquifer system varies largely between 0.1 and 100 m^2/day. Regionally, the mean and median transmissivity values are 9.7 and 2.4 mbgl, respectively (Fig. 2.11b). The secondary data for storativity derived from the Kenyan side averages 0.0027 (Fig. 2.11c). Further, on the Kenyan side the hydraulic conductivity varies from 0.001 to 6.8 m/day based on specified aquifer thickness.


(a)
2°0'0"N
1°30'0"N
1°0'0"N
0°30'0"N
34°30'0"E
35°0'0"E
Groundwater discharge (m3/h)
<1
>1
>5
>10
>20
N
0 5 10 20 Km
Uganda
Kenya
Discharge wells
International_boundary
Rivers


(b)
2°0'0"N
1°30'0"N
1°0'0"N
0°30'0"N
34°30'0"E
35°0'0"E
S Values
<0.0001
>0.0001
>0.001
>0.01
Uganda
N
Kenya
0 5 10 20 Km
Storativity wells
International boundary
Rivers

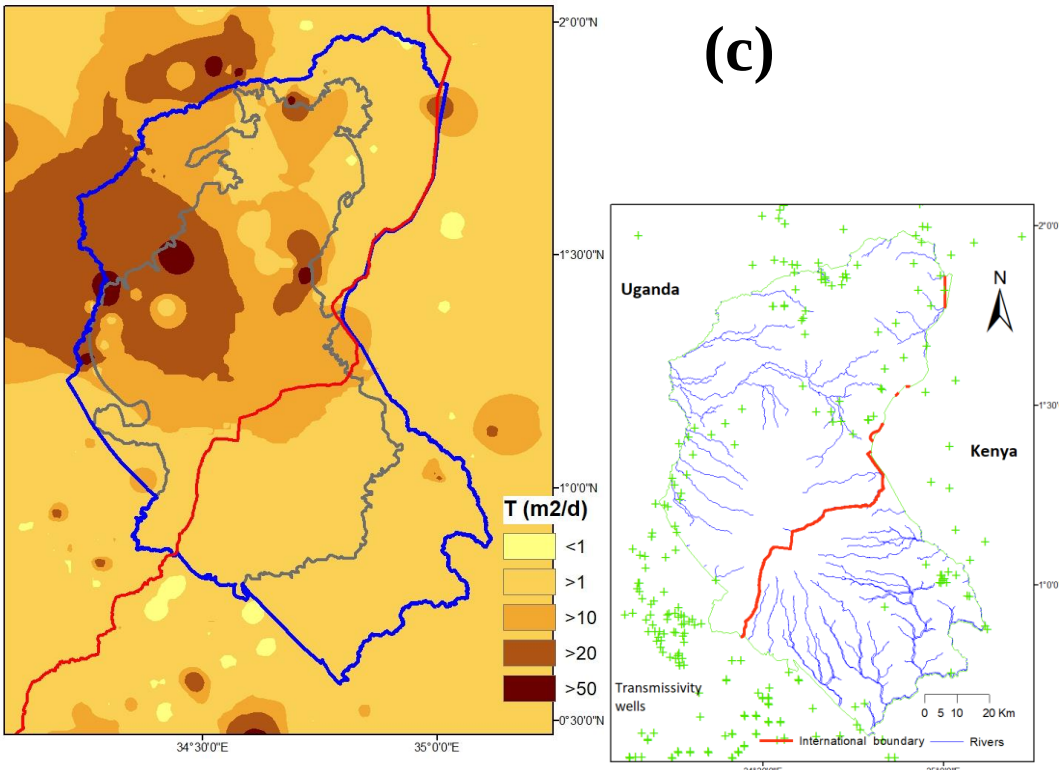


Figure 2.11*: Aquifer hydraulic properties inferred from indicative maps of the Mt. Elgon aquifer across Uganda and Kenya for (a) groundwater discharge at well completion; (b) storativity estimates; and (c) transmissivity estimates.*

2.8.4 Groundwater and spring flow and monitoring

The depth to water table decreases with the direction of decreasing surface elevation. For most of the areas across the aquifer, the water table depth varies between 2 and 28 mbgl with the exception of pockets of much lower groundwater levels of above 28 mbgl. There is a close correlation between the water table depth and the geological formation defining the hydrogeological properties of the aquifer. The direction of groundwater flow mimics the surface elevation and is thus in the direction of the surface drainage. Major potential recharge areas include the upper Mt. Elgon region and Cherenganyi hills in western Kenya. On the Kenyan side, the direction of groundwater flow is considered to be generally from east to west following the surface water drainage into Lake Victoria. On the Ugandan side of the mountain surface drainage is westwards towards Lake Kyoga. Springs emerge all around the slopes of the Mt. Elgon volcanic massif generating radial, varying but perennial discharge.

The two dedicated groundwater level monitoring stations with at least one complete hydrological year of datasets within the Mt. Elgon aquifer region are Bungoma and Pallisa (Figs. 2.12 a and b). Both monitoring wells are located within weathered crystalline basement aquifers and indicate limited storage due to the large temporal variations in water level.

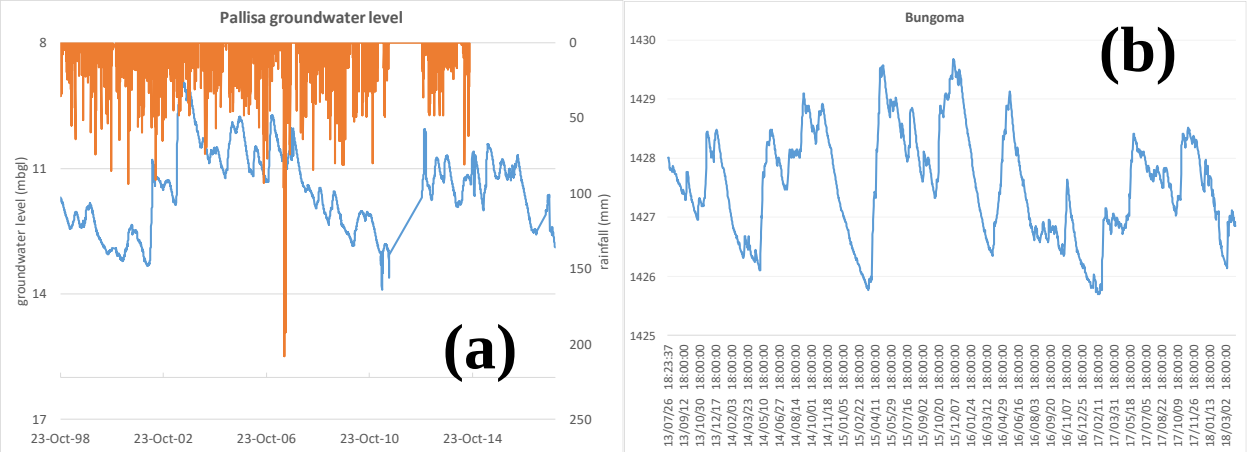


***Figure 2.12**: Time series of the groundwater level and rainfall monitored in stations of the Mt. Elgon aquifer region includes (a) Pallisa in Uganda; and (b) Bungoma in Kenya.*

2.9 Water Demand

2.9.1 Current water demand

In Kenya, surface water is abundant in the aquifer region as most of the rivers and streams are perennial. Based on the available permits, surface water abstraction amount to 9,728 m^3/day which translates to approximately 3.6 Mm^3 annually (Table 2.1). The volume of water abstracted from surface water might be higher given the many illegal abstractions that are often not documented. Hydropower generation is also a key activity; however, the hydropower does not consume water. Water diverted is channeled back to the river after running the turbines.

***Table 2.1**: Surface water abstractors based on the water permit information in the Mt. Elgon aquifer region of Kenya.*

Institution	Sub-catchment	Volume (m3/day)
Western Seed Co. Ltd.	1BG	3,000
Panocal International Limited	1BG	2,528
Regen-Terem Shpp Ltd	1DB	28,8832
Nzoia Sugar Company	1DB	4,200

In Kenya the the daily groundwater abstraction based on the provided records is 2,602 Mm^3/day which translate to approximately 0.9 Mm^3/year (Table 2.2). There many other undocumented groundwater abstractors which implies the actual volume of groundwater abstracted is higher. The average yield in the area is approximately 2.74 m^3/hr. which translates to approximately 20 m3/day. Much of the groundwater abstraction is mainly for domestic and institutional use. There is limited dependency of industry and agriculture on groundwater.

***Table 2.2**: Groundwater use based on the water permit database in the Mt. Elgon aquifer region of Kenya.*

Catchment	Demand (m^3/day)	Annual Demand (m^3)
1AA	159.00	58,035.00
1AB	120.00	43,800.00
1BE	794.00	289,810.00
1BG	789.00	287,985.00
1BH	414.00	151,110.00
1DB	326.00	118,990.00
Total	**2,602.00**	**949,730.00**

In Uganda available water demand was estimated and summarised from various sources in 2004 (Tables 2.3 and 2.4).

***Table 2.3**: Available water from various sources in Uganda.*

Surface Water				**Ground Water**				**Runoff**			
Rivers	Lakes		Total	Average yield	Average success rate	BHs/ km2	GW availability	Annual Rainfall	No of consecutive dry months	Runoff Coefficient	Estimated Annual Runoff
mill m3/year	mill m3/year		million m3/year	m3/day	%		mill m3/year	mm	Months		mm
12595.56	38100		50695.56				3344.862				20680.74

.

***Table 2.4**: Estimate for renewable water resources in 2004 WRM SIP, Uganda.*

		66000	**Water demand 2008**							
		Total								
Estimated Annual Runoff	**Runoff available for abstraction**	**Available for abstraction**	**Domestic NWSC**	**Domestic Small Towns**	**Domestic Rural**	**Livestock**	**Crops**	**Fisheries**	**Rural Industries**	**Total**
million m3/year	million m3/year	mill m3 / year	mill m3 / year	mill m3 / year	mill m3 / year	mill m3 / year	mill m3 / year	mill m3 / year	mill m3 / year	mill m3 / year
40968.27	10242.07	64282.49	56.18399	24.44359	127.3565	106.8109	334.5459	52.3941	4.937509	706.6725

2.9.2 Projected water demand

In Kenya, the water supply master plan provides estimates for demand with projections up to 2030. The annual gross water demand by 2030 for irrigation is estimated as 52.59 m^3/s/1000 Ha (Tables 2.5, 2.6 and 2.7). The total projected area to be irrigated using groundwater by 2030 is 126 Ha. Therefore, groundwater demand for irrigation by 2030 is approximately 7 m^3/s which translates to 6.9 million m^3 per year. The demand is less than 1% of the total annual gross recharge over the delineated aquifer areas.

In Uganda projected estimates for the main demands was made for the periods of 2015, 2020 and 2035 (Table 2.8). The key users include domestic, NWSC, domestic, small towns, domestic, rural, livestock, crops, fisheries and rural industries.

***Table 2.5**: Monthly Unit Irrigation Water Requirement by Sub-basin (4/4) in the Mt. Elgon aquifer region of Kenya.*

Sub-basin	Unit Irrigation Water Requirement under 60% Irrigation Efficiency and Full Cropping* (unit: m3/s/1,000 ha)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1AA	0.83	0.73	0.59	0.05	0	0	0.34	0.32	0.7	0.37	0.32	0.54
1AB	0.83	0.73	0.59	0.05	0	0	0.34	0.32	0.7	0.37	0.32	0.54
1BE	1.01	0.97	0.86	0.48	0.1	0.19	0	0.12	0.57	0.44	0.78	0.87
1BG	1.01	0.97	0.86	0.48	0.1	0.19	0	0.12	0.57	0.44	0.78	0.87
1BH	1.01	0.97	0.86	0.48	0.1	0.19	0	0.12	0.57	0.44	0.78	0.87
1DB	1.01	0.97	0.86	0.48	0.1	0.19	0	0.12	0.57	0.44	0.78	0.87
1DC	0.83	0.73	0.59	0.05	0	0	0.34	0.32	0.7	0.37	0.32	0.54
2BC	1.14	1.22	1.01	0.84	0.99	0.96	0.98	0.94	1.19	1.15	1.09	1.15
Total	**7.67**	**7.29**	**6.22**	**2.91**	**1.39**	**1.72**	**2**	**2.38**	**5.57**	**4.02**	**5.17**	**6.25**

***Table 2.6**: Possible Groundwater Irrigation Area by Sub-basin in 2030 in* the Mt. Elgon aquifer region of *Kenya.*

Sub-basin	Possible Irrigation Area (ha)
1AA	88
1AB	0
1BE	38
1BG	0
1BH	0
1DB	0
1DC	0
2BC	0
Total	126

***Table 2.7**: Summary of Proposed Water Allocation Plans in 2030 in Kenya.*

Water Demand Category	Water Demand	Water Source	
		Surface	**Groundwater**
Domestic	424	363	61
Industrial	19	10	9

Irrigation	1359	1332	27
Livestock	61	61	0
Wildlife	0	0	0
Fisheries	16	16	0
Total	1879	1782	97
Available Water Resources	5077	4969	108
Ratio of Water Demands	37.00%	35.90%	89.80%

***Table 2.8**: Summary of Proposed Water Allocation Plans in 2030 for Uganda.*

Water demand	**% Utilised**	**WR availability per capita**	**Domestic NWSC**	**Domestic Small Towns**	**Domestic Rural**	**Livestock**	**Crops**	**Fisheries**	**Rural Industries**	**Total**
	%	**m3/capita/ year**	**mill m3 / year**	**mill m3 / year**	**mill m3 / year**	**mill m3 / year**	**mill m3 / year**	**mill m3 / year**	**mill m3 / year**	**mill m3 / year**
2015	0.01	2170.5	84.6	35.3	209.8	151.2	389.2	104.8	19.4	994.3
2020	0.02	1739.7	115.9	47.2	305.6	164.2	452.3	157.2	23.2	1265.7
2035	0.02	1480.2	284.4	111.0	587.6	210.8	676.3	209.6	32.9	2112.5

2.9.3 Demography

Table 2.9 shows the current (2008) and projected (2035) demography in the Mt. Elgon region of Uganda. It includes the then parent districst of Kapchorwa, Mbale, Sironko, Bukwa, Manafwa, and Nakapiripirit. In Kenya the population was provided for the three main counties of Trans-Nzoia (sub-counties of Kiminini, Saboti, Kwanza, Endebes, Cherangany), Bungoma and Busia (Table 2.10).

***Table 2.9**: Summary of the current and projected deomography in the Mt. Elgon region for Uganda.*

Ugandan District Name	2008	Projected 2035
Kapchorwa	182,500	493,632.7
Mbale	392,900	492,687.2
Sironko	328,700	565,783.9
Bukwa	62,100	166,658.7
Manafwa	320,500	671,100.8
Nakapiripirit	217,600	620,789.3

***Table 2.10**: Summary of the current demography in the Mt. Elgon region for Kenya.*

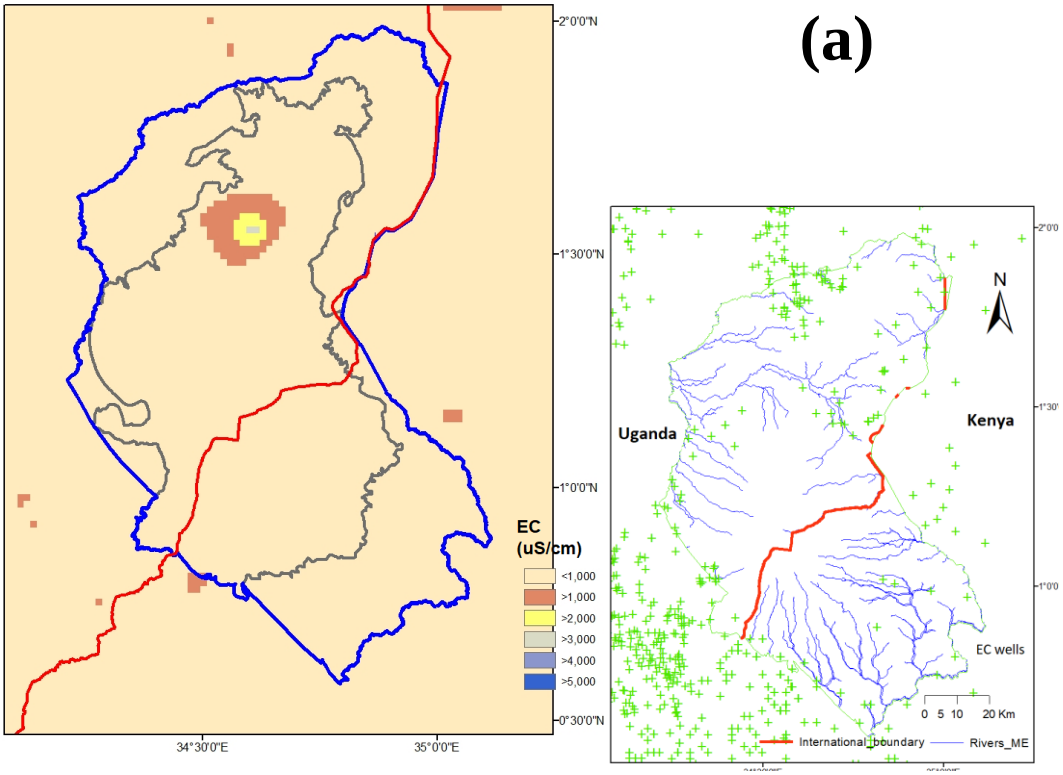
No.	County	Total	Males	Females
1	**Trans - Nzoia**	1,112,026	554,992	557,034
	Kiminini Sub-County	270,721		
	Saboti Sub-County	226,045		
	Kwanza Sub-County	226,102		
	Endebes Sub-County	123, 818		
	Cherangany Sub-County	265,000		
2.	**Bungoma**	1,809,310	883,475	925,835
3.	**Busia**	54,928		

2.10 Groundwater and surface water quality

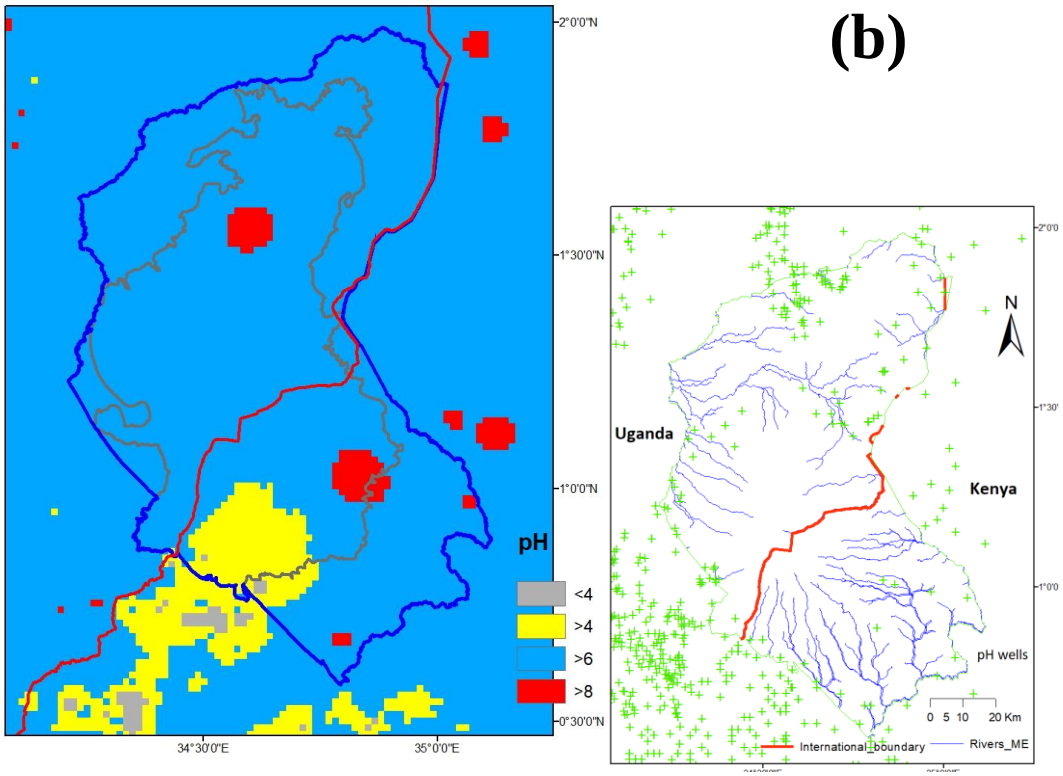
At well completion a set of physico-chemical (e.g. pH, EC) and chemical constituents of interest (e.g. NO_3, F, As) is analysed from water samples collected from new groundwater sources. Spatial groundwater borehole coverage of selected physico-chemical (pH, EC and TDS) constituents in groundwater at well completion is presented in Fig. 2.13.

Electrical conductivity (EC) is generally (<1000 µS/cm) and thus groundwater in these aquifer systems can be considered as fresh (Fig. 2.13a). However, there are pockets of high EC, an indication of some extent of salinity which is a factor of the composition of the host rocks. The pH largely lies within the range of 6-8 which is considered to characterise neutral groundwater that is not corrosive to access infrastructure (Fig. 2.13b). Total dissolved solid (TDS) is an index of salinity in groundwater: high TDS water is felt saline by human. Generally, suitable values of TDS are from 30 to 300 mg/l for potable water. The water quality based on TDS is a good indicator of

the comprehensive water quality including salinity and iron content. Additionally, TDS is an important index as a water quality standard, and is related to potable water and productivity of livestock or agricultural commodity. If TDS is very high, the water must be treated or blended to be useful for most uses. Since the average value of TDS in the study area is approximately 300 mg/l, most of the groundwater is suitable for drinking by humans. Based on TDS, the aquifer exhibits generally good water quality whose values range between 200 and 500 mg/l (Fig. 2.13c).



(b)


2°0'0"N
1°30'0"N
1°0'0"N
0°30'0"N
34°30'0"E
35°0'0"E
pH
<4
>4
>6
>8
Uganda
Kenya
N
pH wells
0 5 10 20 Km
International boundary
Rivers_ME

(c)

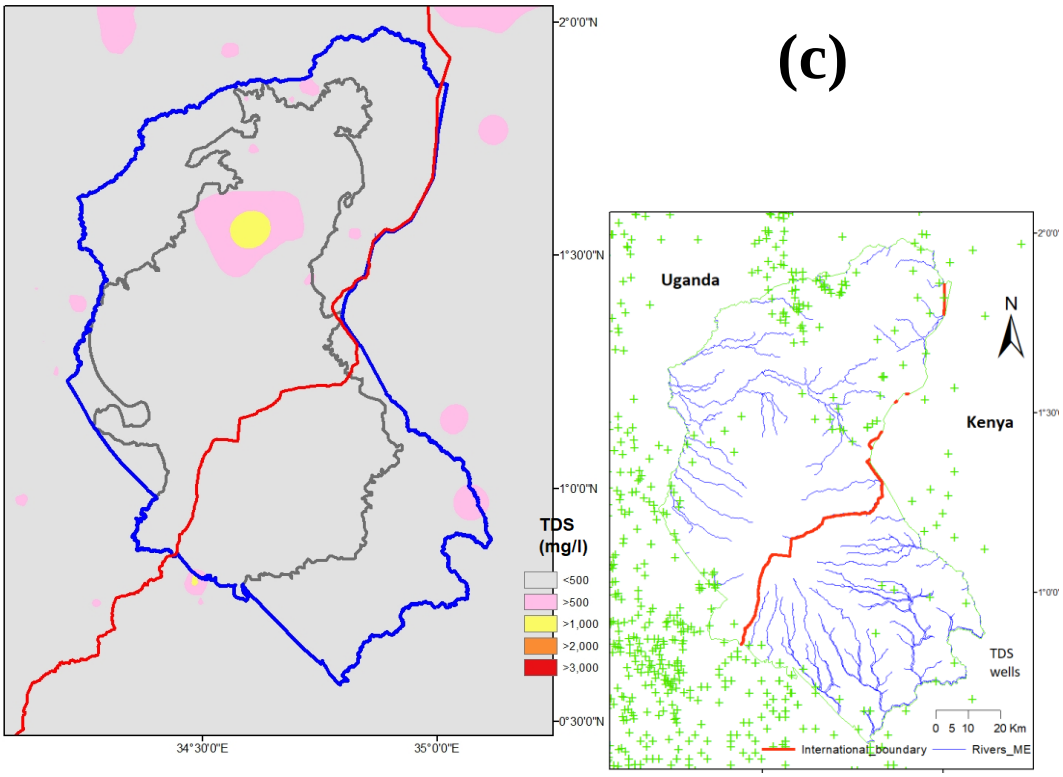

2°0'0"N
1°30'0"N
1°0'0"N
0°30'0"N
34°30'0"E
35°0'0"E
TDS
(mg/l)
<500
>500
>1,000
>2,000
>3,000
Uganda
Kenya
N
TDS
wells
0 5 10 20 Km
International boundary
Rivers_ME

***Figure 2.13**: Groundwater quality inferred from indicative maps of (a) electrical conductivity, EC at well completion, (b) pH, and (c) total dissolved salts, TDS of the Mt. Elgon aquifer across Uganda and Kenya.*

3. METHODS

3.1 Modelling approach

The study initially involved an assessment of a shared groundwater system that was conceptualised in terms of (i) data collection, (ii) harmonisation, (iii) aquifer characterisation including general assessment and indicator-based assessment, and (iv) SADA report write up for information management (Kukuric et al., 2015; IGRAC and UNESCO-IHP, 2015). The study was largely based on a review of existing historical/archived datasets at both national and aquifer levels. Some limited physical and social sciences fieldwork was conducted at aquifer level with the aim of verifying and filling gaps in the existing datasets. The materials and methods for the modelling phase of the SADA of the Mt. Elgon Aquifer region is summarised in Table 3.1;

***Table 3.1**: Summary of the key modelling materials and methods for generating assignment outputs.*

Outputs	Proposed Methods	Potential materials and tools
1. Development of conceptual and numerical groundwater models at a transboundary scale;	• Review of SADA report of the Mt. Elgon aquifer; • Development of groundwater conceptual model; • Groundwater flow model code and GIS platform identification (e.g. GSFLOW); • Model design; • Model calibration and verification; • Sensitivity and uncertainty analyses; • Water balance reporting;	• All relevant in situ and remotely sensed datasets of the Mt. Elgon aquifer region; • Physiographic and surface characteristics; • Lithological characteristics supported by exploratory surface geophysical survey data, drilling and well logs; • Hydraulic tests (*T*, *K* values) and groundwater storage (*S* values); • Recharge estimates (e.g. SMB); • Major chemical and isotopic analyses; • Local water budgets and groundwater models; • Conceptual models of the Mt. Elgon aquifer; • Time series of groundwater and surface water level measurements, abstraction Measurements • Computing system
2. Development of numerical models projecting different socio economic and climate scenarios from present to the year 2050 in the horizon for selected SSPs (Shared Socioeconomic Pathways), and range of climate change	• Scenario analyses of numerical model runs under varying climate change stress and population use pressure up to 2050;	• Groundwater numerical model developed under output 1; • Climate change stress and population use scenarios;

scenarios to identify strategic recommendations for sustainable management and utilization of Mt Elgon aquifer;		
3. Identification of key threats to sustainability of shared groundwater aquifers (climate change scenarios, increased/unsustainable withdrawals, land use/change);	• Sensitivity analyses of climate change scenarios, increased/unsustainable withdrawals, land use/change	• Groundwater numerical model developed under output 1; • climate change scenarios, increased/unsustainable intensive abstractions, land use/change scenarios;
4. Generated historical, recent and future scenarios for different trends in aquifer recharge as a result of changes in precipitation or land use/cover will be quantified and documented in training materials on transboundary groundwater modelling for the aquifer system;	• Recharge estimates for historical, recent and future scenarios based on changes in precipitation or land use/cover; • Training manual learning objectives for level and depth of contents; • Write up of manual by integrating all model materials and approaches	• Groundwater numerical model developed under output 1; • Media for publication (e.g. online, soft or hard copy);
5. Recommendations for sustainable conjunctive groundwater – surface water use covering technical aspects.	• Controlled abstraction scenarios; • Controlled discharges to groundwater from surface water; • Managed aquifer recharge;	• Groundwater numerical model developed under output 1; • Scenario analyses for conjunctive groundwater – surface water use

Numerical models predict the behaviour of groundwater systems in response to future stresses and contribute to the understanding of causes and processes of past stresses. Three-dimensional incomprehensible groundwater flow through porous material is governed by the partial-differential equation (McDonald and Harbaugh, 1988), equation 3.1.

$$\frac{\delta}{\delta x}\left[K_{xx}\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta x}\left[K_{yy}\frac{\delta h}{\delta y}\right]+\frac{\delta}{\delta x}\left[K_{zz}\frac{\delta h}{\delta z}\right]-W=S_s\frac{\delta h}{\delta t} \qquad \text{eqn. 3.1}$$

where, K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinates axes, which are assumed parallel to the principal directions of hydraulic conductivity (LT^{-1}); h is the hydraulic head (L); W is discharge per unit volume (T^{-1}), which represents sources and/or sinks of water; S_s is the specific storage of the porous material (L^{-1}); and t is time (T). The equation 3.1

together with the boundary and initial conditions constitutes a mathematical representation of the groundwater flow system. The proposed model code was the USGS MODFLOW that uses the finite difference approach to solve the groundwater flow equation. MODFLOW uses discretized, algebriac form of equation 3.1 to solve for potentiometric head at every model cell at time steps within each simulated period.

3.1.1 System conceptualisation

GMS (Groundwater Modelling System) is a comprehensive graphical user environment developed by Aquaveo for groundwater simulation including site characterization, model development, post-processing, calibration and visualization. GMS investigates hydrodynamic impacts on a groundwater system of recharge and discharge rates.

Two approaches can be used to construct a MODFLOW simulation in GMS: the grid approach or the conceptual model approach. The grid approach involves working directly with the 3D grid and applying sources/sinks and other model parameters on a cell-by-cell basis. The conceptual model approach was used and it involves using the GIS tools in the map module to develop a conceptual model of the site being modelled. The location of sources/sinks, layer parameters, e.g. hydraulic conductivity, model boundaries, and all other data necessary for the simulation were defined at the conceptual model level. Once this model was complete, the grid was generated and the conceptual model was converted to the grid model and all of the cell-by-cell assignments are performed automatically.

The GMS model flow packages used was the *LPF*, the model solver was *PCG* and the optional packages included *DRN1*, *RCH1* and *WEL1*. The model length units were metres and time was in days. The projection coordinate sytem used was UTM zone 36 N, WGS 1984.

3.1.2 Steady and transient state model runs

The long-tern average stresses on the groundwater system (e.g. rainfall, evapotranspiration, stream flow) were imposed on the system for the steady state sun. However, it was not possible for the simulated groundwater levels to be matched to the observed average groundwater levels that were outside the model region. The simulated steady state groundwater hydraulic heads were used as initial aquifer heads for the transient runs.

The main drainage levels were used to match the simulated aquifer heads at elevations where they interact. A monthly stress period each with 3-time steps was used with the aquifer hydraulic heads generated for only the periods of interest.

3.1.3 Model calibration

Due to poor or inexistent hydraulic properties (e.g. *K*, *T*), the calibration of the observed to the simulated groundwater levels, was manually accomplished, with controlled parameter boundaries based on elevation/empirical value ranges.

The model sensitivity of each of these parameters (e.g. recharge, aquifer bottom, *K* and groundwater discharge) was evaluated individually and in couples against the aquifer heads. The effects of varying these parameters through a wide range of potential values were evaluated by observing the resultant aquifer heads using firstly the steady state and then the transient state

models. There were no data records for a verification process prior to carrying out model projections.

3.1.4 Sensitivity analyses

Because several model parameters do not justify calibration due to the empirical nature of the study site data, it was necessary to evaluate the effect of uncertainty on these parameters using an implicit sensitivity analysis. Parameters that were evaluated included, recharge, hydraulic conductivity, storage coefficient and groundwater discharge.

3.1.5 Projections

Objectives of the numerical model included to project ground/surface water availability for conjunctive use under climate change stress and population use pressure. The current climate conditions were used to run the model to form a baseline.

Data was downloaded from the Climate Change Knowledge Portal (CCKP) of the World Bank (CCKP, 2022). The portal provides global data on historical and future climate, vulnerabilities, and impacts and can be explored via country and watershed views. Climate data for the Mt. Elgon Aquifer was based on Watershed 403 covering Uganda, Kenya and South Sudan. Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100 used to derive greenhouse gas emissions scenarios with different climate policies. Two SSPs temperature projections from the IPCC Sixth Assessment were considered: (i) SSP2-4.5 providing intermediate Green House Gas (GHG) emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100, with estimated warming (2041-2060) of 2.0 °C; (ii) SSP5-8.5 providing very high GHG emissions: CO_2 emissions triple by 2075, with estimated warming (2041-2060) of 2.4 °C. Three scenarios were considered: Historical (1990 – 2019), Future (2020 – 2039 and 2040 – 2059) for both rainfall and temperature.

Based on demographic mode projections from current levels, expected water demand and abstraction rates were determined in relation to past per capita demand and increased demand in the future driven by urbanization (e.g. Okello et al., 2015). The demographic models quantify the current population and expected changes, as well the impacts of population growth on water demand, abstraction rates and, eventually, the effective volume of the aquifer.

3.1.6 System requirements

The current 2022 version, GMS 10.6 system requirements include;

- Operating System: Windows 10
- RAM: 16GB or more recommended
- CPU: GMS software is CPU intensive. Some models and utilities integrated with GMS can take advantage of multiple processor cores simultaneously. We recommend the fastest CPU your budget allows.
- Storage: Recommended storage amount will vary depending on individual data requirements. Latest versions of GMS are very disk I/O intensive.
    - Mechanical hard drive: Basic performance
    - SATA solid state drive: Better performance
    - NVMe solid state drive: Best performance

- Graphics: A dedicated graphics card is better than integrated graphics. A basic or mid-range nVidia card designed for gaming works best.
- Display Resolution: 1920 x 1080 or greater

3.2 Conceptual framework

Groundwater numerical modelling conceptual framework has three requirements;

- **Input maps**, e.g. Mt. Elgon Aquifer areal boundary, Land use/ land cover, Hydrological drainage network, Aquifer parameters (e.g. thickness, *K*, *T*, *S*), Aquifer and confining layer areas and thicknesses;
- **Time series data**, e.g. Daily mean precipitation (rainfall), Daily maximum and minimum air temperature, Daily mean stream, discharge, Daily soil moisture, Potential evapotranspiration, Daily groundwater levels;
- **Modelling conditions**, e.g. Initial conditions (e.g., water table, surface elevation), Boundary conditions, e.g. defined as specified head (e.g. streams/rivers), constant head (e.g. lakes), specified flux (e.g. recharge across water table, abstraction well), and no flow (e.g. impermeable geology), Transient stress period (e.g. daily), Model calibration against stream discharge and/or groundwater levels, Aquifer area to determine model discretization;

The groundwater modelling protocol involve planning, conceptualization, design construction, calibration, sensitivity analysis and projections/predictions (Fig. 3.1). Datasets for the groundwater flow modelling include physical and hydrogeological frameworks;

a) The physical framework data used for defining the geometry of the groundwater domain including the thickness and areal extent of each hydrostratigraphic unit are:
   - Geologic maps and cross sections showing the areal and vertical extent and boundaries of the system;
   - Topographic maps at a suitable scale showing all surface water bodies and divides, surface drainage system, springs, wetlands and swamps;
   - Land use / land cover maps showing agricultural areas, forest cover, wildlife rangelands urban centres;
   - Contour maps showing the elevation of the base of the aquifers and confining layers;
   - Isopach maps showing the thickness of aquifers and confining layers;
   - Maps showing the extent and thickness of stream and lake sediments.

b) The hydrogeological framework datasets include:
   - Water table and potentiometric maps for all aquifers;
   - Hydrographs of groundwater head and surface water levels and discharge rates;
   - Maps and cross sections showing the hydraulic conductivity and/or transmissivity distribution;
   - Maps and cross sections showing the storage properties of the aquifers and confining beds;
   - Hydraulic conductivity values and their distribution for stream and lake sediments;
   - Spatial and temporal distribution of rates of evaporation, groundwater recharge, surface water - groundwater interaction, groundwater pumping, and natural groundwater discharge.

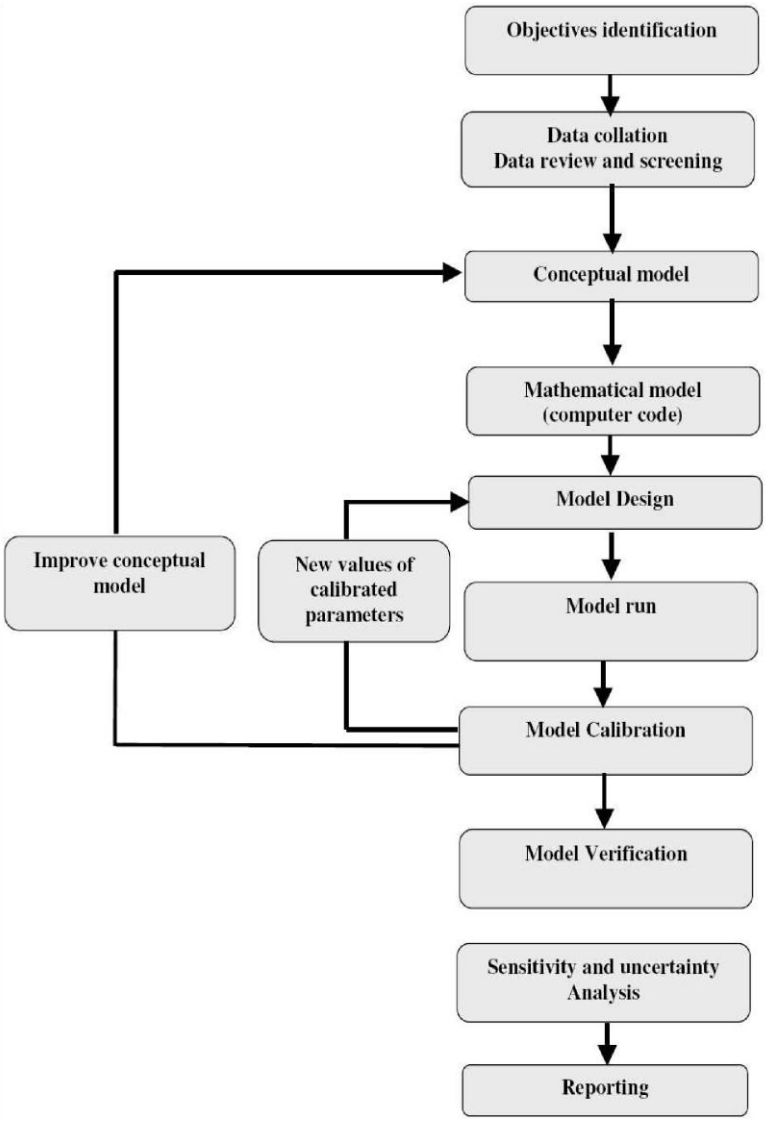


***Figure 3.1**: Generalized groundwater modelling steps.*

3.3 Model region

The modelled Mt. Elgon aquifer region was demarcated from drainage and geological structures within the intrusive igneous and gneissic basement upon which the volcanic formation was extruded (Figs. 3 a and b). The major regional structural domains including the Aswa shear zone were used to demarcate model boundaries. Also included were the main rivers draining westwards into Lakes Victoria and Kyoga.

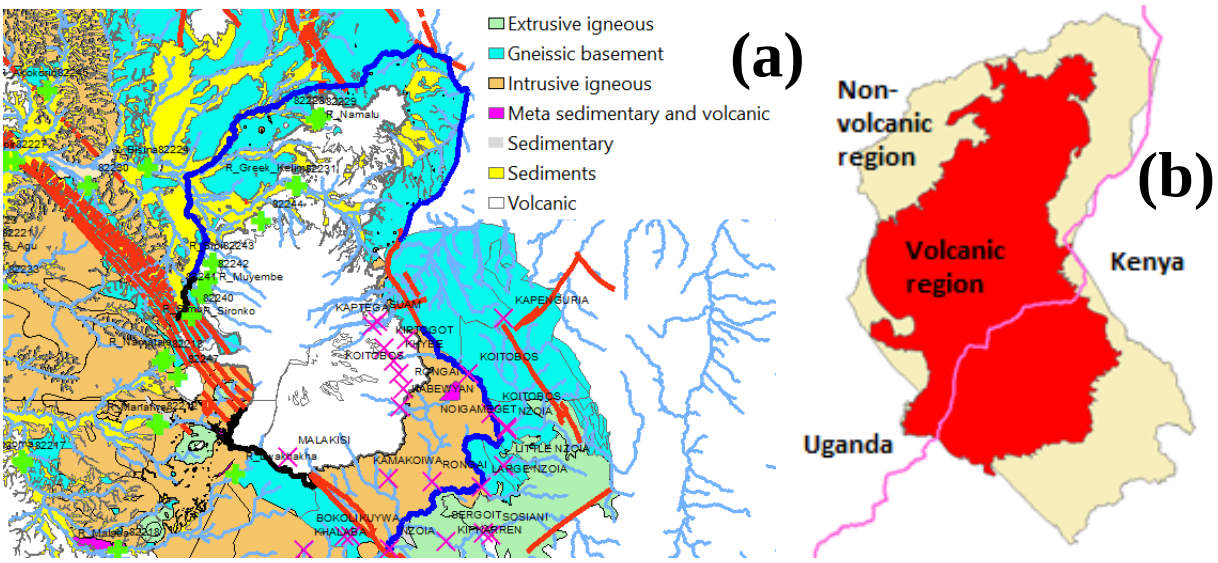


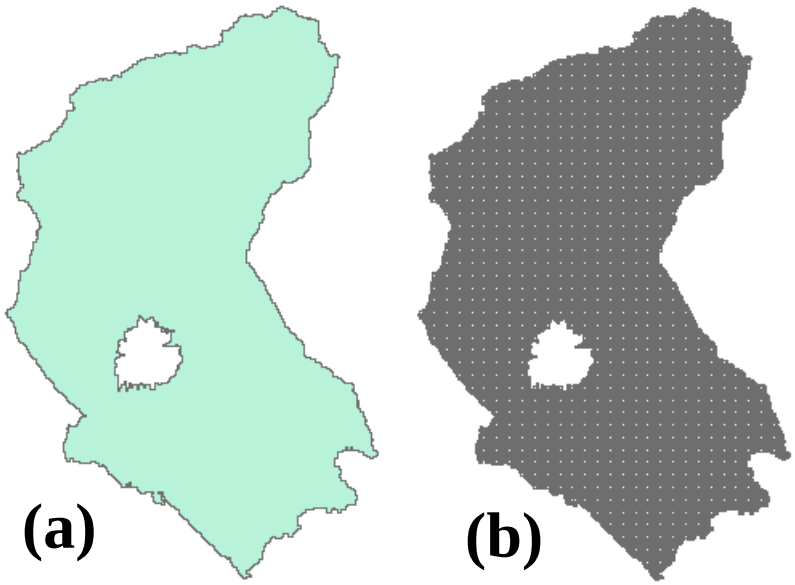
Figure 3.2: *The modelled Mt. Elgon aquifer region showing the (a) drainage and geological structures used to demarcate model boundary, (b) the volcanic and non-volcamic regions of the aquifer area.*

4. MODEL CONCEPTUALIZATION

4.1 Model discretization

4.1.1 Spatial discretization

The Mt. Elgon aquifer region model area covers an area of about 8,500 km^2 (Fig. 4.1a). The model grid was therefore chosen based on an equal cell area, refined to cater for sources and sinks and groundwater flow in one model layer shall be simulated. Although there may be variation from one cell or node to another, it was assumed that within a nodal area the hydraulic characteristics of the system are constant and time-independent. The horizontal spacing was uniformly spaced at a maximum of 500 metres (Fig. 4.1b). Layer is expected to be semiconfined but was simulated as unconfined. The thickness of the model layer was based on the spatial lithostratigraphic profiles of the region. Historical records of monitoring river hydrographs were used to compare with the model drainage discharge. The digital terrain model resampled to the MODFLOW grid is shown in Fig. 4.1c. The model top area elevation is from the low relief region of less than 750 masl up to a top elevation of about 3,500 masl. The aquifer bottom elevation was varied from less 500 masl in the low relief region to 1,750 masl in the mountain area (Fig. 4.2d).



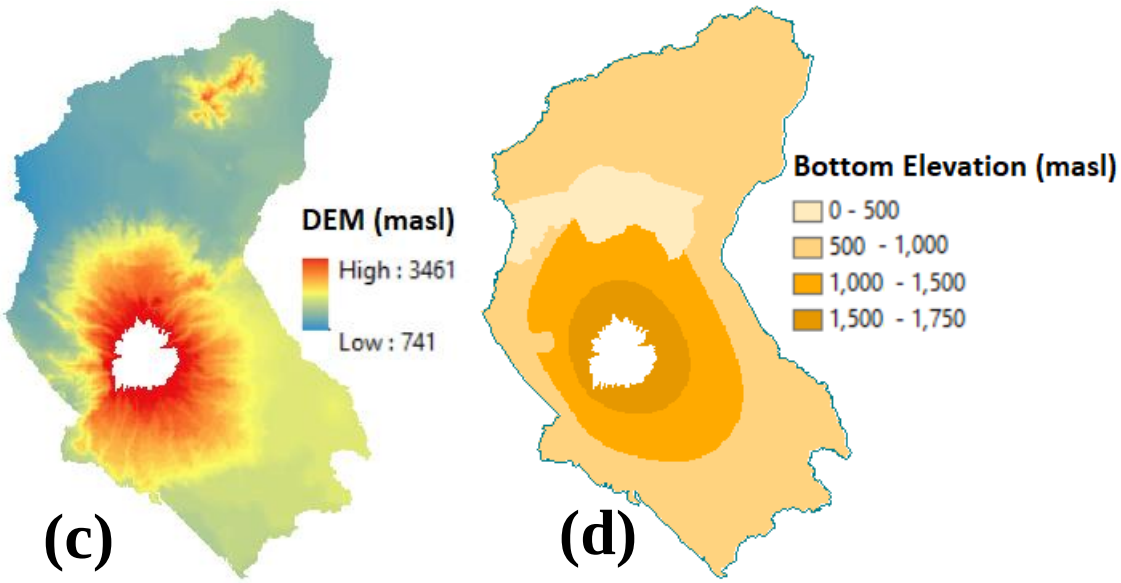


***Figure 4.1**: Spatial discretization of the modelled Mt. Elgon aquifer area indicating the main boundary conditions including (a) model area, (b) cell discretization, (c) aquifer bottom elevation, and (d) digital terrain elevation.*

4.1.2 Temporal discretization

Time series data was available over short and inconsistent periods covering more than 20 years of both stream flow and a few years of groundwater levels outside the modelled domain. Monthly stress periods (n = 408) were used with three (3) time steps each and the time steps was uniform for each stress period. Effective model runs were from 1 January 2018 to 31 December 2051 to cater for the model system stability. A trade-off was made with the time-step size to achieve convergence and mass balance, the length of the model run time, and bulky input and output files that was generated.

4.2 Boundary conditions

4.2.1 Initial conditions

The initial conditions were considered as the hydrologic stresses (groundwater levels and/or river discharge levels) derived as static/rest water levels at the time of well completion. This point measurements were interpolated within the modelled area to obtain the initial piezometric surface (Fig. 4.2). This approach is applicable, (i) where the initial groundwater levels are similar to the final groundwater levels, and (ii) when there are not sufficient groundwater level records to appropriately describe the initial spatial piezometric surface.

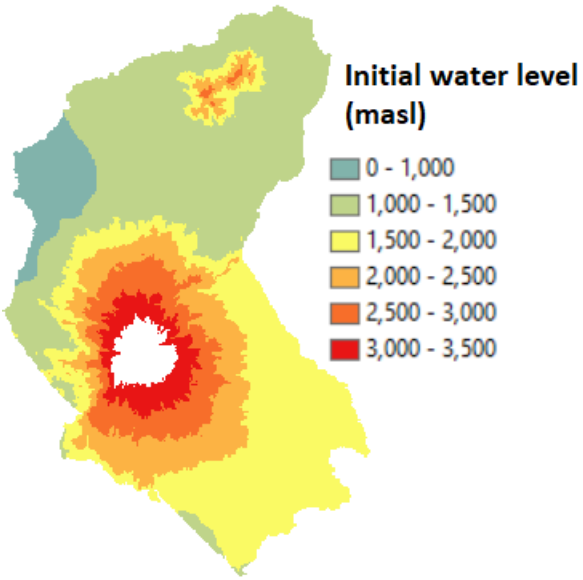


***Figure 4.2**: Initial groundwater spatial level in the Mt. Elgon aquifer modelled area.*

4.2.2 Hydrologic boundaries

Boundary conditions included specified head boundaries to correspond with the river boundaries or at geological structures assumed to be permeable to groundwater flow. The caldera at the top of the steep volcanic massif was considered to be largely a recharge area with discharge on the lower slopes in form of springs and streams. Discharge was also considered radially through the lithological units that are adjacent to and through which the volcanic rocks were extruded. Drains were used to discharge water where rivers form a drainage network.

The riverbed conductance was modelled using the *Drain* package with the model perimeter drainage network having a constant value of 0.29 m^2/d/m, and the internal drainage network at 5 m^2/d/m (Fig. 4.3).



***Figure 4.3**: The network of drains within and forming the perimeter of the Mt. Elgon aquifer modelled area.*

4.3 Hydraulic properties

Daily/monthly rainfall, evapotranspiration, river discharge datasets were obtained from historical records of physical gauging stations in the region, and combined, where not available, with remotely sensed datasets. Groundwater hydraulic properties were obtained from analysis of well and pumping test datasets generated largely at the time of well construction, as well as from previous studies in the region. The hydraulic properties were averaged across the main elevation levels and lithological units in order to limit the modelled aquifer area. Hydraulic conductivity estimates varied from <0.005 to 0.05 m/d (Fig. 4.4a). Specific yield was considered to vary from 0.018 for the volcanic areas assumed to be unconfined to 0.0063 for the non-volcanic areas that is likely to be semi-confined (Fig. 4.4b).

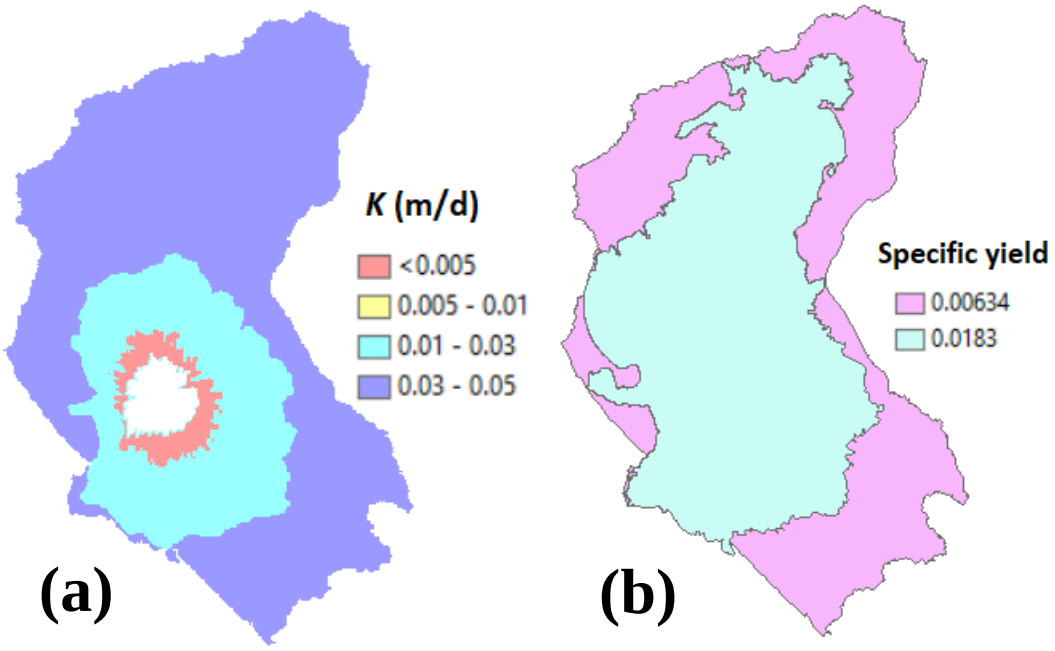


***Figure 4.4**: (a) Horizontal hydraulic conductivity, and (b) specific yield of the Mt. Elgon aquifer model region.*

4.4 Recharge and discharge

Initial recharge estimates were similarly derived from previous studies including the MWE estimates in the region, and amount up to about 5-10% of the annual rainfall distributed according to the regional rainfall pattern. Spatial recharge estimates were derived from the difference between the gridded mean annual rainfall (2010-2020) adapted from CHIRPS (2021) and gridded mean annual (2015-2020) actual evapotranspiration and interception adapted from WaPOR (2021). This initial spatial estimate of recharge was reduced by factors and elevation zones to obtain the final estimate of recharge (Fig. 4.5a). The recharge estimates for steady state conditions had one file with spatial variations in recharge. The transient state recharge estimates had 12 files corresponding to monthly variations in spatial recharge based on proportion of long-term monthly rainfall (Fig. 2.4a).

Discharge was estimated from surface runoff, spring outflow and demand derived from the average number of boreholes abstracting groundwater in the region. Groundwater wells used for abstraction in the modelled region were of two (2) types:

(a) 255 old wells completed in the model region (Fig. 4.5b), with abstraction ranging from 1.7 to 456 m^3/d (average of 65.7 m^3/d);
(b) 494 new model wells located as centroids of sub-county administrative units (Fig. 4.5c), lying at terrain elevations of up to 1,500 masl (Fig. 4.5d).

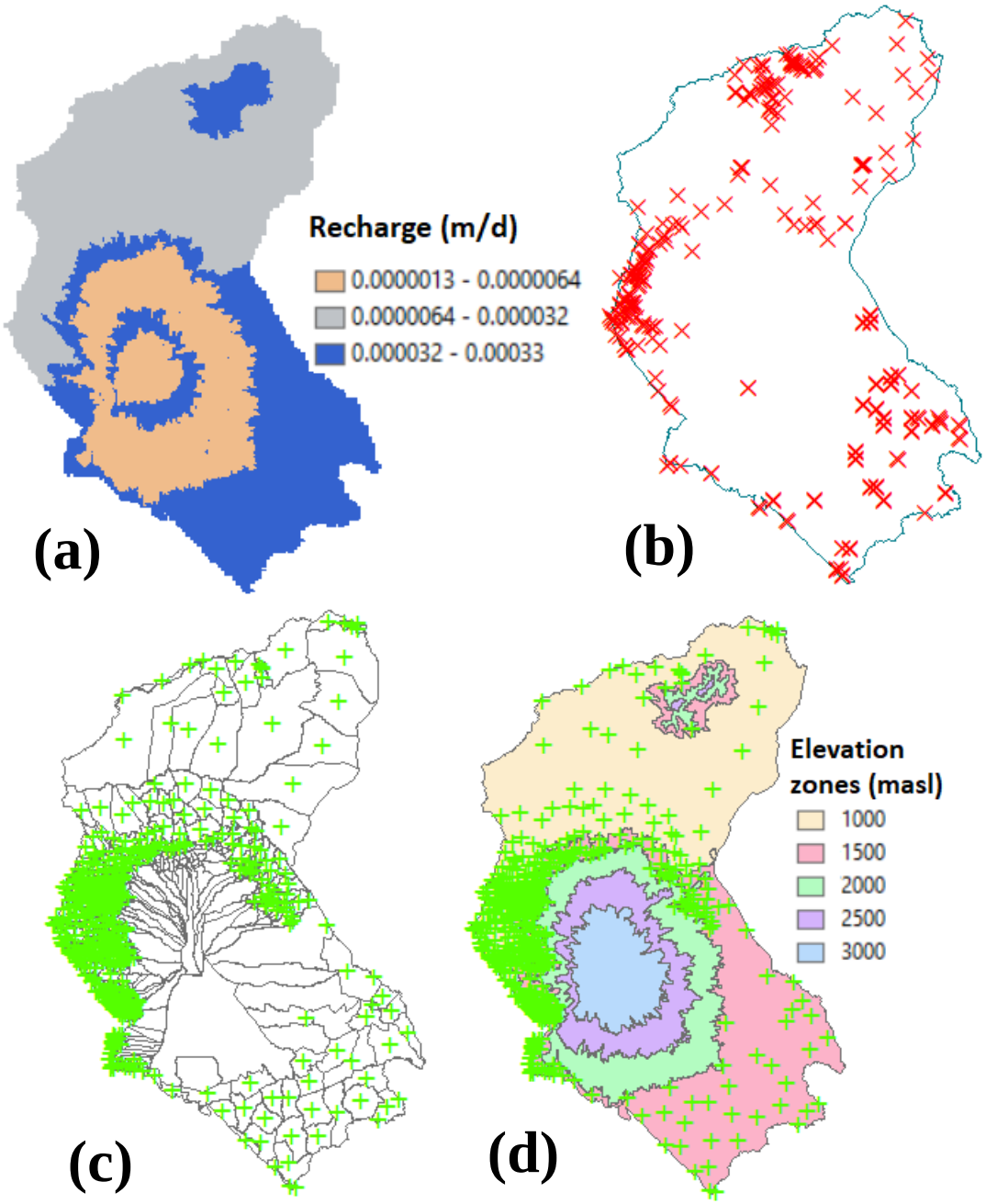


***Figure 4.5**: (a) Recharge estimated regions, (b) old abstraction wells completed in the region, (c) new abstraction wells located as centroids within each sub-county, and (d) new abstraction wells located within elevation zones upto 1,500 masl in the Mt. Elgon aquifer model region.*

4.5 Conceptual water budget

The focus of the Mt. Elgon shared aquifer model is the volcanic hydrogeological formation. Heterogeneous volcanic materials (e.g. lava flows, sheet basalts and pyroclastic rocks such as agglomerate and ash) commonly constitute a single aquifer system of variable extent and thickness. Permeability results from deep weathering and fractures, thick palaeosoils, and gas bubbles within lava flows; groundwater sources can also be shallow or discharge as springs. The presence of deep canyons on the steep soils due to erosion is however likely to limit the lateral extent of the hydroegeological units and induce more discharge and surface runoff.

The region underlain by deeply weathered extrusive igneous rocks and gneissic basement have fairly similar and slightly higher permeability compared to the intrusive igneous rocks which is the most dominant hydrogeological formation (Table 4.1). The conceptual hydrogeological model generated for the Mt. Elgon aquifer system thus depicts recharge in the higher caldera areas, with slopes dominated by runoff and springs, that flow and infiltrate into the low-relief region underlain by deeply weathered and fractured crystalline rocks, and discharge through alluvial and lacustrine sediments, and wetlands (Fig. 4.6). The key water budget parameters influencing the change in aquifer storage include rainfed recharge, surface runoff, spring flow, and discharge to wetlands, rivers and adjacent aquifers.

Table 4.1*: Comparison of transmissivity, TDS and yields of groundwater boreholes across the main geological formations of the Mt. Elgon aquifer region.*

	Extrusive igneous rocks	Gneissic basement	Intrusive igneous rocks	Meta sedimentary and volcanic rocks	Sedimentary rocks	Sediments	Volcanic rocks
Area (km^2)	1,792	10,463	10,471	290	66	9,562	5,463
T **(m^2/d)**							
n	22	56	94	1	2	13	19
mean	11.8	11.4	8.5	1.8	20.6	14.4	17.6
median	2.1	2.1	1.7	1.8	20.6	3.2	2.8
TDS (mg/l)							
n	26	84	240	4	2	14	21
mean	250	290	135	171	244	296	354
median	279	275	98	147	244	255	286
Yield (m^3/hr)							
n	66	130	443	3	5	24	56
mean	3.1	1.7	2.3	1.8	1.8	2.8	2.3
median	1.8	1.0	1.2	2.6	1.8	2.9	1.1

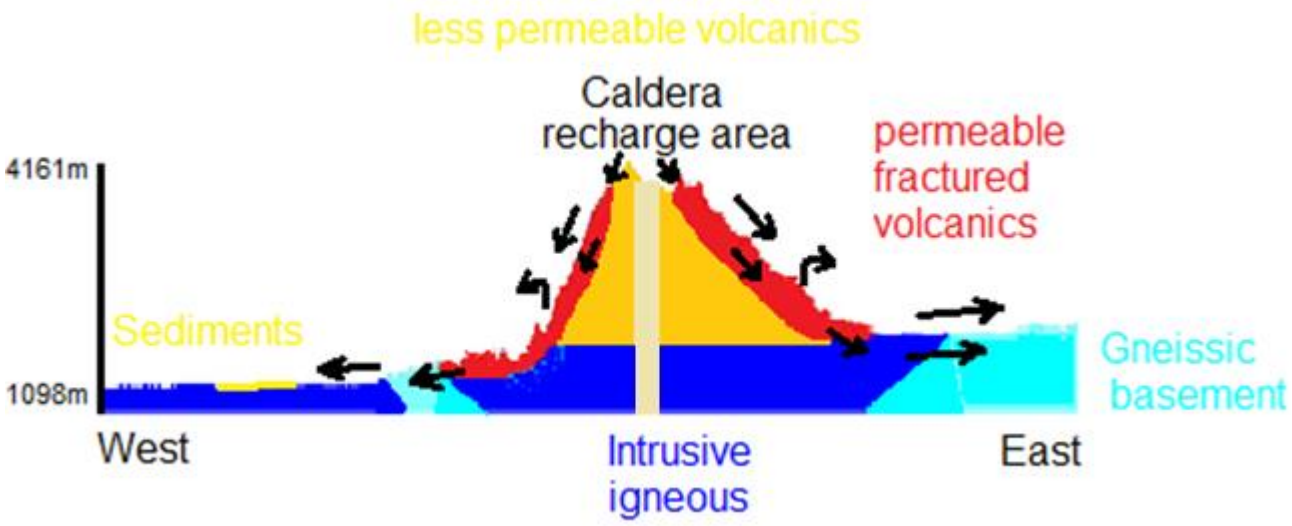


***Figure 4.6**: Conceptual model of the main hydrogeological formations of the Mt. Elgon aquifer system indicating the key water budget parameters.*

5. GROUNDWATER NUMERICAL FLOW MODEL

5.1 Model numerical solution

Due to limited datasets, it was not possible to calibrate, verify and validate the model. However, by matching and varying the main model parameters (e.g. *K*, recharge, aquifer bottom and riverbed conductance, the sensitivity and uncertainty of the model hydraulic heads was qualified. These systematic parameter changes were made until either the model system could not achieve equilibrium resulting in an unstable numerical solution, or the modelled areas consistently dried up.

The steady state condition numerical model solution is illustrated in Fig. 5.1a. Hydraulic head ranges from 720 masl in the low relief region to 3,425 masl in the mountainous area. On the upper reaches of the volcanic massif there is surface discharge corresponding to stream and spring flow drainage; a similar pattern is observed in the central northern low relief area which coincides with wetlands underlain by sediments (Fig. 5.1b). Indicative groundwater flow forms a radial direction away from the volcanic massif and it follows the surface drainage pattern (Fig. 5.1c). Simulated steady state spatial recharge conditions is a much smaller percentage of previous recharge estimtes in the Mt. Elgon region (Fig. 5.1d).

Vertical cross sections drawn across the vent of the volcanic mountain provides a relationship between the terrain elevation and steady state groundwater level. The north-south cross section (Fig. 5.2a) and east-west (Fig. 5.2b) directions capture the elevation sections where the streams or springs discharge water onto the surface that flows downslope.

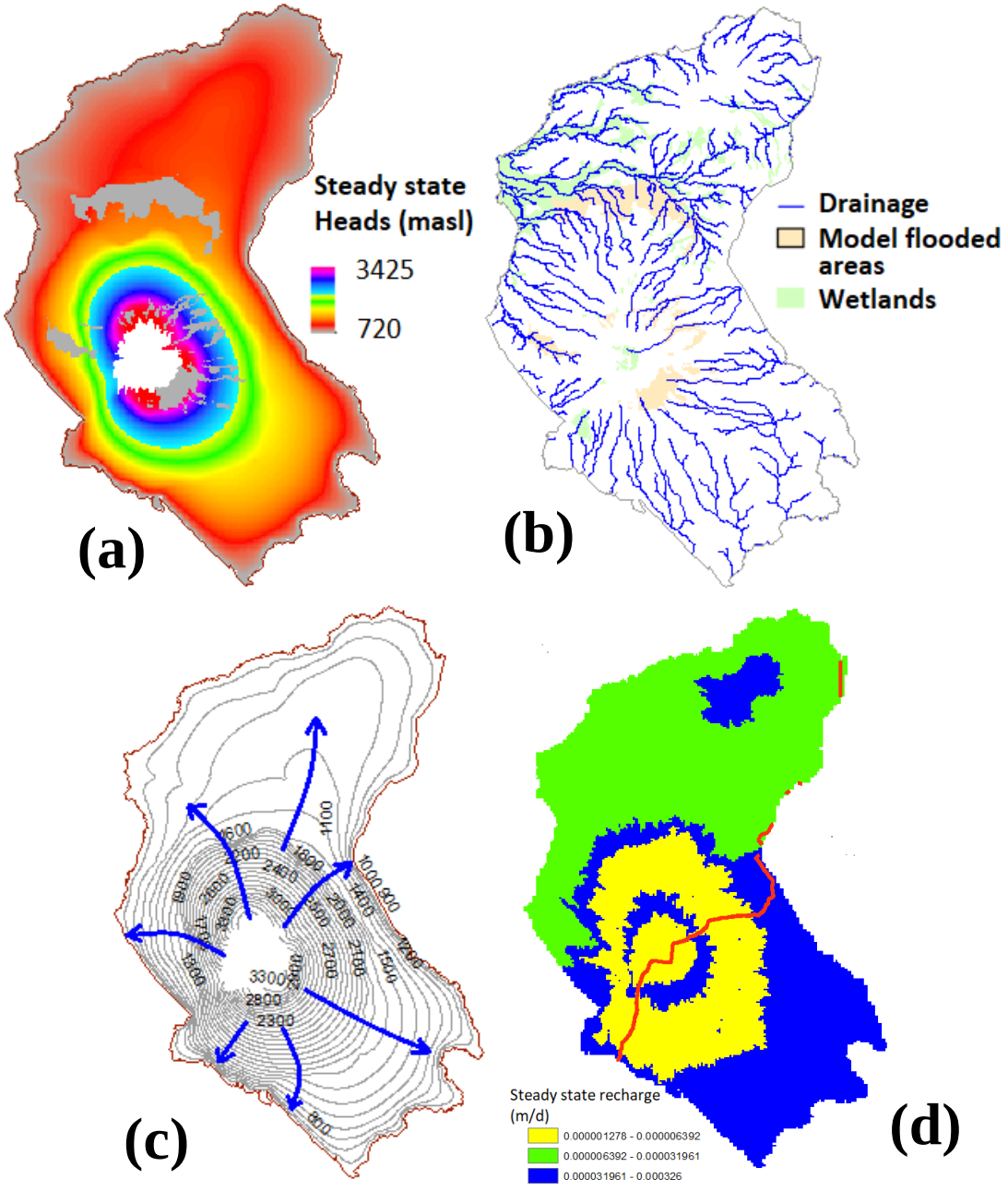


***Figure 5.1**: Mt. Elgon aquifer model steady state solution showing, (a) hydraulic heads, (b) drainage, wetlands and flooded model areas, (c) hydraulic head contours with indicative groundwater flow directions, and (d) simulated steady state spatial recharge conditions.*

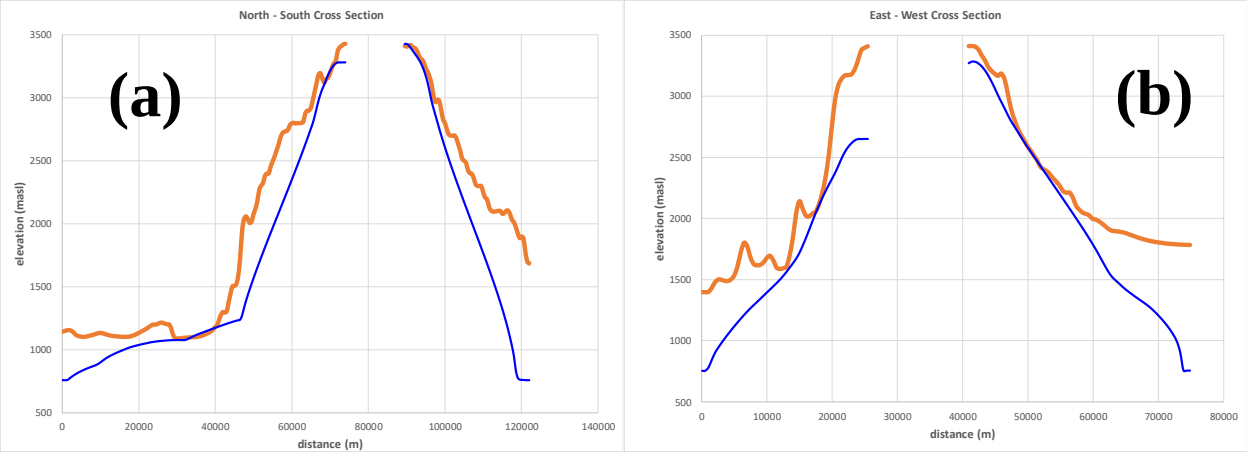


***Figure 5.2**: Mt. Elgon aquifer model steady state solution cross sections of the hydraulic heads across the volcanic massif from (a) North-South, to (b) East-West.*

5.2 Model water balance

The water balance of the steady state model solution is zoned into (a) national context, between Uganda and Kenya (Fig. 5.3a), and (b) hydrogeological formations, between volcanic and non-volcanic areas (Fig. 5.3b). The water budget has main inflows as recharge and fluxes from adjacent hydrogeological units, whereas outflows include groundwater abstraction wells, surface drainage and fluxes to adjacent hydrogeological units (Table 5.1).

National hydrologic budget zones indicate for Ugandan side of the Mt. Elgon aquifer, main inflows as recharge (82%) and fluxes (18%) from adjacent hydrogeological units; whereas outflows include groundwater surface drainage (80%), fluxes (12%) to adjacent hydrogeological units, and abstraction wells (9%). For the Kenyan side main inflows are recharge (89%) and fluxes (11%) from adjacent hydrogeological units; whereas outflows include surface drainage (79%), fluxes (17%) to adjacent hydrogeological units, and groundwater abstraction wells (4%). In the case of hydrogeological zones, the hydrologic budget indicates for the volcanic region main inflows as recharge (85%) and fluxes (15%) from adjacent hydrogeological units; whereas outflows include fluxes (71%) to adjacent hydrogeological units, surface drainage (25%), and groundwater abstraction wells (4%). For the non-volcanic region main inflows fluxes (65%) from adjacent hydrogeological units and recharge (35%); whereas outflows include surface drainage (82%), fluxes (14%) to adjacent hydrogeological units, and groundwater abstraction wells (4%).

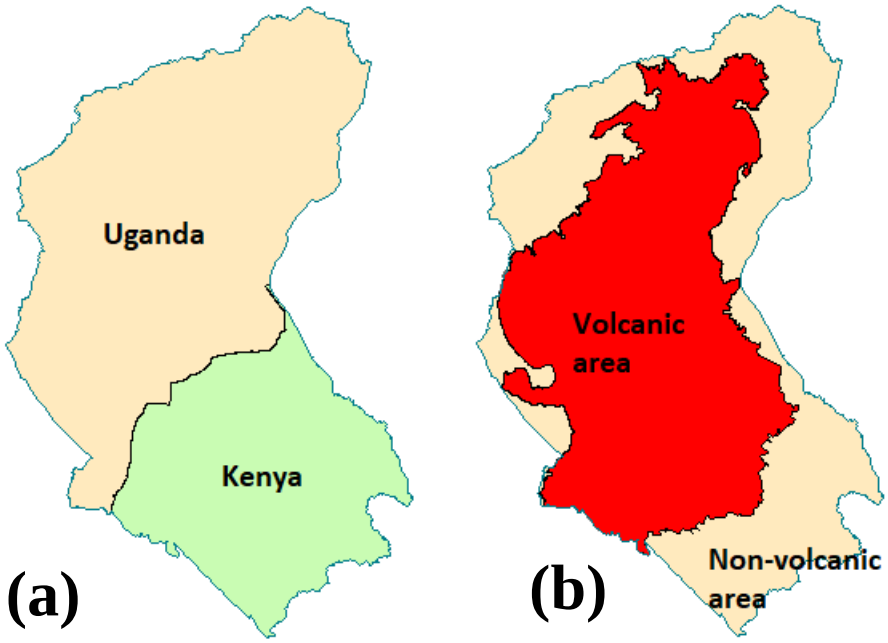


***Figure 5.3**: Mt. Elgon aquifer model water budget zonal areas in terms of (a) national context of Uganda and Kenya, and (b) hydrogeological formations of volcanic against non-volcanic areas.*

***Table 5.1**: Mt. Elgon aquifer steady state model solution estimated water budgets (m^3/yr).*

Zone Name	Recharge	From Other Zones	Wells	Drains	To Other Zones
National zones					
Non-volcanic	25,340,643	48,085,648	3,303,081	60,023,374	10,104,127
Volcanic	57,585,576	10,104,127	2,710,256	16,889,678	48,085,648
Total	82,926,219	58,189,775	6,013,337	76,913,052	58,189,775
Hydrogeological zones					
Uganda	38,870,931	8,320,996	4,125,033	37,599,234	5,474,051
Kenya	44,055,281	5,474,051	1,888,306	39,313,822	8,320,996
Total	82,926,212	13,795,047	6,013,339	76,913,056	13,795,047

6. PREDICTIVE GROUNDWATER NUMERICAL FLOW MODEL

The climate projections for SSP2-4.5 and SSP5-8.5 were used to generate monthly rainfall and minimum and maximum temperatures for the historical period (1990-2019), and future perids (2020-2039 and 2040-2059), (Fig. 6.1). Regionally, over the projected period trends in SSP2-4.5 and SSP5-8.5 is similar ad therefore only the SSP5-8.5 projections were used. A positive trend is registered in mean monthly rainfall, as well as the mean monthly minimum temperature. The mean monthly maximum temperature has a stable trend during the projected climate period. This suggests a reduction in evapotranspiration over the projected climate period, which is expected to contribute to increased recharge. The postive trend in projected recharge was related to the spatial estimate of excess of rainfall over actual evapotranspitation (Fig. 6.2). Using the trend (factors used to increase recharge was from 1.0006281 to 1.0971387) of the extreme SSP5-8.5 projected on the difference between rainfall and actual evapotranspiration, recharge was estimated from 2022 to 2050.

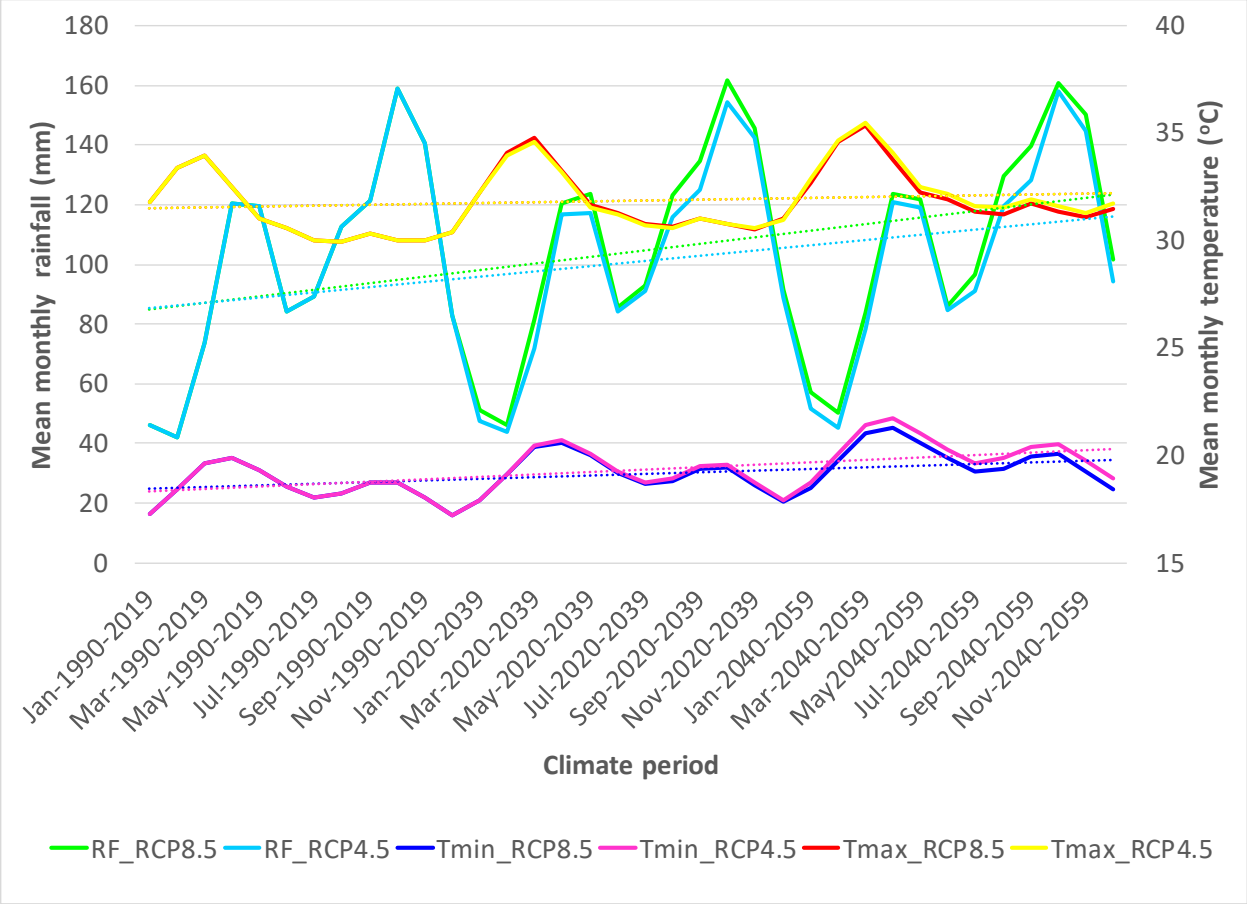


***Figure 6.1**: Current (1990-2019) and projected (2020-2039 and 2040-2059) mean monthly rainfall, minimum and maximum temperature for* SSP2-4.5 *and* SSP5-8.5 *in the region of the Mt. Elgon aquifer system.*

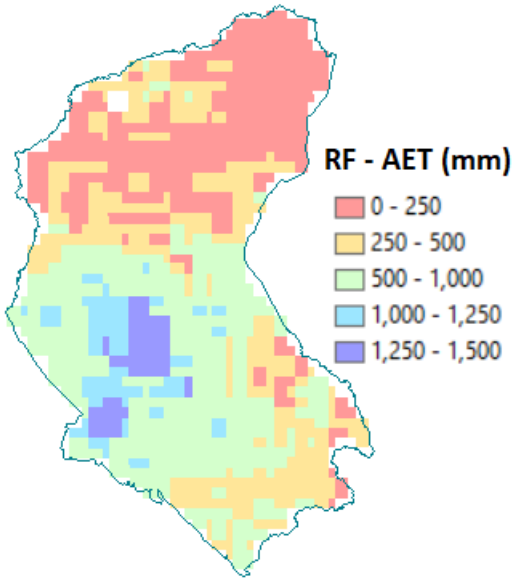


***Figure 6.2**: Gridded mean annual rainfall (2010-2020) adapted from CHIRPS (2021) minus gridded mean annual (2015-2020) actual evapotranspiration and interception adapted from WaPOR (2021).*

The predictive groundwater numerical flow model was run using six (6) scenarios outlined in Table 6.1. SC1 was the baseline, with old wells pumped at completion rates until 2050. SC2 had the old wells abstraction rates were increased to 2.5 times of the completion abstraction rates with a maximum of 20 m^3/hr (380 m^3/d) and pumped until 2050. SC3 included new wells added within the zone of up to 1,500 masl elevation with uniform abstraction rates of 7 m^3/hr (170 m^3/d) and pumped until 2050. SC4 was a phased increase in recharge (SSP5-8.5) while only old wells were pumped until 2050. SC5 was a phased increase in recharge (SSP5-8.5) while pumping old wells at the original completion abstraction rates and new wells abstracted at increased rates from 7 m^3/hr to 8.33 m^3/hr until 2050. SC6 was a phased increase in recharge (SSP5-8.5) while pumping old wells at 3 times of the completion abstraction rates until 2050. These scenarios were informed by hydraulic properties of the aquifer system. It was noted that water demand based on estimates of population distribution was high and could not be met by potential of the aquifer system. Based on the estimated Mt. Elgon model region population of 2,663,038 with a 2022 growth rate of Uganda (3.04%) and Kenya (1.93%) and assuming a 25L per capita water demand, this would result into a starting water demand in 2022 of 243,168,657 m^3/yr up to 475,237,847 m^3/yr in 2050. The scenarios were also informed by the water demand levels that led to the drying up of the aquifer system and influenced the system not to achieve equilibrium as the numerical solution became unstable.

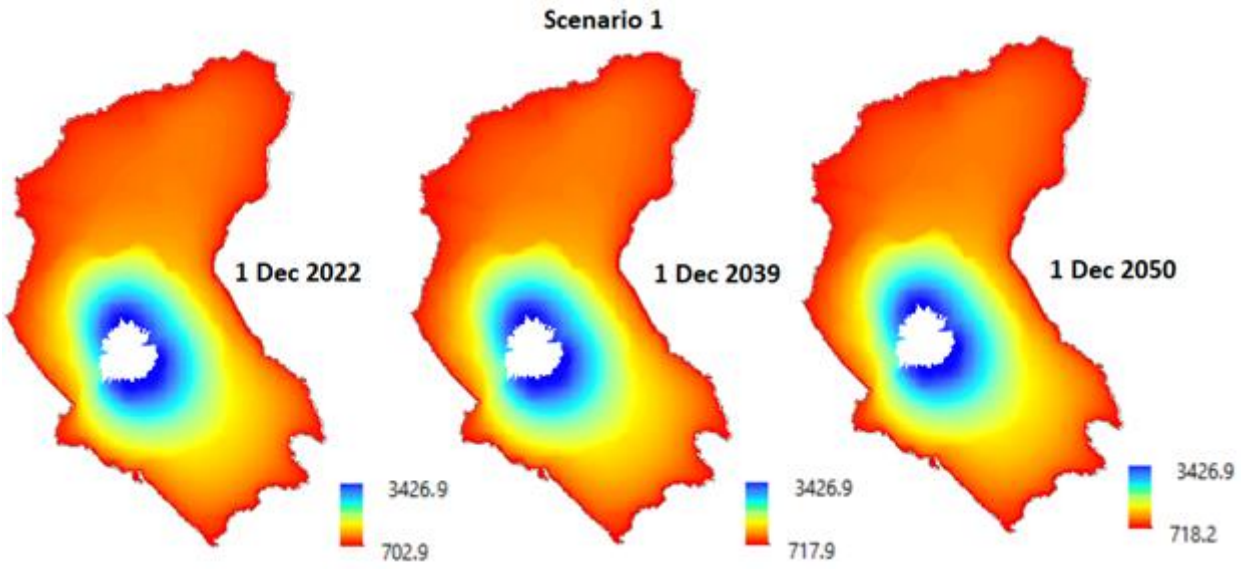
***Table 6.1**: Mt. Elgon aquifer transient state water demand and climate change scenarios.*

Scenario	Projection stress
SC1	Baseline, old wells at completion rates were pumped until 2050;
SC2	The old wells abstraction rates were increased to 2.5 times of the completion abstraction rates with a maximum of 20 m^3/hr (380 m^3/d) and pumped until 2050;

SC3	New wells were added within the region of up to 1,500 masl elevation with uniform abstraction rates of 7 m^3/hr (170 m^3/d) and pumped until 2050;
SC4	Phased increase in recharge (SSP5-8.5) while only old wells were pumped until 2050;
SC5	Phased increase in recharge (SSP5-8.5) while pumping old wells at the original completion abstraction rates and new wells abstracted at increased rates from 7 m^3/hr to 8.33 m^3/hr until 2050;
SC6	Phased increase in recharge (SSP5-8.5) while pumping old wells at 3 times of the completion abstraction rates until 2050;

6.1 Impact of increased/unsustainable withdrawals from Recent to 2050 on water balance

The spatial changes in groundwater heads due to projected increased water demand from recent to 2050 under scenarios 1, 2 and 3 is illustrated from current (1 December 2022) to future (1 December 2039 and 1 December 2050) periods (Fig. 6.3). Across the model region, currently from scenario 1, the lowest hydraulic head was simulated at about 702 masl on 1 December 2022, which will fall to 717 masl on 1 December 2039, and maintains a level of 718 masl on 1 December 2050. In scenario 2, the lowest hydraulic head was simulated at about 715 masl on 1 December 2022, which will fall to 712 masl on 1 December 2039, and this level further falls 705 masl on 1 December 2050. For scenario 3, the lowest hydraulic head was simulated at about 688 masl on 1 December 2022, which recovers to 701 masl on 1 December 2039, but falls again to 693 masl on 1 December 2050. The spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by each of the three projected scenarios, however, there is a total fall in water level of about 14 m.



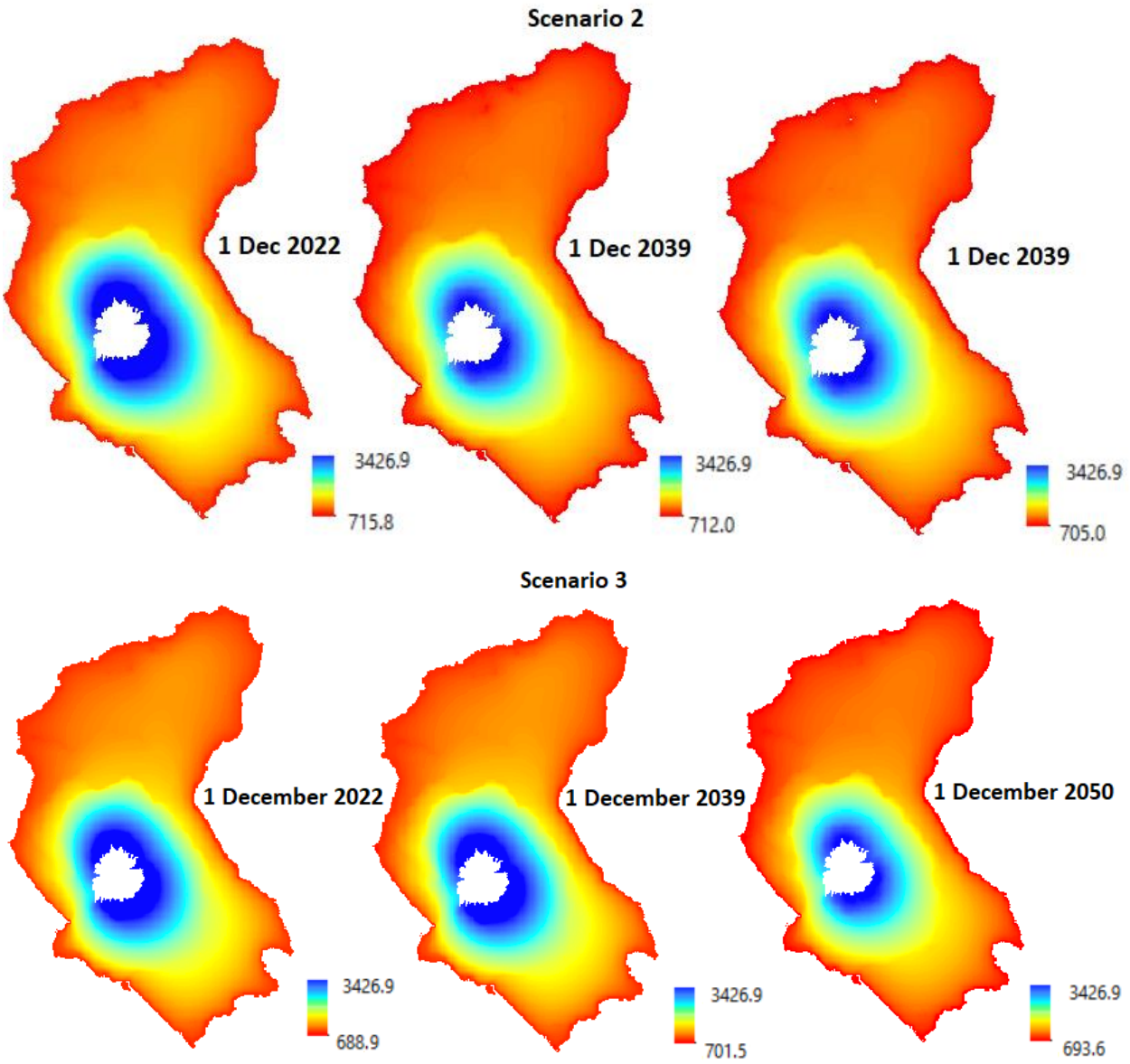


***Figure 6.3**: Impact of projected increased water demand from recent to 2050 under scenarios 1, 2 and 3 in the Mt. Elgon aquifer region.*

The estimated water balance for the model area over each of the zoned (e.g., non-volcanic, vocanic, Ugandan and Kenyan sides) regions is summarized for the current period (1 January 2022) and future periods (1 January 2039 and 1 January 2050) in Table 6.2. In the non-volcanic region, it is only scenario 3 that generates the most increase in flux from other zones (5%), abstraction wells (4%), drains (7%) and flux to other zones (5%). The volcanic region similarly shows the most increase in scenario 3 with flux from other zones (5%), drains (7%) and flux to other zones (5%); however, the most increase in outflow due to abstraction wells (7%) is in scenario 2. For the Ugandan side, scenario 3 also generates the most increase in flux from other zones (0.4%), abstraction wells (2%), drains (13%) and flux to other zones (3%). On the Kenyan side, likewise

scenario 3 also generates the most increase in flux from other zones (3%), abstraction wells (7%), drains (1%) and flux to other zones (0.4%).

***Table 6.2**: The estimated water budget (m^3/yr) for projected increased water demand in the non-volcanic, volcanic, Ugandan and Kenyan sides of the Mt. Elgon aquifer region.*

Non-Volcanic region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC1					
01/01/2022	31/12/2022	25,980,664	48,458,893	3,402,244	60,378,358	10,180,885
01/01/2039	31/12/2039	25,977,657	48,434,789	3,303,081	60,580,703	10,178,085
01/01/2050	31/12/2050	25,977,657	48,419,216	3,303,081	60,623,708	10,176,209
	SC2					
01/01/2022	31/12/2022	25,974,649	48,820,038	8,082,607	59,476,046	10,149,342
01/01/2039	31/12/2039	25,974,010	48,781,965	7,990,627	58,406,644	10,236,799
01/01/2050	31/12/2050	25,973,372	48,609,650	7,802,287	57,942,614	10,161,163
	SC3					
01/01/2022	31/12/2022	25,943,217	49,144,082	14,534,581	56,355,477	9,247,784
01/01/2039	31/12/2039	25,917,941	47,779,755	13,892,608	53,653,968	8,896,894
01/01/2050	31/12/2050	25,913,474	46,936,572	13,892,608	52,519,194	8,750,143

Volcanic region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC1					
01/01/2022	31/12/2022	25,980,664	48,458,893	3,402,244	60,378,358	10,180,885
01/01/2039	31/12/2039	25,977,657	48,434,789	3,303,081	60,580,703	10,178,085
01/01/2050	31/12/2050	25,977,657	48,419,216	3,303,081	60,623,708	10,176,209
	SC2					
01/01/2022	31/12/2022	58,337,207	10,149,342	7,155,913	16,607,352	48,820,038
01/01/2039	31/12/2039	58,334,200	10,236,799	6,982,465	16,382,461	48,781,965
01/01/2050	31/12/2050	58,332,925	10,161,163	6,649,585	16,296,029	48,609,650
	SC3					
01/01/2022	31/12/2022	58,337,207	9,247,784	21,263,206	16,096,375	49,144,082
01/01/2039	31/12/2039	58,331,187	8,896,894	21,118,082	15,417,049	47,779,755
01/01/2050	31/12/2050	58,331,187	8,750,143	21,118,082	15,047,816	46,936,572

Ugandan side of Region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC1					
01/01/2022	31/12/2022	39,813,648	8,313,129	4,125,033	38,067,654	5,527,509

01/01/2039	31/12/2039	39,813,648	8,310,934	4,125,033	38,187,431	5,527,130
01/01/2050	31/12/2050	39,813,648	8,310,915	4,125,033	38,200,970	5,528,129
	SC2					
01/01/2022	31/12/2022	39,813,648	8,311,170	11,000,651	36,980,363	5,531,973
01/01/2039	31/12/2039	39,813,006	8,296,367	10,908,671	35,903,176	5,546,767
01/01/2050	31/12/2050	39,811,091	8,292,854	10,387,451	35,492,953	5,545,278
	SC3					
01/01/2022	31/12/2022	39,779,305	8,341,935	31,457,689	33,741,079	5,470,735
01/01/2039	31/12/2039	39,759,952	8,359,085	30,950,635	30,693,259	5,356,723
01/01/2050	31/12/2050	39,755,481	8,371,852	30,950,635	29,376,712	5,304,720

Kenyan side of Region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC1					
01/01/2022	31/12/2022	44,504,223	5,527,942	1,987,469	39,368,990	8,313,474
01/01/2039	31/12/2039	44,501,219	5,527,037	1,888,306	39,510,270	8,310,947
01/01/2050	31/12/2050	44,501,219	5,528,026	1,888,306	39,538,985	8,310,891
	SC2					
01/01/2022	31/12/2022	44,498,209	5,531,973	4,237,869	39,103,034	8,311,170
01/01/2039	31/12/2039	44,495,196	5,546,767	4,064,421	38,885,929	8,296,367
01/01/2050	31/12/2050	44,495,196	5,545,278	4,064,421	38,745,696	8,292,854
	SC3					
01/01/2022	31/12/2022	44,501,120	5,470,735	4,340,099	38,710,780	8,341,935
01/01/2039	31/12/2039	44,489,182	5,356,723	4,060,056	38,377,765	8,359,085
01/01/2050	31/12/2050	44,489,182	5,304,720	4,060,056	38,190,299	8,371,852

6.2 Impact of climate change projections from Recent to 2050 on water balance

The spatial changes in groundwater heads due to projected climate change from recent to 2050 under scenarios 4 and 5 is illustrated from current (1 December 2022) to future (1 December 2039 and 1 December 2050) periods (Fig. 6.4). Across the model region, currently from scenario 4, the lowest hydraulic head was simulated at about 702 masl on 1 December 2022, which will fall to 718 masl on 1 December 2039, and maintains a level of 719 masl on 1 December 2050. In scenario 5, the lowest hydraulic head was simulated at about 683 masl on 1 December 2022, which will fall to 692 masl on 1 December 2039, and this level further falls 676 masl on 1 December 2050. Again, the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by each of the two projected scenarios, however, there is a total fall in water level of about 26 m.

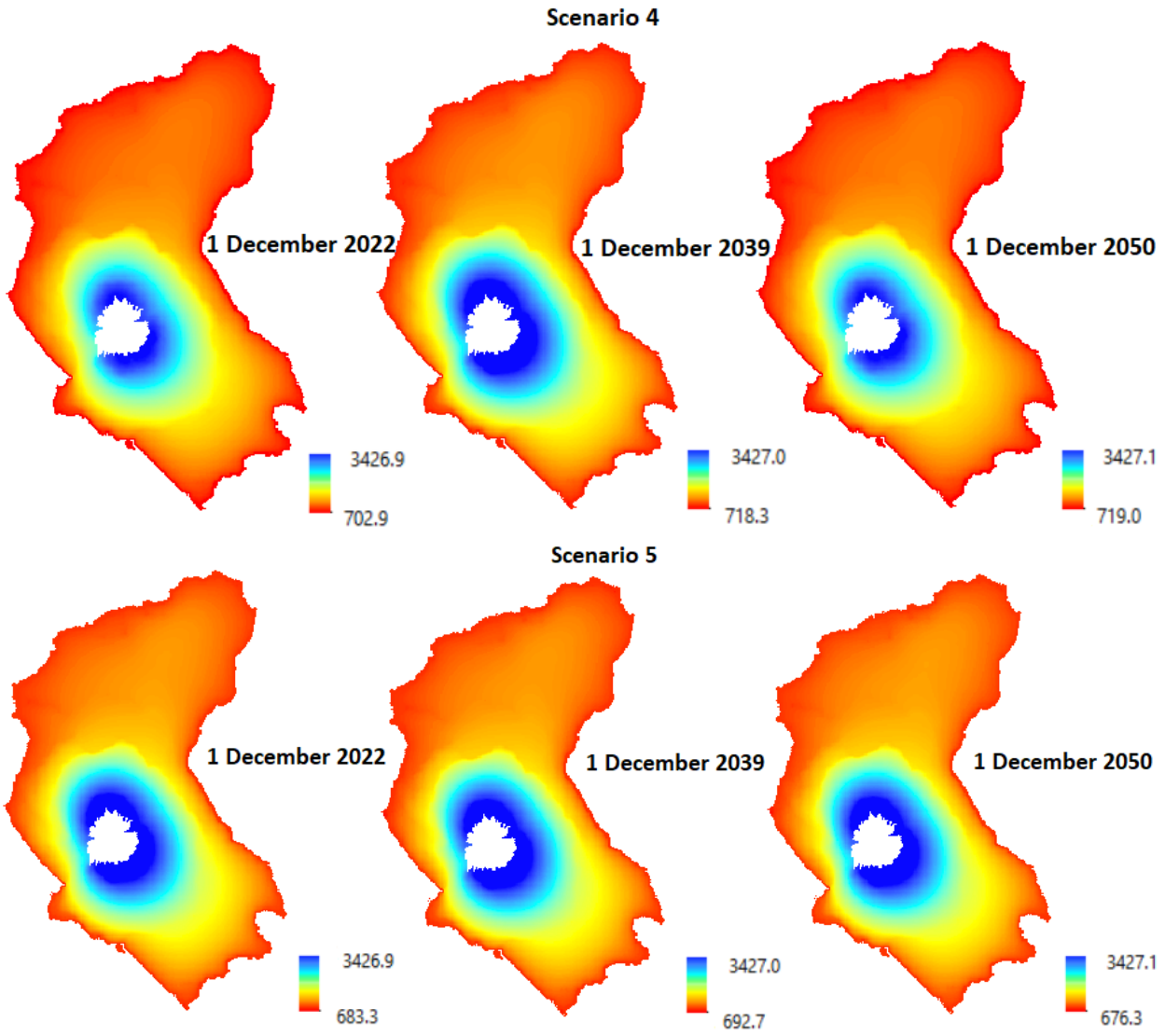


***Figure 6.4**: Impact of projected climate change from recent to 2050 under scenarios 4 and 5 in the Mt. Elgon aquifer region.*

The estimated water balance for the model area over each of the zoned (e.g., non-volcanic, volcanic, Ugandan and Kenyan sides) regions is summarized for the current period (1 January 2022) and future periods (1 January 2039 and 1 January 2050) in Table 6.3. In the non-volcanic region, both scenarios 4 and 5 generate a relatively substantial change in recharge (3%); however, it is in scenario 5 that there is the most increase in flux from other zones (5%), abstraction wells (6%), drains (8%) and flux to other zones (7%). The volcanic region shows a similar pattern, with both scenarios 4 and 5 generating a relatively substantial change in recharge (3%); scenario 5 has the most increase in flux from other zones (7%), abstraction wells (12%), drains (6%) and flux to other zones (5%). For the Ugandan side, both scenarios 4 and 5 also generate a substantial change in recharge (3%); scenario 5 has most increase in flux from other zones (0.5%), abstraction wells (11%), drains (15%) and flux to other zones (3%). On the Kenyan side, equally both scenarios 4 and 5 generate a substantial change in recharge (3%); scenario 5, generates the most increase in

flux from other zones (3%) and flux to other zones (0.5%); whereas, scenario 4 generates the most increase in abstraction wells (5%) and drains (1%).

***Table 6.3**: The estimated water budget (m^3/yr) for projected climate change in the non-volcanic, volcanic, Ugandan and Kenyan sides of the Mt. Elgon aquifer region.*

Non-Volcanic region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC4					
01/01/2022	31/12/2022	26,007,439	48,458,367	3,402,244	60,381,605	10,181,054
01/01/2039	31/12/2039	26,459,571	48,423,342	3,303,081	60,720,858	10,185,777
01/01/2050	31/12/2050	26,754,077	48,407,703	3,303,081	60,900,794	10,191,351
	SC5					
01/01/2022	31/12/2022	25,968,359	49,159,105	14,773,783	56,313,866	9,234,616
01/01/2039	31/12/2039	26,398,752	47,815,863	15,076,647	53,304,091	8,817,578
01/01/2050	31/12/2050	26,688,637	46,934,294	15,682,502	51,932,469	8,624,181

Volcanic region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC4					
01/01/2022	31/12/2022	58,397,325	10,181,054	2,710,256	17,068,547	48,458,367
01/01/2039	31/12/2039	59,419,432	10,185,777	2,710,256	17,243,473	48,423,342
01/01/2050	31/12/2050	60,080,789	10,191,351	2,710,256	17,360,300	48,407,703
	SC5					
01/01/2022	31/12/2022	58,397,325	9,234,616	21,696,521	16,085,980	49,159,105
01/01/2039	31/12/2039	59,413,299	8,817,578	23,174,574	15,415,064	47,815,863
01/01/2050	31/12/2050	60,074,587	8,624,181	24,226,848	15,063,434	46,934,294

Ugandan side of Region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC4					
01/01/2022	31/12/2022	39,854,679	8,313,135	4,125,033	38,069,106	5,527,541
01/01/2039	31/12/2039	40,552,230	8,312,783	4,125,033	38,276,654	5,531,021
01/01/2050	31/12/2050	41,003,594	8,316,546	4,125,033	38,381,888	5,537,043
	SC5					
01/01/2022	31/12/2022	39,819,194	8,342,390	32,085,901	33,681,682	5,470,075
01/01/2039	31/12/2039	40,497,539	8,364,800	33,948,818	30,251,811	5,349,487
01/01/2050	31/12/2050	40,944,351	8,384,394	35,482,941	28,623,594	5,291,326

Kenyan side of Region						
Period		Recharge	From Other Zones	Wells	Drains	To Other Zones
	SC4					
01/01/2022	31/12/2022	44,550,092	5,527,541	1,987,469	39,381,046	8,313,135
01/01/2039	31/12/2039	45,326,770	5,531,021	1,888,306	39,687,679	8,312,783
01/01/2050	31/12/2050	45,831,271	5,537,043	1,888,306	39,879,203	8,316,546
	SC5					
01/01/2022	31/12/2022	44,546,495	5,470,075	4,384,403	38,718,169	8,342,390
01/01/2039	31/12/2039	45,314,509	5,349,487	4,302,403	38,467,339	8,364,800
01/01/2050	31/12/2050	45,818,876	5,291,326	4,426,408	38,372,306	8,384,394

6.3 Impacts of projected climate change and increased demand from Recent to 2050 on water balance

The spatial changes in groundwater heads due to projected climate change from recent to 2050 under scenario 6 is illustrated from current (1 December 2022) to future (1 December 2039 and 1 December 2050) periods (Fig. 6.5). Across the model region, currently from scenario 6, the lowest hydraulic head was simulated at about 715 masl on 1 December 2022, which will fall to 712 masl on 1 December 2039, and further falls to 705 masl on 1 December 2050. Again, the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by the scenario, however, there is a total fall in water level of about 10 m.

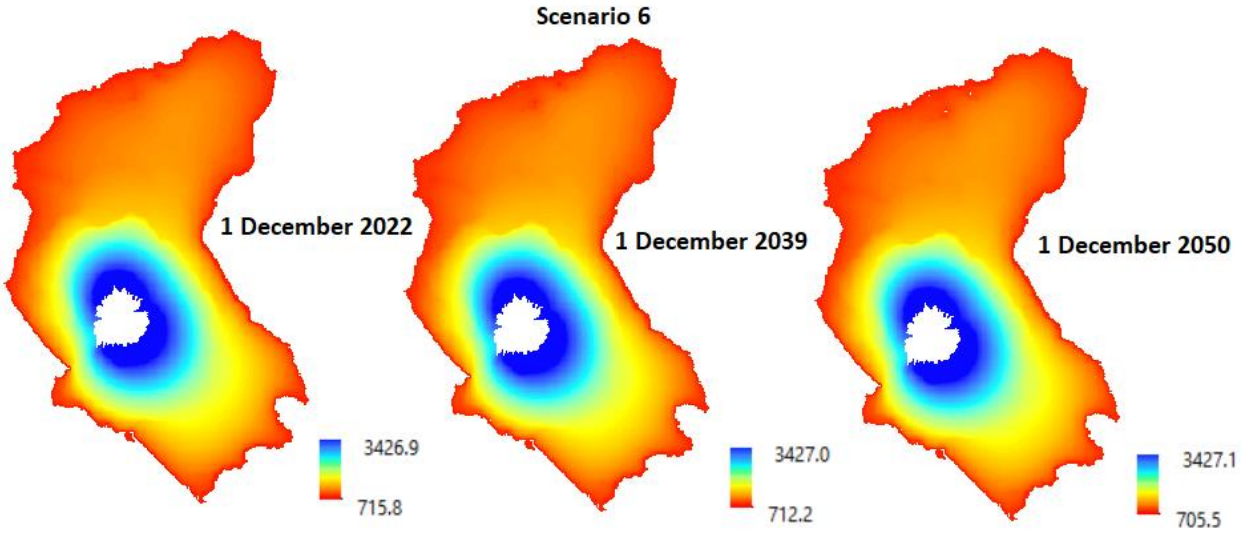


***Figure 6.5**: Impact of projected increased water demand and climate change from recent to 2050 under scenario 6 in the Mt. Elgon aquifer region.*

The estimated water balance for the model area over each of the zoned (e.g., non-volcanic, vocanic, Ugandan and Kenyan sides) regions is summarized for the current period (1 January 2022) and future periods (1 January 2039 and 1 January 2050) in Table 6.4. In the non-volcanic region, a relatively substantial change in recharge (3%), flux from other zones (0.5%), abstraction wells (4%), and drains (2%) is realised by 31 December 2050; however, the most change in flux to other zones (1%) is generated by 31 December 2039. The volcanic region on the other hand shows a a relatively substantial change in recharge (3%), abstraction wells (7%) and flux to other zones (0.5%) by 31 December 2050; whereas, the most increase in flux from other zones (1%) and drains (0.6%) is realised by 31 December 2039. For the Ugandan side, a substantial change in recharge (3%), abstraction wells (6%), drains (4%) and flux to other zones (0.4%) is generated by 31 December 2050 except for in flux from other zones (0.5%) that is realised by 31 December 2039. On the Kenyan side, however, a substantial change in recharge (3%) and in flux from other zones (0.4%) is generated on 31 December 2050, whereas, the most change in abstraction wells (4%), drains (0.1%) and flux to other zones (0.2%) is obtained by 31 December 2039.

***Table 6.4**: The estimated water budget (m^3/yr) for projected increased water demand and climate change in the non-volcanic, volcanic, Ugandan and Kenyan sides of the Mt. Elgon aquifer region.*

Non-volcanic region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC6					
01/01/2022	31/12/2022	26,001,420	48,819,506	8,082,607	59,479,293	10,149,517
01/01/2039	31/12/2039	26,455,859	48,770,685	7,990,627	58,546,058	10,244,529
01/01/2050	31/12/2050	26,749,665	48,598,588	7,802,287	58,217,402	10,176,664

Volcanic region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC6					
01/01/2022	31/12/2022	58,397,325	10,149,517	7,155,913	16,609,945	48,819,506
01/01/2039	31/12/2039	59,416,363	10,244,529	6,982,465	16,506,808	48,770,685
01/01/2050	31/12/2050	60,076,375	10,176,664	6,649,585	16,537,904	48,598,588

Ugandan side of Region						
Period		**Recharge**	**From Other Zones**	**Wells**	**Drains**	**To Other Zones**
	SC6					
01/01/2022	31/12/2022	39,854,679	8,311,176	11,000,651	36,981,802	5,532,004
01/01/2039	31/12/2039	40,551,586	8,298,213	10,908,671	35,991,253	5,550,670
01/01/2050	31/12/2050	41,000,963	8,298,455	10,387,451	35,671,204	5,554,175

Kenyan side of Region

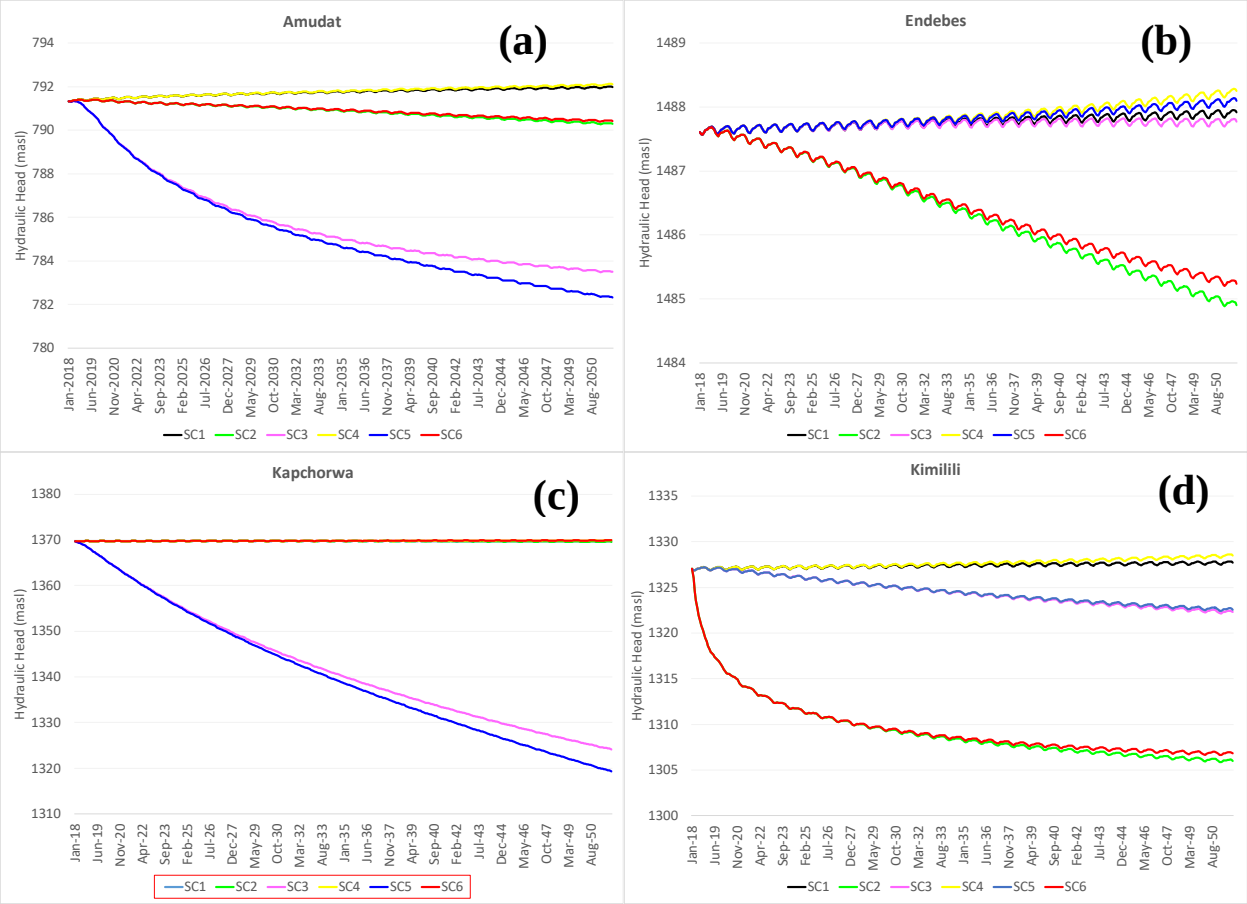
Period		Recharge	From Other Zones	Wells	Drains	To Other Zones
	SC6					
01/01/2022	31/12/2022	44,544,067	5,532,004	4,237,869	39,107,432	8,311,176
01/01/2039	31/12/2039	45,320,636	5,550,670	4,064,421	39,061,615	8,298,213
01/01/2050	31/12/2050	45,825,072	5,554,175	4,064,421	39,084,103	8,298,455

6.4 Impacts of climate change and increased demand on groundwater levels

Selected urban growth population centres in the modelled Mt. Elgon aquifer region include on the Ugandan (e.g. Amudat, Kapchorwa and Sironko) and Kenyan sides (e.g., Endebess, Kamilili, Kiminini and Kitale), (Fig. 6.6). Simulated transient groundwater levels from the current (2022) to future (2050) were generated for fictitious wells located at the centre of each of these urban centres (Fig. 6.7). At Amudat the highest fall in water level is during scenarios 3 and 5 where up to a 9 m drawdown is generated (Fig. 6.7a). For Endebess there is a minimal drawdown of up to 3 m during scenarios 6 and 2 (Fig. 6.7b). At Kapchorwa a significant drawdown of up to 50 m is generated during scenarios 3 and 5 (Fig. 6.7c). In Kimilili a substantial drawdown of up to 21 m is realised during scenarios 6 and 2 (Fig. 6.7d). At Kiminini there is a drawdown of up to 7 m during scenarios 6 and 2 (Fig. 6.7e). For Kitale there is also a drawdown of up to 7 during scenarios 3 and 5 (Fig. 6.7f). At Sironko a significant drawdown of up to 50 m is generated during scenarios 3 and 5 (Fig. 6.7g).



Figure 6.6: *Selected towns with groundwater level changes due to projected climate change and increased water demand in the Mt. Elgon aquifer modelled area.*


Amudat
(a)
Hydraulic Head (masl)
794
792
790
788
786
784
782
780
Jan-2018
Jun-2019
Nov-2020
Apr-2022
Sep-2023
Feb-2025
Jul-2026
Dec-2027
May-2029
Oct-2030
Mar-2032
Aug-2033
Jan-2035
Jun-2036
Nov-2037
Apr-2039
Sep-2040
Feb-2042
Jul-2043
Dec-2044
May-2046
Oct-2047
Mar-2049
Aug-2050
SC1 SC2 SC3 SC4 SC5 SC6
Endebes
(b)
Hydraulic Head (masl)
1489
1488
1487
1486
1485
1484
Jan-18
Jun-19
Nov-20
Apr-22
Sep-23
Feb-25
Jul-26
Dec-27
May-29
Oct-30
Mar-32
Aug-33
Jan-35
Jun-36
Nov-37
Apr-39
Sep-40
Feb-42
Jul-43
Dec-44
May-46
Oct-47
Mar-49
Aug-50
SC1 SC2 SC3 SC4 SC5 SC6
Kapchorwa
(c)
Hydraulic Head (masl)
1380
1370
1360
1350
1340
1330
1320
1310
Jan-18
Jun-19
Nov-20
Apr-22
Sep-23
Feb-25
Jul-26
Dec-27
May-29
Oct-30
Mar-32
Aug-33
Jan-35
Jun-36
Nov-37
Apr-39
Sep-40
Feb-42
Jul-43
Dec-44
May-46
Oct-47
Mar-49
Aug-50
SC1 SC2 SC3 SC4 SC5 SC6
Kimilili
(d)
Hydraulic Head (masl)
1335
1330
1325
1320
1315
1310
1305
1300
Jan-18
Jun-19
Nov-20
Apr-22
Sep-23
Feb-25
Jul-26
Dec-27
May-29
Oct-30
Mar-32
Aug-33
Jan-35
Jun-36
Nov-37
Apr-39
Sep-40
Feb-42
Jul-43
Dec-44
May-46
Oct-47
Mar-49
Aug-50
SC1 SC2 SC3 SC4 SC5 SC6

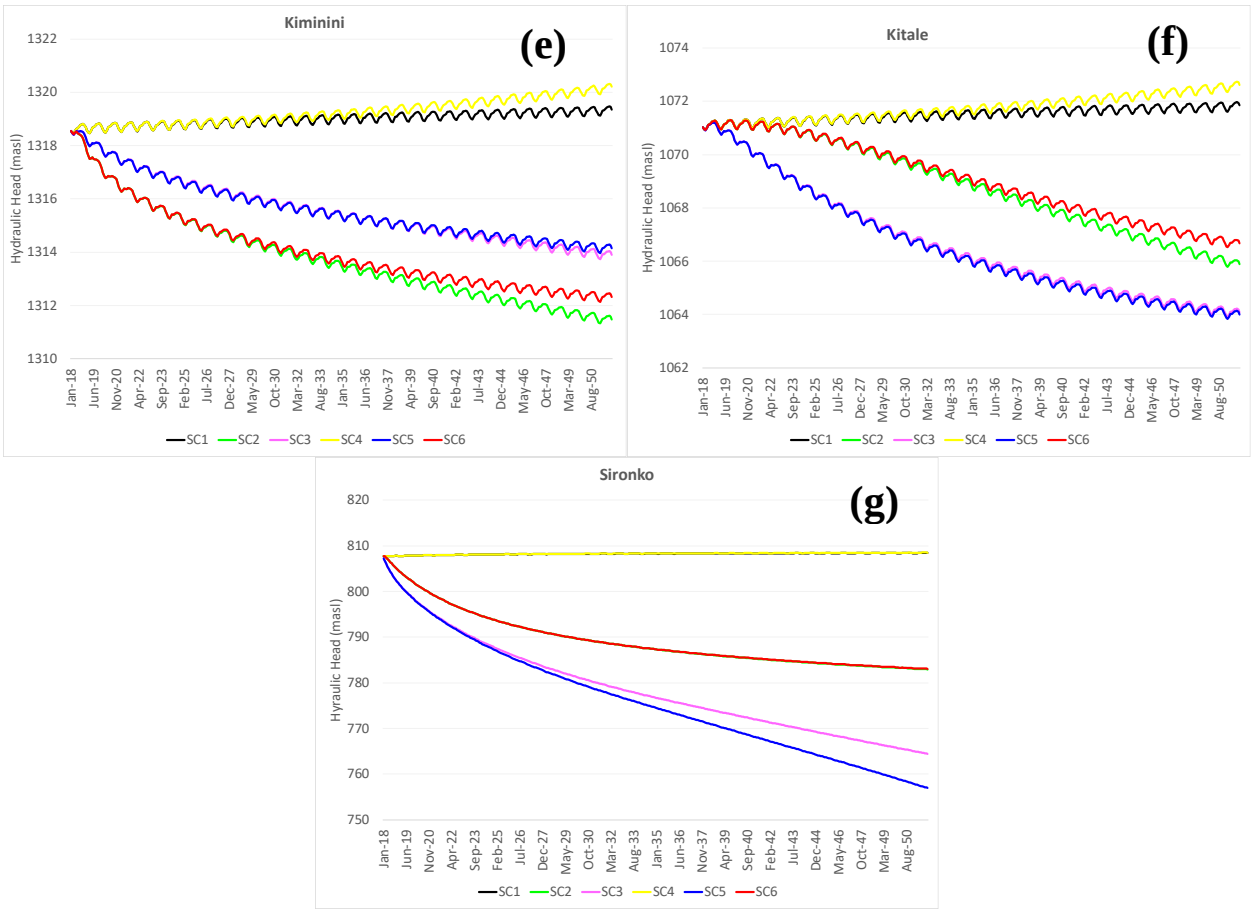


***Figure 6.7**: Groundwater level changes in the Mt. Elgon aquifer modelled area due to projected climate change and increased water demand in selected urban centres of, (a) Amudat, (b) Endebess, (c) Kapchorwa, (d) Kamilili, (e) Kiminini, (f) Kitale, and (g) Sironko.*

7. REGIONAL GROUNDWATER SUITABILITY

The multi-criteria analysis method Analytic Hierarchical Process (AHP) Earned Value Management (EVM) multiple inputs (Goepel, 2018) was coupled with GIS to generate groundwater suitability maps for the modelled Mt. Elgon aquifer region. AHP is a multi-criteria decision-making approach that evaluates both quantitative and qualitative criteria and alternatives on the same scale of preferences; this integrates both empirical data and subjective opinions for a robust decision-making process. The approach incorporates of hydrogeological, geological, and geomorphological characteristics of an area (Fig. 7.1). The method involves, (i) identification and elaboration of decision factors, (ii) classification and standardization of these factors, and (iii) assigning weights to the factors and combining them according to the multi-criteria approach. Eight (8) key factors were used; i.e., rainfall, geology, weathered zone thickness, slope, drainage density, land use / land cover (LULC), lineament density and soils.

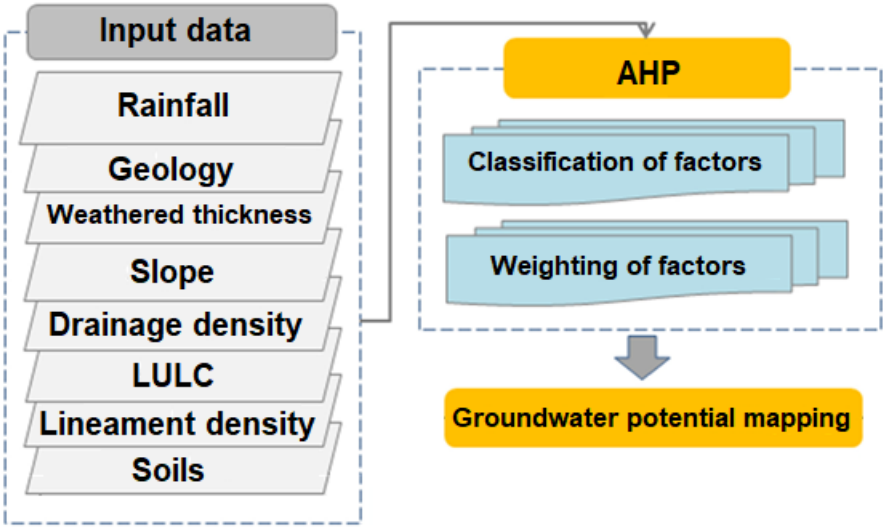


***Figure 7.1**: Flowchart of the approach used in the Mt. Elgon aquifer region to map out the groundwater potential.*

7.1 Decision factor maps

7.1.1 Rainfall

Rainfall is the main source of groundwater recharge in the region (Fig. 7.2a). High intensity rainfall generates recharge as well as high surface runoff.

7.1.2 Geology

The main geological formations vary in permeability from high permeability derived from primary pores in sediments (Fig. 7.2b). To weathered and fractured flow with moderate to low permeability in the volcanic and consolidated basement rocks.

7.1.3 Weathered zone thickness

The depth to bedrock determines the thickness of the weathered and fractured horrizons (Fig. 7.2c). A thick regolith or saprolite/saprock provides a higher volume storage for groundwater.

7.1.4 Surface slope

Geomorphology influences groundwater recharge, with the slope largely determining the runoff to infiltration ratio (Fig. 7.2d). Higher slopes induce very low infiltration which is characteristic of most of the region around the volcanic massif.

7.1.5 Drainage density

Drainage density is the ratio of the sum of the lengths of the drainage network to the basin's surface (Fig. 7.2e). It reduces infiltration at the expense of runoff and it is likely to control groundwater recharge in areas dominated by the drainage networks.

7.1.6 Land use land cover (LULC)

Land use and land cover (LULC) determine the infiltration rates necessary to recharge groundwater (Fig. 7.2f). This ranges from highly permeable porous soils to paved urban centres with minimal infiltration.

7.1.7 Lineament density

Geological structures commonly follow regional orientations (Fig. 7.2g). These lineaments can accumulate/transmit large volumes of water that recharge groundwater.

7.1.8 Soils

The soil types have different hydraulic properties (Fig. 7.2h). The soil types range from permeable sandy to clayey wetland/bog soils that impede the infiltration of water.

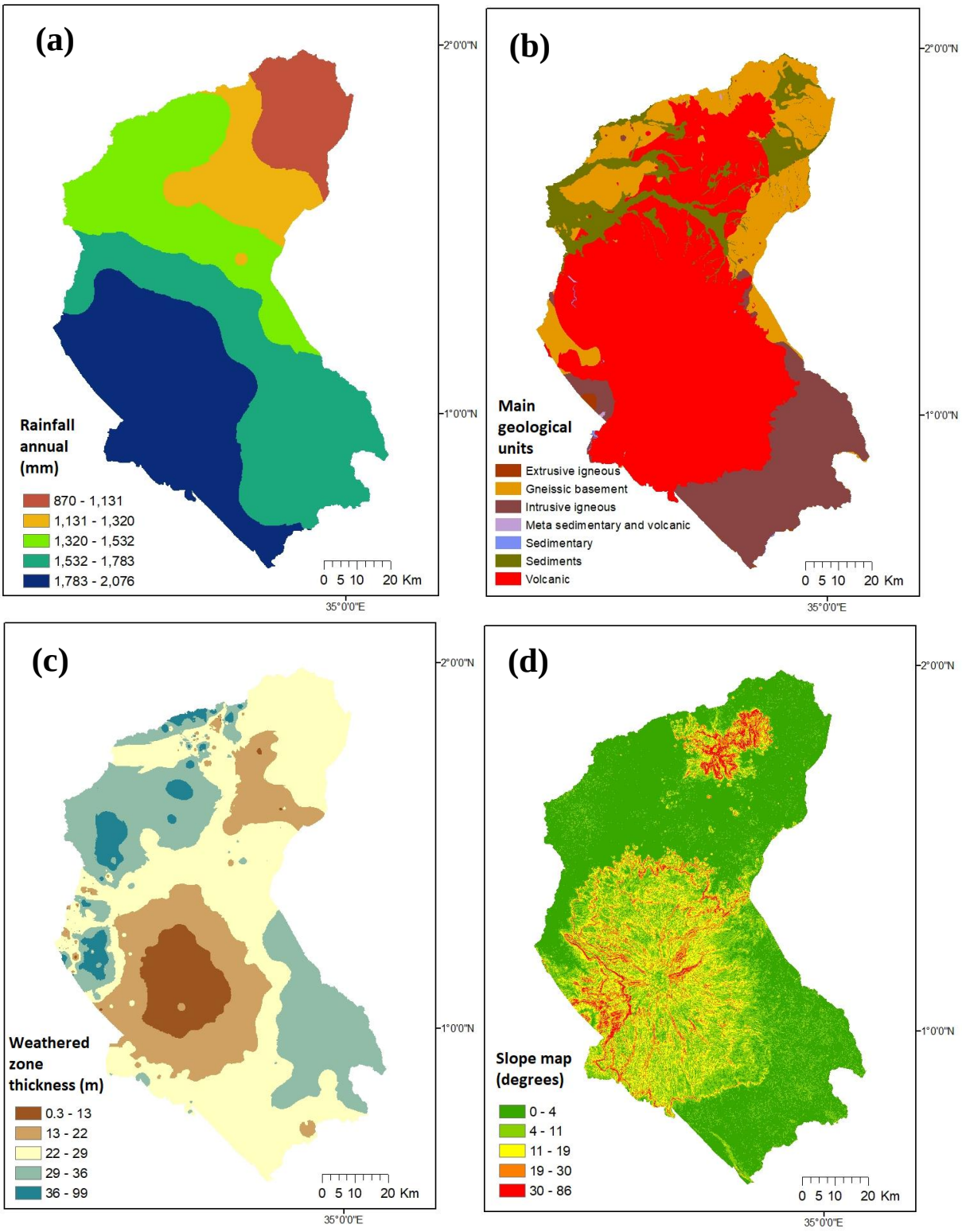
7.2 Classification and weighting of factors

Table 7.1 shows the classification of the factors for creating the groundwater potentiality map. The classes consider the variance of the data and for better interpretation they have been reduced to five classes and to standardize the factors that are measured on different scales and units. A high score corresponds to a significant performance of the considered indicator, whereas following a linear distribution, a minor factor contributes to a low score.

The analytical hierarchy process (AHP) model was used to weight the deciding factors through the pairwise comparison method. Each factor influencing groundwater was given a score from 1 to 4 based on its relative importance to other factors and where 1 and 4 indicate equal and extreme influences of a factor relative to other factors. This approach is more appropriate than the direct weight assignment method because its consistency can be checked by calculating the consistency ratio. Further, AHP is based on mathematical calculations that generate standardized weights whose sum is equal to 1.

Each criterion involved in the development of a given indicator had the standardised and weighted values summed up spatially in ArcGIS 10.8. The groundwater potential in the region is suggested

to be spatially controlled by rainfall distribution, geology, thickness of the weathered zone and surface slope.



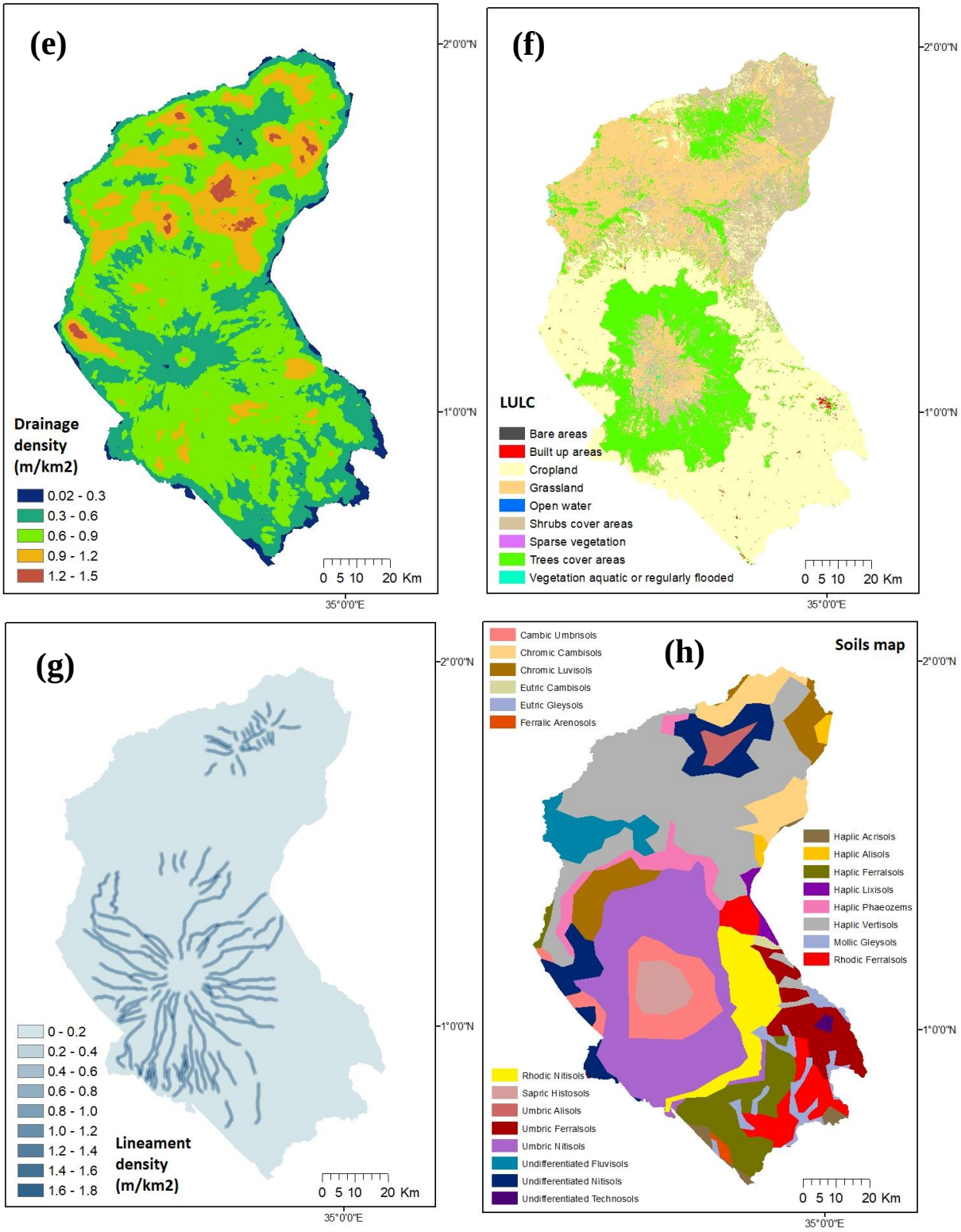


Figure 7.2: *Variation maps of the factors influencing the groundwater potential map, (a) rainfall, (b) geology, (c) weathered zone thickness, (d) surface slope, (e) drainage density, (f) LULC, (g) lineament density, and (h) soil types.*

***Table 7.1**: Classification of groundwater potentiality factors.*

Factor (units)	**Class**	Rating	**AHP weight (%)**
Geology	Meta sedimentary	3	22.6
	Gneissic basement	2	
	Intrusive	3	
	Extrusive igneous rocks	3	
	Volcanics	4	
	Sediments	5	
	Sedimentary	1	
LULC	water body	3	4.9
	Forests/trees	3	
	Shrub	2	
	Grassland	2	
	Vegetation aquatic or regularly flooded	3	
	Cropland	4	
	Built Area	1	
	Bare rocks	1	
Lineament Density (m/km2)	0 - 0.4	1	3.4
	0.4 - 0.8	2	
	0.8 - 1.2	3	
	1.2 - 1.6	4	
	1.6 - 1.8	5	
Soils	Acrisols	2	3.1
	Alisols	1	
	Arenosols	4	
	Combrisoils	3	
	Fluvisols	3	
	Gleysols	1	
	Histosols	4	
	Luvisols	3	
	Lixisols	4	
	Nitisols	4	
	Technosols	1	
	Umbrisols	3	
	Vertisols	1	
Drainage Density (m/km^2)	0.02 - 0.3	1	6.7
	0.3 - 0.6	2	
	0.6 - 0.9	3	
	0.9 - 1.2	4	

	1.2 - 1.5	5	
Slope (%)	0 - 4	1	9.0
	4 - 11	2	
	11 - 19	3	
	19 - 30	4	
	30 - 86	5	
Rainfall (mm/year)	870 - 1,131	1	32.8
	1,131 - 1,320	2	
	1,320 - 1,532	3	
	1,532 - 1,783	4	
	1,783 - 2,076	5	
Weathered zone thickness (m)	0.3 - 13	1	17.5
	13 - 22	2	
	22 - 29	3	
	29 - 36	4	
	36 - 99	5	

Five classes of the groundwater potential are identified including excellent (17%); high (39%); moderate (19%); low (15%); very low (9%) (Fig. 7.3). The high potentiality areas mainly cover the central and southern parts of the lower relief region that receive higher annual rainfall, with higher permeability sediments and weathered/fractured consolidated rocks, and also, areas where surface drainage interact with groundwater. Parts of the volcanic region also show high potential due to the mixed permeability options from the heterogeneous materials. The lower potential regions are likely to cover areas where the slopes are steeper, with a low density of lineaments, and less permeable consolidated basement rocks.

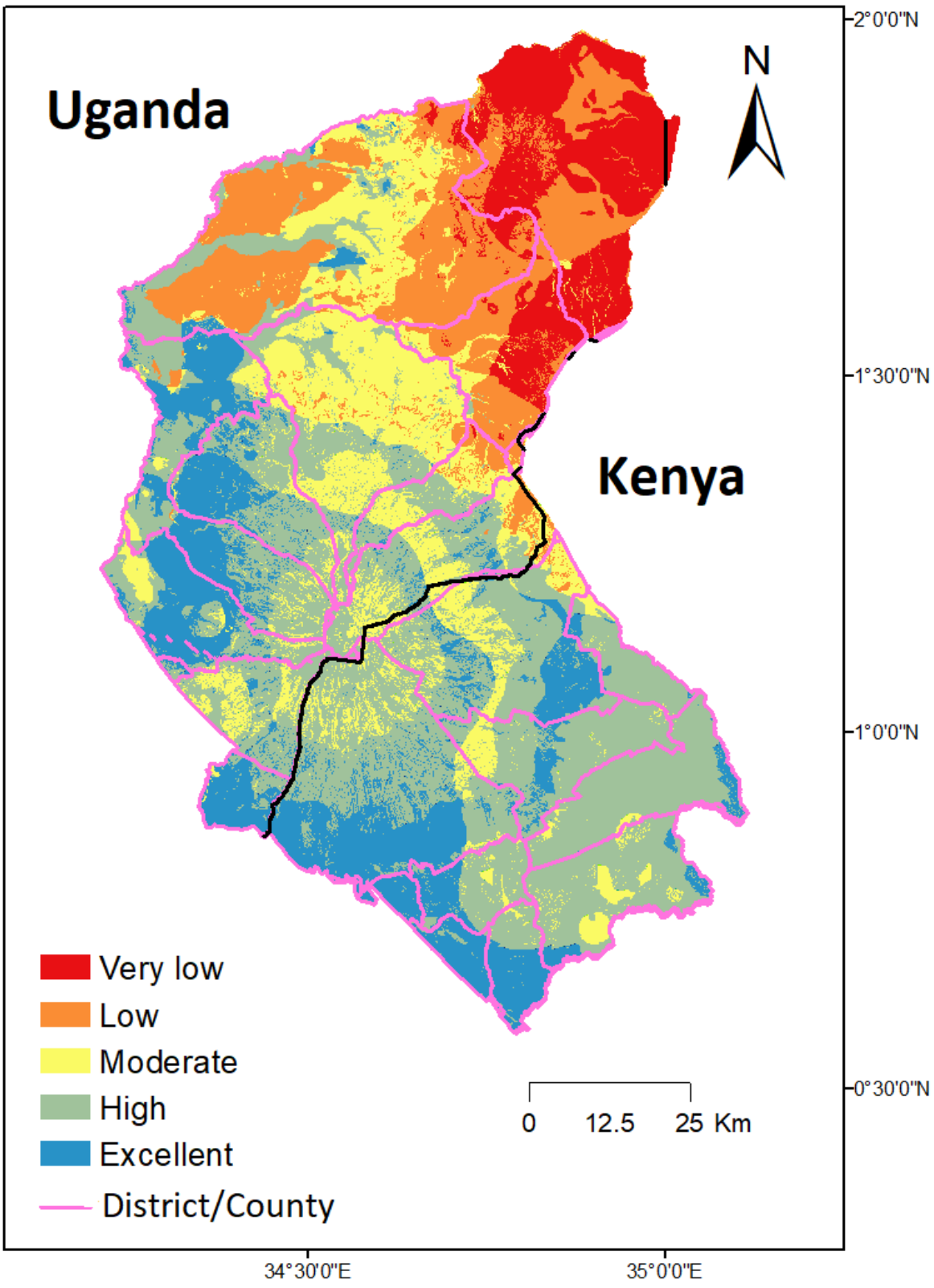


Figure 7.3: *Groundwater potential of the Mt. Elgon aquifer region.*

8. CONCLUSIONS AND RECOMMENDATIONS

1) Development of conceptual and numerical groundwater models at a transboundary scale;
    - Mt. Elgon aquifer is a transboundary system shared between Uganda and Kenya, spanning three lake basins and several administrative units, covering an area from about 4,900 km^2 modelled over an area of nearly 8,500km^2;
    - Drainage over the slopes of Mt. Elgon is largely radial towards streams on the foot slopes joining to form larger river that drain into Lakes Kyoga, Turkana or Victoria, a similar pattern largely followed by the groundwater flow directions;
    - A bimodal annual rainfall (MAM and SON) also controls a temporal pattern of groundwater recharge in the region;
    - Average aquifer drilled depths is 60 mbgl with the regional aquifer system having largely varying degrees of confinement (semi-confinement/leakiness);
    - Recharge is regionally indicated to be very low to medium, with values that vary between 0 to 400 mm/ annum and discharge is through baseflow to join streams and springs;
    - Hydraulic properties include mean *T* values of 9.7 m^2/d values of and *S* values of 0.0027 derived from deep weathering and fractures, thick palaeosoils, and gas bubbles within lava flows; shallow sources and spring discharge;
    - Mt. Elgon aquifer system depicts recharge in the higher caldera areas, with slopes dominated by runoff and springs, that flow and infiltrate into the low-relief region underlain by deeply weathered and fractured crystalline rocks, and discharge through alluvial and lacustrine sediments, and wetlands;
    - National hydrologic budget zones indicate for Ugandan side of the Mt. Elgon aquifer, main inflows as recharge (82%) and fluxes (18%) from adjacent hydrogeological units; whereas outflows include groundwater surface drainage (80%), fluxes (12%) to adjacent hydrogeological units, and abstraction wells (9%). For the Kenyan side main inflows are recharge (89%) and fluxes (11%) from adjacent hydrogeological units; whereas outflows include surface drainage (79%), fluxes (17%) to adjacent hydrogeological units, and groundwater abstraction wells (4%). For the volcanic region main inflows as recharge (85%) and fluxes (15%) from adjacent hydrogeological units; whereas outflows include fluxes (71%) to adjacent hydrogeological units, surface drainage (25%), and groundwater abstraction wells (4%).
2) Development of numerical models projecting different socioeconomic and climate scenarios from present to the year 2050 in the horizon for selected SSPs, and range of climate change scenarios to identify strategic recommendations for sustainable management and utilization of Mt Elgon aquifer;
    - For the impact of increased/unsustainable withdrawals from Recent to 2050 on water balance the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by each of the three projected scenarios, however, there is a total fall in water level of about 14 m;
        - The volcanic region shows the most increase in scenario 3 with flux from other zones (5%), drains (7%) and flux to other zones (5%);

however, the most increase in outflow due to abstraction wells (7%) is in scenario 2. For the Ugandan side, scenario 3 also generates the most increase in flux from other zones (0.4%), abstraction wells (2%), drains (13%) and flux to other zones (3%). On the Kenyan side, likewise scenario 3 also generates the most increase in flux from other zones (3%), abstraction wells (7%), drains (1%) and flux to other zones (0.4%).

- For the impact of climate change projections from Recent to 2050 on water balance again, the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by each of the two projected scenarios, however, there is a total fall in water level of about 26 m.
    - The volcanic region shows a similar pattern, with both scenarios 4 and 5 generating a relatively substantial change in recharge (3%); scenario 5 has the most increase in flux from other zones (7%), abstraction wells (12%), drains (6%) and flux to other zones (5%). For the Ugandan side, both scenarios 4 and 5 also generate a substantial change in recharge (3%); scenario 5 has most increase in flux from other zones (0.5%), abstraction wells (11%), drains (15%) and flux to other zones (3%). On the Kenyan side, equally both scenarios 4 and 5 generate a substantial change in recharge (3%); scenario 5, generates the most increase in flux from other zones (3%) and flux to other zones (0.5%); whereas, scenario 4 generates the most increase in abstraction wells (5%) and drains (1%).
- Impacts of projected climate change and increased demand from Recent to 2050 on water balance, again, the spatial pattern of the hydraulic heads is not altered significantly by the increased water demand simulated by the scenario, however, there is a total fall in water level of about 10 m.
    - The volcanic region on the other hand shows a relatively substantial change in recharge (3%), abstraction wells (7%) and flux to other zones (0.5%) by 31 December 2050; whereas, the most increase in flux from other zones (1%) and drains (0.6%) is realised by 31 December 2039. For the Ugandan side, a substantial change in recharge (3%), abstraction wells (6%), drains (4%) and flux to other zones (0.4%) is generated by 31 December 2050 except for in flux from other zones (0.5%) that is realised by 31 December 2039. On the Kenyan side, however, a substantial change in recharge (3%) and in flux from other zones (0.4%) is generated on 31 December 2050, whereas, the most change in abstraction wells (4%), drains (0.1%) and flux to other zones (0.2%) is obtained by 31 December 2039.
- Impacts of climate change (increased recharge) and increased demand on groundwater levels indicate drawdowns of up to 50m in selected urban growth centres;

3) Groundwater suitability regions; five classes of the groundwater potential are identified including excellent (17%); high (39%); moderate (19%); low (15%); very low (9%);
4) Training materials on transboundary groundwater modelling for the aquifer system;
    - Groundwater Modelling System (GMS) Training Manual for the Mt. Elgon Aquifer System;

5) Recommendations for sustainable conjunctive groundwater – surface water use;

- Conjunctive development and management of surface and ground waters in the Mt. Elgon aquifer region is critical where there is a significant portion of surface water fluxes.
- Transboundary shared aquifer management policies and frameworks to include data sharing protocols across the region to support initiatives that generate and need to equip/run water budget accounting tools and models over temporal, spatial and projected frameworks.
- Dedicated groundwater level and quality monitoring proximate to climate observatories is critical for the development and management of groundwater and its interaction with surface water resources in the Mt. Elgon aquifer region.
- Alternative approaches (e.g. use of chemical isotopes and tracers) to provide more information on groundwater dynamics, age and interactions with surface water in a region with a dearth of datasets.
- Harnessing of relevant remote sensing approaches (e.g. gravity, infrared and altimetry methods) to support limited collection of in situ datasets from inaccessible terrains in the region.
- Delineation of key recharge areas and processes prevailing, and influence of extreme weather conditions.

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10. ANNEXES

Annex 10.1: Inventory of archived/historical and secondary datasets used in the currect assignment.

Category	Parameter	Data type	File attachment
Topography	Digital terrain model	Elevation map (1:50,000) contours for interpolation	DEM tiff map, 12.5 resolution
Drainage	Drainage	Shapefile	Rivers
Catchment	Catchment boundaries	Shapefile	Catchment maps
Admin	County/district/sub-county/Location/Sub-Location/Parish/Village	Shapefile	Ugandan and Kenyan admin units
Land use land cover	Land use land cover	Shapefile	Map
Geology	Lithological units	Shapefile	Map
	Soils	Shapefile	Map
Climate	Rainfall daily/monthly in situ	Time series and location coordinates	Daily hydrographs
	Temperature minimum/maximum daily/monthly in situ	Table and location coordinates	Daily hydrographs
Groundwater physical parameters	Depth to water table	Table of location coordinates and depth (mbgl)	Depth to water table map
	Drilled borehole depth	Table of location coordinates and depth (mbgl)	Includes shape files
	First water strike	Table of location coordinates and depth (mbgl)	Includes shape files
	Static water level	Table of location coordinates and depth (mbgl)	Includes shape files
	Borehole and spring yields	Table of location coordinates and yields (m3/hr)	Includes shape files
	Transmissivity	Table of location coordinates and transmissivity (m2/d)	Includes shape files
	Storativity	Table of location coordinates and storativity	Includes shape files
Quality	Groundwater physico-chemical (e.g. EC, pH, TDS) and selected chemical (e.g. major)	Time series and Location coordinates	Includes shape files

	Surface water chemical parameters	Time series and Location coordinates	Includes shape files
Monitoring	Groundwater levels daily/monthly	Time series and Location coordinates	Daily/monthly hydrographs
	River daily/monthly discharge	Time series and Location coordinates	Daily/monthly hydrographs
Water demand	Surface water and groundwater usage/demand for various sectors (domestic, livestock, irrigation, industry, etc.)	Time series	Table
Demography	Population in Elgon sub-region by village/parish	Table	Includes shape files
Socio-economics	Water related issues	Table	Includes shape files

Annex 10.2: Conceptual model materials.

Groundwater numerical modelling parameters defined for conceptual models include:

Category	Parameter	Data type	File attachment
	Mt. Elgon Aquifer areal boundary	Map	Shapefile
	Land use/ land cover	Map	Shapefile
	Hydrological drainage network	Map	Shapefile
	Aquifer parameters (e.g. thickness, *K*, *T*, *S*)	Map	Shapefile
	Aquifer and confining layer areas and thicknesses	Map	Shapefile
	Daily mean precipitation (rainfall)	Time series	Table
	Daily maximum and minimum air temperature	Time series	Table
	Daily mean stream discharge	Time series	Table
	Potential evapotranspiration	Time series	Table
	Daily groundwater levels	Time series	Table
	Initial conditions (e.g. water table, surface elevation)	Initial conditions	Table
	Boundary conditions, defined as specified head (e.g. streams/rivers), constant head (e.g. lakes), specified flux (e.g. recharge across water table, abstraction well), and no flow (e.g. impermeable geology)	Boundary conditions	Table
	Aquifer area to determine model discretization	Model discretization	Table

Annex 10.3: National Mt. Elgon Groundwater Modelling Reports B.

The National Mt. Elgon Groundwater Modelling Reports B for both the Ugandan and Kenyan sectors of the Mt. Elgon Aquifer are each attached separately.

Annex 10.4: Groundwater Modelling System (GMS) Training Manual for the Mt. Elgon Aquifer System.

The Groundwater Modelling System (GMS) Training Manual (Report C) for the Mt. Elgon Aquifer System is attached separately.



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