Barriers to, and opportunities for off-grid sanitation provision in the rapidly urbanizing city of Mekelle, Ethiopia: Reimagining human waste as "brown gold" for environmental management and livelihood improvement

Kifle Woldearegay[1*], James Ebdon[1], Diogo Gomes Da Silva[2], Lyla Mehta[3], Solomie Gebrezgabher[4], Alan Nicol[5], Tanvi Bhatkal[3]

[1] *School of Earth Science, Mekelle University, Ethiopia*

[2] *School of Applied Sciences, University of Brighton, UK*

[3] *Institute of Development Studies, UK*

[4] *International Water Management Institute, Accra, Ghana*

[5] *International Water Management Institute, Addis Ababa, Ethiopia*

[*]Corresponding author; Email: kiflewold@gmail.com

Abstract

Inappropriate or poorly constructed sanitation is becoming one of the major challenges confronting rapidly urbanizing cities in the global south such as Ethiopia. This study was carried out to understand the sanitation and solid waste management challenges present in the city of Mekelle, in order to identify opportunities for sustainable faecal and solid waste management. This involved conducting: (a) a review of previous studies, (b) field and laboratory investigations (water and faecal sludge quality), (c) assessments of the status of existing sanitation services, (d) analysis of hydrogeological connectivity between septic tanks and surface & ground waters, (e) participatory assessments of solid waste management issues, and (f) identification of good practice in terms of sustainable waste management. Our findings revealed that the water supply coverage in 2021 only reached 67.3% of the population with water mainly from treated groundwater wells and surface water (dam); with some communities using untreated water from other sources. Though 65.8% of the households were found to have access to toilet facilities, sanitation remains a major challenge due to multiple inter-related factors: (i) open defecation, (ii) dumping of liquid and solid waste into surface waters, and (iii) lack of maintenance of the municipal faecal sludge treatment facilities. Our study highlighted contamination pathways likely to be impacting shallow wells, streams/rivers and springs in the city. In order to reduce water consumption and promote sustainable circular waste management the following emerging practices should be supported and up-scaled: urban agriculture, green space development, waste separation at source, organic waste reuse, and support for small businesses involved in waste management. If the full benefits of sustainable waste management are to be recognized in Mekelle, then appropriate policies, strategies, and regulatory frameworks need to be developed and implemented, along with governmental support for capacity building and local innovation.

Keywords: Circular economy, Urban agriculture, WaSH, Climate change adaptation, Waste management.

Introduction

Sanitation is becoming one of the major challenges particularly within the global South. Nearly 4.5 billion people lack safely managed sanitation and about 700 million still practice open defecation (OD) [1]. According to the UN DESA [2] report, with the current rate of investments and progress, 2.8 billion people will lack safely managed sanitation by 2030. It will require a fourfold increase in the pace of progress to meet the drinking water, sanitation and hygiene targets by 2030. The situation is particularly acute in rapidly urbanizing cities due to unsafe excreta disposal, inadequate faecal sludge management (FSM), and lack of adequate infrastructure for wastewater collection, treatment and disposal [3].

Sanitation is not just a functioning assemblage of pipes, ducts, pits and hardware, but is also about bodies, shit, pathogens, health and rights [4]. The capital-intensive nature of conventional sanitation and waste management systems and the failure to expand centralized networks to small towns is contributing to sanitation challenges. This has meant that policy-driven practices have often struggled to meet the needs of the poor in peri-urban areas and the realisation of their right to water and sanitation [5-8]. Nelson and Murray [9] have suggested approaches for alternative technologies that prioritise wastewater treatment close to where it is created (‘decentralized’ or ‘off-grid’). Other researchers [10,11] have promoted the use of solutions based on local skills, needs and materials; with households as key stakeholders in the planning process [12].

The concept of the ‘circular economy’ provides an alternative to the linear, “take-make-dispose” economy, with an aim to decouple economic growth from natural resource use, largely through capturing value in otherwise waste materials [13]. Millions of tonnes of faecal matter are generated every day and collected as faecal sludge from onsite sanitation systems in the global South [14]. This waste is rich in nutrients and organic compounds [15-17] and can provide additional income streams for low-income households [18].

Ethiopia is one of the least urbanized countries in the world, but is now urbanizing rapidly [19]. As reported by various researchers [20-32], waste management is becoming a major issue in Ethiopia. Rapid increases in population, often lead to unplanned urbanization and limitations with existing WaSH provision, with sanitation and solid waste management a major challenge, unless they can be addressed systematically. Therefore, the following study which is part of *GCRF project ‘Towards Brown Gold: Re-imagining off-grid sanitation in rapidly urbanising* *areas in Asia and Africa" (Project No. ES/T008113/1)* sought to understand the nature of sanitation and waste management challenges confronting the city of Mekelle and to identify opportunities for promoting sustainable circular waste management more broadly in rapidly urbanizing cities within the global South.

Materials and methods

Study site

Mekelle is the capital city of the Tigray National Regional State, located in northern Ethiopia between 13^{0}20'30" to 13^{0}30'40" latitude and 39^{0}20'10" to 39^{0}30'35" longitude (Fig 1).

Fig 1. *Study site: (a) topography, drainage and location of the municipal Faecal Sludge treatment (FS) and Solid Waste disposal (SW) facilities within Mekelle municipality and (b) study location with respect to with regional states of Ethiopia.*

The city is among the fastest growing urban centers in Ethiopia, with the population increasing from about 14,000 in 1950, to nearly 740,000 in 2022 [33,34] (Supporting information S1 Fig). In recent years there has also been an increase in population due to arrival of internally displaced people, with numbers rising from 24,000 in 2018 to about 175,000 in 2022, largely due to conflict in the region [34]. Rural-urban economic migration from within and beyond Ethiopia has also contributed to the population increase and the city is home to people of various social, economic and cultural status. Mekelle, has been the focus of previous efforts to manage waste, with initiatives most notably from the regional government, research institutions and donors (World Bank, African Development Bank, UNICEF, USAID, Relief

Society of Tigray). Previous research in Mekelle has also reported on water, sanitation and hygiene (WaSH)-related issues including the impact of landfill leachate on water resources [35]; microbial quality of river waters [36]; nitrate concentration in groundwater wells [37]; and mapping of water resource pollution vulnerability [31,38]. These studies have begun to shed light on the emerging WaSH challenges and increasing need for effective waste management in the city [39].

In terms of its climate, the Mekelle area is generally categorized as a semi-arid, with average rainfall of about 700 mm/year, with high spatial and temporal variability [40], with most rainfall recorded between June and September (Supporting information S2 Fig). In terms of temperature, Mekelle experiences mild climatic conditions with average annual temperatures ranging from 28.3 ^{0}C to 12.1^{o}C. May is typically the hottest month and December the coolest. Therefore, with the exception of June to September, the potential evapotranspiration (PET) of the area is higher than the monthly average rainfall. The topography is dominated by gently sloping terrains, hills (Endayesus and Choma) and fault escarpments (Messebo) and the altitude of the city varies from 1900m to 2300 m a.s.l (average elevation of 2100m a.s.l). Mekelle is located on the upper reaches of the river Tekeze Basin and has an overall topographic tilt towards the west and northwest. The two major rivers which drain the city are “R. Illala” and “R. May Tena”; which both join the R. Geba (a tributary of the R. Tekeze) and which are susceptible to flooding, siltation and erosion [41-43].

In terms of land-use, the city and its surrounding areas is characterized by sparse vegetation cover due to urbanization (and associated buildings, roads and other infrastructures) and most of the land is used for arable agriculture, leaving small areas of woodland. Some vegetation coverage is observed in the vicinity of churches, along riparian corridors (streams/river channel banks) and in some of the more hilly areas. As part of urban development and beautification, there have been some initiatives by the Mekelle city administration to promote tree planting along roads, though still at an early stage.

Methods

This study involved quantitative and qualitative approaches including: (a) a desk-based review of previous academic studies and governmental literature, (b) field-based hydrological monitoring (groundwater and stream/river channel level measurements) and water sampling for detection and quantification of physical, chemical and microbiological parameters in water, wastewater and faecal sludge samples, (c) characterization of soils and rocks: hydrogeological connectivity of sanitation facilities (e.g. septic tanks and surface & ground waters) and engineering properties in relation to waste management, (d) participatory assessment and evaluation of existing waste management and sanitation provision through three rounds of stakeholder workshops and associated field visits, (e) participatory assessments and evaluations e.g. key informant interviews (with key experts of WaSH sectors) and discussions with decision-makers at various levels of the government about liquid and solid waste management issues, (f) participatory assessments on existing practices and potentials for circular economy, and (g) data analysis and identification of future intervention areas for sustainable sanitation and waste management.

Hydrogeological monitoring

The quantity and quality of surface water recharge to groundwater sources can be adversely affected by urbanization [44] and knowledge of the underlying hydrogeology is critical for ensuring effective management of waste streams. The geohydrology of Mekelle was evaluated by reviewing previous studies and by conducting field investigations (Supporting information S1 Table), and laboratory analysis. Historical data on 12 water supply boreholes developed for

Mekelle water supply by WWDE [45] was also reviewed.

Field investigations were carried out during 2021-2022 and involved assessments of the lateral and vertical distributions, thicknesses and permeability of soils and rock strata. This was performed in areas having rock and soil exposures, such as those in open spaces, river channel sections, road cuttings, and areas excavated for construction or urban agriculture. Rock characterization e.g. degree of weathering, characteristics of discontinuities (infill, apertures, continuity) and overall hydraulic connectivity was assessed in the field. This involved *in-situ* tests on 15 test pit locations using the inverse auger-hole method [46] to estimate the permeability of the dominant soils and highly weathered rocks. Pits were excavated to variable depths ranging from 1.0 to 2.3m and soil samples were collected and analyzed from known depths. Gradation curves from the laboratory tests (Supporting information S2 Table) were used to estimate hydraulic conductivity of the soils using the empirical equation proposed by Hazen [47].

Engineering properties of soils and rocks

Various authors [48-53] have promoted the need for proper geotechnical site investigations and characterizations of soils and rocks for design and constructions of waste management systems. For Mekelle area different researchers [42,54,55] have studied the engineering properties of soils and rocks with more focus to civil engineering applications. As part of our study, the engineering properties of soils and rocks in Mekelle area were characterized using in-situ and laboratory investigation methods with due attention to their applications for surface and sub-surface fluid flow, design of sanitation and drainage systems, and waste management. Natural moisture content, atterberg limits (liquid limit, plastic limit and plasticity index) and free swell behaviours of the soils were determined in the laboratory (for a total of 36 samples from the different soil units) (Supporting information S2 Table) as these parameters have implications for surface and sub-surface contaminant transport as well as for siting and design of sanitation, drainage and waste management infrastructure.

Assessments of groundwater and septic tank connectivity

Changes in groundwater levels, spring discharges and faecal sludge levels in septic tanks were monitored, as there can be potential interactions with surface and ground waters and sanitation facilities (e.g. septic tanks). Woldearegay [43] previously classified the groundwater sources in Mekelle and its surrounding areas into four major categories: open hand-dug wells (<15m deep); machine-drilled shallow boreholes (<100m deep); machine-drilled intermediate depth boreholes (100-200m deep); and machine-drilled deep boreholes (>200m deep).

Open hand-dug wells - Assessments was carried out to monitor groundwater depth using meter tapes. A total of 6 hand-dug wells were monitored for their groundwater levels over 20-month period from May 2021 to December 2022. Water samples were also collected from these wells during this period for laboratory analysis.

Boreholes (water supply) - Assessment of boreholes, which varied from shallow (65m) to deep (250m) [45], was carried out to monitor groundwater depths using a micro-diver water level logger (from Eijkelkam). A total of 10 boreholes were monitored over 20-month period from May 2021 to December 2022 in collaboration with the Mekelle City Municipality. Historical data was also accessed for these boreholes for the years 1998 [45], 2004-2005 [56], 2017 and 2020 [57]. Water samples were also collected from the boreholes during this period for laboratory analysis.

Springs – Seventeen springs (10 urban and 7 peri-urban), many of which were located in religious centres and used as holy water were monitored (Supporting information S3 Table). Springs were classified based on the work of Meinzer [58] for their characteristics of points of issue and lithology of aquifer. The majority of these springs emerge at the interface between soil and underlying bedrock or between two rock types with different hydraulic conductivity with some in depression areas. In order to assess the discharge of the springs, measurements were carried out using bucket method [59] during the months of March to April 2022 (under dry season conditions). This involved recording the amount of time required to fill a bucket of known volume (suitable for discharges less than about 4 l/s). In order to determine the water quality, analysis was conducted on eight spring samples located within the main urban center of Mekelle (where contamination is most likely).

Assessment of water supply, drainage and sanitation systems

Water supply: Mekelle is one of the regional centers with critical shortages of water in Ethiopia [60-62]. To meet the ever-increasing demand of the city, several studies have been carried out since 1982, with most projects focused on short-term solutions. In 2021, the water supply coverage was only 77.1% [63] with water supplies originating mainly from groundwaters and the Gereb Segen Dam. Though Woldearegay [43] previously recommended the use of water from springs and hand-dug wells for urban agriculture usage, the interaction with surface water and wastewater was not fully evaluated. In this study, the status of water supply sources for the city and the existing challenges were assessed using data from: (a) government reports, published papers, and unpublished consultancy reports, (b) discussions with key experts at the bureaus of Water Resources and City Municipality, (c) participatory field assessments with stakeholders representing local communities, government bodies, private sector, non-governmental organizations and academia, and (d) groundwater level monitoring of boreholes and hand-dug wells mentioned above.

Drainage systems: Mekelle city has approximately 46 km of either enclosed drainage, or open ditches; though many of them are not large enough to carry expected storm run-off volumes [64]. Some upgrading of drainage systems was carried out between 2015 and 2019. Most of the natural drainage channels follow the topography of the city and intercept streams and river channels which later enter the main R. Illala. To assess the state of the drainage systems, field investigations were carried out during the 2021 and 2022 rainy seasons (July to September) and (July to August), respectively. The field investigations sought to characterize problems with drainage systems such as blockages, siltation, erosion (scouring and gullying), flooding and resulting damage to infrastructure. In addition, participatory stakeholder field assessments (with local community and experts of Mekelle municipality) was carried during August 2022.

Sanitation condition: Mekelle like many rapidly urbanizing cities does not have a centralized sewerage system. Due to the rapid population increase and associated development, the city was not properly planned and the water and sanitation services poorly implemented [64]. The status of sanitation services in the city was assessed based on reports of the government mainly from MCM [64-66], MWSSO [63,67,68] and TBoWR [69-71] as well as discussions with key WaSH experts and decision makers (Bureau of Water Resources, Mekelle City Municipality) (Supporting information S3 Fig). Field-based investigations to assess the status of on-site sanitation services (toilets), faecal sludge drying beds as well as the locations/conditions of municipal solid waste transfer sites (containers) and disposal in the city were also conducted. This included assessment of the functionality of the sanitation and drainage facilities and effects on the environment. Moreover, participatory stakeholder workshops were organized in three rounds as summarized below:

- ***First round workshop (July 2021):*** Organised to discuss on the status of water and sanitation in Mekelle and to identify major issues for further studies and interventions. During this workshop areas with frequent problems related to waste management were identified to be condominium houses, hospitals, schools, and some residential areas.

- ***Second round workshop (August 2022):*** Undertaken to assess and evaluate the conditions of sanitation services in the field (for problems identified in the first round workshops) which included faecal sludge drying beds, areas with frequent problems with filling and overflow of liquid wastes (4 condominium sites; 3 hospitals, 5 schools, 3 hotels and 12 residential areas where seepages/runoff and overflow from septic tanks were visible), solid waste transfer sites (containers) as well as disposal site and road drainage systems.
- ***Third round workshop (January 2023):*** Organized to feedback results of this study with the stakeholders, as co-learning, and to identify future opportunities/pathways for promoting circular economy within Mekelle.

Assessments of policy, strategy and regulatory issues related to sanitation: This involved review of existing federal and regional policy and strategy documents as well as legislation and regulatory frameworks, stakeholder workshops (mainly during round two and three), and (c) focused group discussions with key stakeholders and discussions with government bodies.

Assessments of solid waste management in relation to sanitation and circularity*:* As reported by different researchers [20,22,72], solid waste management is another challenge for the city of Mekelle. Ineffective management of solid waste is expected to have an adverse effect on the sanitation and drainage, which if managed properly could be turned into economic benefit. To understand the composition and quantities of solid waste generated by households, a total of 13 transfer containers located in different areas were assessed in the month of June 2022. The study also assessed existing practices for solid waste income generation to establish sustainability issues.

Assessment of surface water impacts associated with waste management: A 12km stretch of road bordered by open ditches and prone to floodings and sanitation problems, was selected for assessment of its drainage condition. Selection of the roads (for detail assessment) was based on the first round participatory workshop coupled with field observations. The study included visual inspection for any damage to infrastructure, siltation and flooding potential, as well as connectivity of drainage systems with surface and ground water source. In addition to roadside ditches, streams and river channels in the city were also assessed in the same manner. Detailed assessment was made on 7 streams which have different levels of managements: poorly managed (3) and well managed (4). The assessments included the in-stream dimensions (widths and depths) and the environmental conditions (degree of contamination with solid and liquid waste) using field observations and laboratory analysis as discussed in the next section.

Analysis and assessment of water quality and faecal sludge composition

Over abstraction and water quality deteriorations are common in many urban areas [73]. Except for limited analysis of groundwater quality [35-37,41,45,54,74], there is paucity of data for other water sources in Mekelle. In this study, a total of 51 samples were collected from a variety of sources, namely open hand-dug wells (10), boreholes (10), springs (8), seepage/runoff (6), stream/river channels (12), and faecal sludge (5). These were exposed to different chemophysical and biological laboratory or field-based tests which included:

- ***Physical-chemical characteristics:*** Sodium and potassium (using flame photometer); main cations (using Atomic Absorption Spectroscopy (AAS); main anions (using Double beam UV spectrophotometry); total hardness; electrical conductivity (EC), Dissolved Oxygen (DO), temperature color, turbidity, and total dissolved solids (TDS) (using Multi 3410 Multiparameter Meter with Sentix 940 and Tetracon 925 Probes); pH (using handheld pH meter; model: HI 991300-HANNA); Alkalinity, Carbonate and Bi-carbonate (using titration method recommended by American Public Health Association [75]. All equipment was calibrated prior to use using standard solutions. Another test carried out is Biological Oxygen Demand (BOD) which is a measure of the amount of biochemically degradable organic matter is present in a sample and is defined by the amount of oxygen required for the aerobic micro-organisms present in the sample to oxidise the organic matter to a stable inorganic form [76]. For (BOD) and Chemical Oxygen Demand (COD) first day tests were carried and then repeated after five days in accordance with standard methods (ISO 5815-1) [77].

- ***Biological analysis:*** Faecal indicator bacteria (total coliforms and *E. coli*) were detected and enumerated in accordance with APHA [78] to check the various water and faecal sludge sources in relation to the presence of potentially pathogenic microorganisms. The presence of pathogens, such as bacteria, virus, or protozoa, represents the most severe threat for human health [79] as they are responsible for water-related waterborne diseases. Micro-organisms such as bacteria, algae, fungi and protozoa are commonly present in surface waters but they are usually absent from most groundwater sources, as they are suspended solids and are removed by the filtering action of the aquifer [80].

All laboratory testing was carried out at the School of Earth Science at Mekelle University. The accuracy of the laboratory analysis was checked with the electro-neutrality concept indicated by APHA [78] and Fetter [81]. Results of the water and wastewater quality analysis (Supporting information S4 Table to S9 Table) was compared with existing standards for different uses: drinking water quality using WHO (2022) [82], wastewater quality for irrigation using WHO (2006) [83] and irrigation water quality in terms of SAR (sodium absorption ratio) using USDA [84] and Wilcox [85].

Understanding water source and septic tank connectivity

Interactions between groundwater, surface water and faecal waste streams can be particularly complex in urban settings due to natural and anthropogenic processes such as compaction, dewatering (during excavations), construction of surface water storage, groundwater abstraction, flooding, and other processes that may alter surface and sub-surface flow dynamics and lead to adverse impacts on human health. To better understand the different potential interactions between septic tanks and surface and ground water sources, six sites displaying differing proximities to septic tanks were monitored over a 20-month period (May 2021-Dec 2022) (Table 1). The horizontal distance between the water sources and septic tanks at the sites varied from 15 to 30m (detailed below). The groundwater level in wells and faecal sludge levels in septic tanks were measured using meter tapes. All septic tanks were similar in terms of the population served and construction. To record maximum flood levels in streams/river channels flood markers of known height were used. The depth of stream/river channel bed was measured using meter tapes with reference to the surface topography on both sides of the stream/river channel.

Table 1. Scenarios considered for assessing interactions between septic tanks and surface and ground water sources.

Scenario	**Description/condition**
1	Shallow well situated 17.5 m away (at higher elevation) from septic tank
2	Shallow well situated 15 m away (at lower elevation) from septic tanks

3	Surface water (stream/river channel) 18.2 m away from septic tank
4	Shallow well situated 26.4 m away (at higher elevation) from septic tank but close to surface water (stream/river channel)
5	Spring at lower elevation and 30 m away from septic tank
6	Shallow well situated 22.6m away (at higher elevation) upstream of septic tank, but adjacent to surface water (stream/river channel)

Assessment of management status of streams/river channels and embankments

The management status of streams/river channels and embankments were assessed which involved local communities and experts of the municipality. Streams/river channels with different degree of management were first identified through participatory approaches and then detail evaluation was carried out. It involved assessment of: width of the streams/river channels, any signs of instability (such as collapse and gullys), sanitation conditions, use/economic benefit/ of stream/river channel banks and ownership of the streams.

Identification of current and future opportunities to support the circular economy

To identify potential opportunities to promote the circular economy (which considers waste as a resource) within Mekelle city, assessments of previous and current waste management practices were carried out through a combination of desk-based and field-based observations. Focus group discussions were also carried out with stakeholders (private businesses, government bodies, local communities, etc) involved in circular economy-related practices, such as urban agriculture (arable farming, livestock rearing, and fruits vegetables and ornamental tree cultivation) and solid and liquid waste management. Government bodies who are involved in promoting small business development were also consulted via face-to-face meetings/discussions. Future potentials which could support circular economy were also explored through: assessments of the types and characteristics of waste and wastewater streams; existing circular economy related practices and challenges; and expected demand for circular economy products and services within the city.

Ethical considerations

The main focus of the study was to evaluate the quality of water and faecal sludge, the contamination pathways and opportunities for circularity with waste management in Mekelle city, Tigray region in northern Ethiopia. In this study some discussions with stakeholders were carried out. Whilst the conflict in the Tigray Region (and resulting communications breakdown) prevented formal ethical clearance paperwork from being completed/lodged at Mekelle University - All the stakeholders involved in the study were clearly informed about the objectives of the research, before verbally agreeing to take part. The stakeholder discussions were carried out in three rounds: July 15, 2021; August 10-11, 2022; and January 20, 2023. No payment was made to the participants for their involvements. All information gathered from stakeholders was treated with confidentiality by the research team and all participant information was anonymised.

Results and discussion

Hydrogeology of the study area

The major rocks and soils in Mekelle and its surrounding areas include [41,42,45,54,55,74,86-89]: Adigrat sandstone, Antalo limestone, Agulae shale, dolerites and unconsolidated deposits (Fig 2). In terms of their hydrogeological characteristics these different soils and rocks have the following characteristics (detail description is presented in Supporting information S1 Table):

- ***Unconsolidated deposits***: include residual, colluvial and alluvial types and have limited thickness (mostly less than 3m) and occur in localized areas. Hand dug wells are common in areas of unconsolidated deposits. It is common to observe springs at the interface between such soils and the underlying less-fractured rocks.
- ***Dolerites:*** are generally fractured at shallow depths and act as good conduits for groundwater storage and movement. Wells with good yields are often located above fractured dolerite. Some seepage/runoff and springs are common between the dolerites and the surrounding less-fractured rocks.
- ***Agulae shale:*** covers extensive area in and around Mekelle and is dominated by shale, marl and clay interlaminated with limestone (Fig 3); with about 70% of Mekelle city being founded on this unit. Thin beds of gypsum and dolomite are also commonly found. Because of the interbedded fractured limestone and shale beds groundwater exists under confined to semi-confined conditions (as multi-layered aquifers).
- ***Antalo limestone:*** covers significant areas and is composed of limestone which shows karst features, solution channels and caves. Many of the water supply wells in the Aynalem well field (see Fig 3) are found within this unit and have good potential for groundwater. Due to the presence of shale units as intercalations the aquifer in this unit is multi-layered.
- ***Adigrat sandstone:*** lies under the Antalo limestone unit and is expected to have much better groundwater potential than all the other formations in the study area. Drilling carried out in Chenferes area (see Fig 2) in this formation has resulted in higher groundwater yields and could be the focus of further deep exploration.

Fig 2. *Simplified geology of Mekelle city and its surroundings (modified after EGS [90], Chernet & Eshete [87], EGS [88]) and soil, water and faecal sludge sampling points for laboratory analysis. BH= Boreholes; HDW= Hand-dug wells.*

Fig 3. *Examples on hydrogeology of Mekelle area: (a) limestone and shale internationals in road cuts; (b) shallow water level in foundation excavations in Mekelle. RS= Residual Soil; SH= Shale; LS= Limestone.*

Engineering properties of weathered rocks and soils

Results of our laboratory analysis for the engineering properties of the different soils (36 samples) (Table 2) show that:

- The natural moisture of the soils varied from 11.5% to 71.2%; with higher values for residual soils derived from Agulae shale and Limestone.
- The plasticity index of the soils varied from a minimum of 7% for alluvial soils to a maximum of 72% for soils derived from Agulae shale.
- The free swell of the soils of the area is highly variable: from 10% for alluvial soils to as high as 1000% for Agulae shale derived soils. Additional information on results of the laboratory analysis for engineering properties of the soils is presented in Supporting Information S4.

Table 2. Results of lab-based soil analysis for Mekelle city and its surroundings.

Soil property	**RSH (n=13)**	**RLS (n= 11)**	**RDO (n= 6)**	**AL (n= 6)**
Natural moisture content (%)	17.5-43.2	15-71.2	14.3-38.2	11.5-31.5
Liquid limit (%)	24-91	20-76	18-66	15-59
Plastic limit (%)	9-37.1	7-27.5	10-20.1	8-26
Plasticity index (%)	15-72	11.5-67	10-46	7-33
Free swell (%)	17-100	15-84	12-45	10-37
% Gravel	0-5	0-6	0-7	0-10
% Sand	3.5-55	8-81	15-76	18-82
% Silt	21-89	5-76	19-53	12-48
% Clay	4.5-65	9-60	2-46	6-41

RSH= Residual soils derived from Agulae shale; RLS= Residual soils derived from Antalo limestone; RDO= Residual soils derived from dolerite; AL= Alluvial soils. n= number of tests.

From gradation curves, the coefficient of permeability of the different soils was found to be variable: $3.2*10^{-5}$ to $6.7*10^{-7}$ cm/sec for residual soils derived from Agulae shales; $1.5*10^{-4}$ to $5.3*10^{-6}$ cm/sec for soils derived from Antalo limestone; $3.6*10^{-4}$ to $1.4*10^{-6}$ cm/sec for soils derived from dolerites; and $4.8*10^{-3}$ to $7.2*10^{-5}$ cm/sec for alluvial soils. Results of the in-situ hydraulic conductivity tests using inverse auger-hole method [46] have shown slightly higher values: $4.6*10^{-4}$ to $2.1*10^{-6}$ cm/sec for residual soils derived from Agulae shales; $1.8*10^{-4}$ to $6.8*10^{-5}$ cm/sec for soils derived from Antalo limestone; $8.2*10^{-4}$ to $5.8*10^{-6}$ cm/sec for soils derived from dolerites; and $7.5*10^{-4}$ to $2.8*10^{-5}$ cm/sec for alluvial soils. Our study show that the residual soils derived from Agulae shale and Antalo limestone have low permeability while the soils derived from dolerites have low to moderate permeability. The alluvial soils on the other hand have moderate permeability values. The data from previous studies [41,54,55] are found to fall within these categories. The low permeability of the soils and weathered rocks promotes more surface runoff and less infiltration into groundwaters. The high free swell potential of the soils has been shown to have an adverse effect on the stability of shallow structures including water, sanitation and drainage systems.

Assessment of groundwater levels in Mekelle

Understanding fluctuation in the upper level of groundwater is important as it has implications for surface and groundwater contamination and management. Previous studies [41,45,74,87] have indicated that the main aquifer in Mekelle is multi-layered. Results from this study revealed variable groundwater levels in open hand-dug wells and boreholes as summarized below:

Water levels in open hand-dug wells: Our assessment of 6 open hand-dug wells, showed that the groundwater level varied between 0.5m and 3.5m below surface-level, indicating the very shallow nature (Fig 4) of the water table which was extremely close to surface in the months September to October. In all six of the observed open hand-dug wells, maximum raise in water level was recorded in the months of September to October and minimum water level was recorded in the months of April to May. Less notable decline in water levels over the study period was observed in wells close septic tanks and close to streams which had perennial flow.

Water levels in boreholes: Results of the water level measurements taken from the 10 boreholes, carried tested during the years 2021 to 2022, showed that the static water level ranged from 28m to 43m below surface (Fig 5) indicating a general decline in groundwater level over the years, when compared with earlier data [45]. This reduction in the water table is therefore likely to be chiefly due to increased abstraction, as no significant change in annual average precipitation was observed for Mekelle and its surrounding areas in the years 1995-2018 [40].

Fig 4. *Groundwater level in selected six hand-dug wells (HDW1-6) in Mekelle city. Depth of wells (m): HDW1= 11.5; HDW2= 13; HDW3= 12.5; HDW4= 9; HDW5= 14; HDW6= 8).*

Fig 5. *Groundwater level in ten water supply boreholes (BH1 to BH10) from Aynalem well field for the years 1998 [45], 2004-2005 [56], 2017 and 2020 [63]. (Depth of boreholes (m): BH1= 120; BH2=117.5; BH3=120; BH4=120; BH5= 75; BH6=65; BH7= 71.5; BH8= 75; BH9=80). WWDE= Water Works Design Enterprise; TBoWR= Tigray Bureau of Water Resources; MWSSO (Mekelle Water Supply and Sewage Office).*

Assessment of status of water and sanitation services

Water supply sources and coverage: Currently the main water source of Mekelle city is from groundwater (Aynalem, Chenferes, Quiha areas) and from Gereb Segen Dam. Water from groundwater wells and the water treatment plants is pumped into several reservoirs in the city and then delivered to various parts of the distribution network, predominantly by gravity. The water supply coverage in 2021 was only 67.3% [66]. Due to shortages, water is distributed to residents on a shift basis: whereby people get water mostly once every five days to once every ten days. Shortage of treated water is forcing residents to use untreated sources from open hand-dug wells, springs and surface waters for domestic uses (mainly washing but in some cases for household cooking and consumption) and irrigation of urban agriculture. In order to increase the water supply of Mekelle city a new reservoir "Geba Dam" is currently under construction and is expected to be completed by 2026 [71].

Increases in water usage, resulting from rising demand from urban agricultural producers, who use various sources, is compounding the current shortage of water and leading to competition for water not only among communities but also among sectors (e.g. drinking water and irrigation). This in-turn is driving the need to seek alternative water sources, like the reuse of wastewater for irrigation and livestock rearing. As a result, private water service providers have increased from less than 115 in 2019 to over 580 in 2020, accessing water predominantly from open hand-dug wells across Mekelle city and its surrounding areas [64]. This practice is raising significant health concerns, given that such source waters are not treated prior to use.

With regard to water quality challenges, a report by TBoH [92] indicate contamination of drinking water sources (particularly shallow groundwater wells, springs and streams/river channels). Moreover, TBoH [93] has reported an increase in incident of waterborne diseases and hence environmental and health concerns of the populations in Tigray due to sanitation issues.

Sanitation services: The ten most widely reported diseases (categorized as diarrheal diseases, respiratory infections, trachoma, lymphatic filariasis, soil-transmitted helminth infections, schistosomiasis and malnutrition) are associated with poor hygiene and sanitation conditions [94]. According to World Bank [19], 48% of the urban population in Mekelle use shared toilet facilities, mainly on-site sanitation systems (OSS) and 4% of the population do not have access to a toilet facility and resort to unsafe sanitation means or to open defecation. A recent report from MCM [66] (Supporting Information S6) indicate that the majority of Mekelle residents (54.3%) use improved toilets while 11.5% use unimproved toilets (following the WHO & UNICEF [95] criteria). Evidence from the first-round participatory stakeholder discussions, focus group discussions and key informant interviews suggest that open defecation (OD) remains a persistent and common practice in Mekelle. This was confirmed during field assessments conducted in the different parts of the city during the second-round stakeholder workshops, when people were observed practicing OD in open spaces, near stream/river channel banks and drainage areas.

According to MCM [96], over the years, there has been improvements in the provision of onsite sanitation facilities (mainly septic tanks and cesspools). The recommended capacity of septic tanks for residential areas is typically about 27m^3 (3m×3m×3m), though the mechanism for enforcing this guidance is loose and some households have septic tanks with storage capacities as low as 12m^3 (2m×2m×3m). In most cases septic tanks have masonry walls and are unlined (uncontained), with the exception of some who provide cement lining when households expect higher inflow (of groundwater and/or effluent from upstream sanitation systems) into their septic tanks. The participatory workshops, field assessments and discussions with experts of the municipality and decision makers all indicated that faecal sludge emptying from residential septic tanks is low. This was also confirmed by private faecal sludge management (FSM) businesses tasked with faecal sludge emptying via use of vacuum trucks. FSM businesses reported that their main clients were condominium residents and those involved in providing services such as hotels, restaurants, schools, hospitals, etc. Participants of the stakeholder workshops indicated that they never emptied their septic tanks (in the last 10 years) as these sanitation facilities never filled up. A similar observation was noted by Heymans et al. [19] who indicated a lower incidence of reported septic tank filling and emptying in several towns of Ethiopia including Mekelle. These low rates of emptying observed in residential areas can be attributed mainly to poor containment of faecal waste within unsealed septic tanks.

Faecal sludge management: Pit latrines and cesspools are the two main sanitation facilities in Mekelle [64] for those having access to toilet facilities. Data for the years 2018 to 2020 [64] show that collection (emptying, transport, and disposal) of faecal sludge accumulating in on-site facilities was done using 31 vacuum trucks: 13 privately owned, 2 owned by Red Cross, 2 owned by the Defense Ministry, 2 owned by the municipality, 7 owned by large hotels in the city, and 5 owned by Mekelle University. With regard to desludging, based on the stakeholder discussions and interviews with the vacuum truck operators, there have been an increase in the numbers of users, especially amongst households having cesspools and which are accessible for vacuum/ sludge collection trucks. But still problems exist for those areas that are inaccessible to vacuum trucks and for communities who cannot afford to pay the de-sludging fee which has increased from 800 Eth. Birr (15 USD)/1500m^3 in 2018 to over 1400 Eth. Birr (26 USD)/1500m^3 in 2021 (personal communication with vacuum track operators).

Faecal sludge from across Mekelle is transported to a faecal sludge drying beds located close to Illala river (as shown in Fig 1 andFig **2**). The participatory stakeholder discussions indicated that overall amounts of faecal sludge going for treatment has reduced due to the on-going conflict in the Tigray Region. This finding is in accordance with MCM [96] and has led to an increase in liquid waste discharges into drainage channels and surface waters in the city. Results of our study show that liquid waste management problems in the city include: the non-functioning of toilets due to water shortages; the overflow of liquid waste from condominium houses and public toilets; OD in open spaces close to streams and river channels; poor performance of faecal sludge drying bed facility due to improper design and construction; and leakages from uncontained septic tanks and cesspools and poor storm water management and hazard mitigation.

Solid waste management: In 2017 the solid waste collection and disposal service coverage across the city was reported to be 41% [72]. In this study a total 13 solid waste transfer stations (containers) were assessed for the types and amount of solid waste present and results show that the dominant components of the solid waste included: discarded vegetable matter (23 to 50%); fruit matter (12 to 23%); grass and tree cuttings (26 to 45%); animal remains (2 to 12%); and other items such as plastics (0 to 7%). This indicates that the solid wastes streams are predominantly comprised of biodegradable organic matter; an opportunity for reuse (promotion of circular economy). Examples of poor solid waste management practices in Mekelle can be seen in Fig 6.

Fig 6. *Poor solid waste management practices in Mekelle city: (a) solid waste dumped along roadsides close to stream/river channel; (b) solid waste causing blockages of roadside ditches; (c) a stream as open defecation (OD) and solid waste disposal site; and (d) poorly managed solid waste contaminating farmlands around Mekelle city.*

Assessment of the 12km stretch of road revealed that the road drainage system (open ditches) were blocked by solid waste at 35 locations with different types of waste mainly: organic wastes (leaves, grass, vegetable, fruit, animal remains) (40 to 70%), plastic materials (less than 5%) and silt (10 to 25%). The blockages of drainage systems are likely to be exacerbating flooding, siltation, and erosion in the city.

Physical-chemical and biological analysis of water and faecal sludge

Water quality monitoring results for physical-chemical and biological parameters for samples from open hand-dug wells, water supply boreholes, springs, streams/river channels, seepage/runoff, and faecal sludge are summarized below (Table 3 andTable 4; Fig 7).

Fig 7. *Range of water (a, b, c) and faecal sludge (d) sampling points: (a) open hand-dug well used for domestic (mainly for washing and cooking with some for consumption) and irrigation purposes, (b) seepage/runoff from residential areas, (c) surface water used for urban agriculture, and (d) municipal faecal sludge drying bed.*

Physical-chemical characteristics

The physical parameters analyzed included turbidity and total dissolved solids (TDS) (Table 3 andTable 4) and results show the following:

Turbidity (NTU): Springs, open hand-dug wells, boreholes and streams/river channels were found to have turbidity values below the maximum allowable value for consumption < 7 NTU [83].

Total dissolved solids (TDS): Boreholes had relatively lower TDS values (compared to other sources) ranging from 454-1512mg/L, while the other water sources exhibited much higher TDS values (Maximum = 3144.8 mg/L for stream/river channel water). Samples from faecal sludge were found to have higher TDS values than water sources (Maximum= 3772.4 mg/L).

Various tests were also carried out to determine the chemical characteristics of water and faecal samples (Table 3 andTable 4) and revealed that all the samples analyzed for fluoride, sodium, chloride, nitrite, phosphate, were within the maximum allowable WHO [82] limits for drinking water.

Copper (mg/L): Some samples from open hand-dug wells and streams exceeded the 1.0 mg/L maximum allowable limit recommended by WHO [82] for drinking water (though all had values less than 2mg/L).

Manganese (mg/L): Most of the water and faecal sludge samples had values within the maximum allowable limit of 0.08 mg/L for drinking recommended by WHO [82]. However, samples from boreholes had manganese values 0.1-0.3 which exceeded the WHO limit.

Total hardness (mg/L $CaCO_3$): Hardness values varied from 616.7-763.3 mg/L in open hand-dug wells, 120-855 mg/L in spring water, 582.5-991 mg/L in streams/river channels, 232.8-1107 mg/L in boreholes, 796.7-968.6 mg/L in seepage/runoff and 786.2-967.5 mg/L in faecal sludge. According to Pincus [97] total hardness value (mg/L $CaCO_3$) greater than 180mg/L is categorized as very hard water. Based on this classification: water from hand-dug wells, streams/river channels and boreholes are categorized as very hard, while water from springs have variable hardness which ranged from hard to very hard. The maximum hardness value for drinking water recommended by WHO [82] is 500mg/L. Based on this recommendation the analyzed drinking water samples are partly compliant with the admissible limits. Similar results were reported by different researchers [45,74,98] whereby they categorized the water in Mekelle area to be hard.

pH: pH varied from 7.2 - 9.1 for hand-dug wells; 7.6 - 8.8 for springs, 8.0 - 9.2 for streams/river channels, 7.9 - 9.0 for seepages/runoff, and 7.2 - 8.4 for borehole water. In the case of faecal sludge the pH value ranged from 7.0 - 8.1. The allowable pH range for drinking water is 6.5-8.5 and most of the water samples were within this range. Results of the analysis (Table 3 andTable 4) showed that the water and faecal sludge have pH value which is close to neutral. The alkaline (carbonate) nature of the underlying geology of Mekelle city may have attenuated (neutralized) to some extent the pH of liquid wastes and contaminated water, which have been shown to be slightly acidic in the literature [99-101].

Electrical Conductivity (EC) (μS/cm): The different water sources were found to have variable EC values: 1425-3162 for hand-dug wells, 682-2018 for boreholes, 1243.6-2600 for springs, 1407-4410 for stream/river channels, and 2190-2698.5 for seepage/runoff. Samples from faecal sludge have shown relatively higher EC values than the water sources (range: 4068.7-5290).

Ammonium (mg/L NH4): Values varied from 0.1-6.4 mg/L for open hand-dug wells, 0.7-5.3 mg/L for springs, 0.7-1.2 mg/L for boreholes, 3.5-7.2 mg/L for streams/river channels, 3.0-4.1 mg/L for seepage/runoff and 3.1-4.2 mg/L for faecal sludge. The maximum allowable limit for drinking water is 2 mg/L [82]. All the analyzed water samples from boreholes were within the admissible limit, while the other samples had variable values, some of which exceeded permissible limits. Maximum concentration (7.2 mg/L) was recorded from a stream/river channel water sample, suggesting faecal contamination from human, agricultural or wild sources.

Nitrate (mg/L NO_3): Values varied from 18.0-39.2 mg/L for open hand-dug wells, 23.4-32.6

mg/L for springs, 11.2-28.3 mg/L for boreholes, 19.3-43.7 mg/L for streams/river channels, 30.6-61.5 mg/L for seepages/runoff and 39.2-56.2 mg/L for faecal sludge. According to WHO [82] maximum allowable limit for drinking water is 50 mg/L. Based on this recommendation the analyzed samples from open hand-dug wells, springs, boreholes, and streams/river channels were all within the allowable limit. Tekle et al. [37] have reported nitrate concentrations in the range 6.6-209 mg/L in groundwater wells in Aynalem area (Mekelle) with lower concentration upstream of animal feedlots, while higher values at downstream.

Carbonate (mg/L $CaCO_3$): Carbonate content varied considerably from 1.0-3.6 mg/L for open hand-dug wells, 0.3-24.0 mg/L for springs, 1.7-110.9 mg/L for streams/river channels, 2.6-8.2 mg/L for boreholes, 34.0-68.5 mg/L for seepage/runoff and 2.0-4.1 mg/l for faecal sludge.

Bicarbonate (Bicarbonate (mg/L HCO3): Bicarbonate content varied from 323.3-471.0 mg/L for open hand-dug wells, 175.3-828.7 mg/L for springs, 283-1117.7 mg/L for streams/river channels, 56.3-346.2 mg/L for boreholes; 694.2-1027.4 mg/L for seepages/runoff and 993.2-2007.3 mg/L for faecal sludge. Bicarbonate concentrations in surface waters are usually <500 mg/L and commonly <25 mg/L, according to Chapman & Kimstach [102]. The samples were found to have high variability in terms of bicarbonate content: minimum value of 56.3mg/L in samples from boreholes and maximum value of 2007.3mg/L in faecal sludge.

Alkalinity (mg/L CaCO3): Values varied from 265-425 mg/L for open hand-dug wells, 270-1450 mg/L for springs, 125-1490 mg/L for streams/river channels, 117-274 mg/L for boreholes, 635-1036 mg/L for seepages/runoff and 1060-2465 mg/L for faecal sludge. The alkalinity of water is mostly taken as an indication of the concentration of carbonate, bicarbonate and hydroxide [102]. The high alkalinity results for the different tests is related to the high bicarbonate concentrations found in waters samples from alkaline environments (Agula shale and Antalo limestone formations) in Mekelle city and its surrounding areas.

Sulphate (mg/L SO4): Values varied from 281.2-431.5 mg/L for open hand-dug wells, 125.7-322.4 mg/L for springs, 229.7-325.4 mg/L for faecal sludge, 249.5-391.6 mg/L for streams/river channels, 276.3-336.7 mg/L for seepages/runoff and 56.3-876.4 mg/L for boreholes. The presence of sulfate in drinking-water can cause noticeable taste, and very high levels can cause a laxative effect in unaccustomed consumers [82]. Sulphate concentrations in natural waters are usually between 2 and 80 mg/L, although they may exceed 1,000 mg/L near industrial discharges, or in arid regions where sulphate minerals, such as gypsum, are present [102]. Though no health-based guideline value has been derived for sulfate, taste impairment is minimal at levels below 250 mg/L [82]. Water samples from boreholes were found to have very high variability in sulphate content up to 876.4mg/L. Previous research has suggested that this could be due to the presence of gypsum layers in the aquifers encountered during drilling [45]. This can force consumers to use alternative, shallower groundwater or surface water sources which may be more susceptible to faecal contamination.

Dissolved Oxygen (DO mg/L): Values varied from 4.1-7.3 mg/L for open hand-dug wells, 1.0-5.0 mg/L for springs, 2.6-8.6 mg/L for boreholes, 0.6-11.4 mg/L for streams/river channels, 4.6-10.7 mg/L for seepages/runoff, and 1.0-1.8 mg/L for faecal sludge. As expected faecal sludge had the lowest average values.

Biochemical Oxygen Demand (BOD mg/L): Values varied from 18.0-1020 mg/L for open hand-dug wells, 13-1254 mg/L for springs, 415-1313 mg/L for streams/river channels, 14.2-27.2 mg/L for boreholes, 11.5-1683 mg/L for seepages/runoff, and 1185-1413 mg/L for faecal sludge. There are no WHO or similar guidelines for BOD in drinking waters as it is not expected to be present in such waters. The fact that the maximum levels found in hand-dug well, springs and streams/river channels were similar to those found in seepages/runoff and faecal sludge are very concerning. Borehole samples exhibited the lowest levels.

Chemical Oxygen Demand (COD mg/L): Values varied from 28.0-2051.0 mg/L for open hand-dug wells, 25-2517 mg/L for springs, 13.2-26.5 mg/L for boreholes, 826-2753 mg/L for streams/river channels, 2424-2824 mg/L for seepages/runoff, and 2290-2831 mg/L for faecal sludge. Except for samples from boreholes, all the other tests show high COD values. There are no WHO or similar guidelines for COD in drinking waters as it is not expected to be present in such waters. Water samples from borehole samples exhibited the lowest levels. The fact that water samples from hand-dug well, springs and streams/river channels have shown maximum levels, similar to those found in seepages/runoff and faecal sludge, are very concerning.

Microbiological characteristics

In this study total coliforms (general bacterial indicator) and *E. coli* (faecal indicator) were detected and enumerated in the various water sources and faecal sludge samples (Table 3).

Total Coliform (cfu/100mL): Levels varied from 500-3100cfu/100mL for open hand-dug wells, 500-1000cfu/100mL for boreholes, 600-7300cfu/100mL for springs, 1800-10,500cfu/100mL for streams/river channels, 7100-12,400cfu/100mL for seepage/runoff, and 3900-7500 cfu/100mL for faecal sludge.

E. coli (cfu/100mL): *E. coli* levels varied from 1500cfu/100mL for open hand-dug wells, 200-400cfu/100mL for boreholes, 200-3300cfu/100mL for springs, 800-5300cfu/100mL for streams/river channels, 4200-5600cfu/100mL for seepages/runoff, and 1200-3100 cfu/100mL for faecal sludge. All sources failed to meet the WHO Drinking Water Guideline of 0 cfu/100mL, with extremely high levels of contamination observed in all sources (except boreholes, which still exceeded WHO Guidelines). The levels found in hand-dug wells, springs and streams/river channels are particularly concerning.

Suitability of the analyzed water and wastewater for irrigation

The suitability of the different water sources and faecal sludge for irrigation purposes was analyzed in terms of sodium absorption ratio (SAR) and pathogens as discussed below:

Sodium absorption ratio (SAR): Elevated sodium in certain soil types has been shown to degrade soil structure [102], thereby restricting water movement and affecting plant growth. Results of this study show (Table 3 andTable 4) that the SAR value of the different samples is relatively low: 0.7-1.1 for open hand-dug wells; 0.4-0.8 for boreholes; 0.6-1.0 for springs; 0.7-1.5 for streams; 0.9-1.4 for seepage/runoff; and 1.2-1.4 for faecal sludge. According to Wilcox [103], SAR values less than 10 is categorized as low sodium hazard. All the water and faecal sludge samples were under this figure and are suitable for irrigation (in terms of sodium levels).

Safety of irrigated food crops: Irrigation of food crops presents a possible health risk to consumers if the quality of the irrigation water is poor, particularly with respect to microbes and toxic compounds. Risk is elevated when water is sprayed directly onto the crop rather than flooded around the base of the plants [102]. A guideline for the safe use of wastewater, excreta and greywater for irrigation, developed by WHO [83], suggests that reclaimed water can be reused as long as the concentration of *E. coli* fulfil the following conditions: (a) treated faeces and faecal sludge: *E. coli* (cfu per 100 mL) <1000/g total solids; (b) restricted greywater use for irrigation: *E. coli* (cfu per 100mL) $<10^5$ where this could be relaxed to $<10^6$ when exposure is limited, or regrowth is likely; (c) unrestricted greywater use for irrigation of crops eaten raw: *E. coli* (cfu per 100 mL)$< 10^3$ where this could be relaxed to $<10^4$ for high-growing leaf crops or drip irrigation.

Results of the analysis (Supporting information S4 Table to S9 Table) show that the different water and faecal sludge samples exhibited variable *E. coli* count ranging from 200cfu/100mL (open hand-dug wells) to 5600 cfu/100mL for seepage/runoff. Based on these results and the WHO [83] recommendations for irrigation use:

- Water from the tested boreholes is generally suitable for irrigation (both restricted and unrestricted types).
- Water from the tested open hand-dug wells, springs, streams/river channels, seepages/runoff and faecal sludge could be used for restricted irrigation use. However, some of the open hand-dug wells and springs had *E. coli* concentration that exceed the WHO recommendations for unrestricted use for irrigation. Low-cost water treatment e.g. sand filters could help reduce the risk from micro-organisms.

Health risks associated water usage: Field observations of areas in and around Mekelle used for crop production and horticulture revealed that farmers are using the different sources of water for growing vegetables, fruits, field crops, ornamental trees, etc. Moreover, households are using water from boreholes, open hand-dug wells and springs for domestic purposes including drinking and washing. Though residents within the centre of Mekelle are not using stream/river channel water for drinking purposes, communities downstream of the city and located close to the Illala river are using the river water for drinking, washing, irrigation and livestock purposes. Another issue is the widespread use of spring water as ‘holy water” in church areas despite the high levels of *E. coli* present in such sources (Mean =

2137.5cfu/100mL) . There is therefore an urgent need to create awareness on the health-related risks and to manage and reduce contamination of open water sources and springs with human waste (both faecal and municipal solid waste).

Table 3. Levels of parameters found in samples from hand-dug wells (HDW), boreholes (BH) and springs collected from Mekelle municipality between May 15 and June 20, 2020 (n=28).

Parameter	**Hand-dug wells (HDW) (n=10)**			**Boreholes (BH) (n=10)**			**Springs (n= 8)**		
	Range	Mean	St. Dev	Range	Mean	St. Dev	Range	Mean	St. Dev
Salinity (mg/L Sal)	0.7-1.8	1.2	0.4	0.3-1.6	0.8	0.4	0.8-2.1	1.3	0.4
Dissolved Oxygen (DO mg/L)	4.1-7.3	5.5	1.1	2.6-8.6	4.6	1.8	1.0-5.0	3.2	1.6
Biochemical Oxygen Demand (BOD) (mg/L)	18.0-1020.0	572.6	348.1	14.2-27.2	20.2	4.2	13-1254	824.9	504.8
Chemical Oxygen Demand (COD) (mg/L)	28.0-2051.0	1148.1	709.4	13.2-26.5	19.1	4.3	25-2517	1700.4	1042.9
Fluoride (mg/L F^-)	0.3-1.2	0.9	0.3	0.2-1.1	0.7	0.3	0.6-1.1	1.0	0.2
Total Hardness (mg/L $CaCO_3$)	616.7 -763.3	686.3	54.1	232.8-1107	581.0	285.9	120-855	531.2	263.1
Total Dissolved Solid (mg/L)	1016.2-2254.7	1625.0	409.3	454-1512	854.0	402.8	874.6-1854.1	1537.2	390.1
Electrical Conductivity (µS/cm)	1425.0-3162.0	2278.0	574.2	682-2018	1239.5	488.9	1243.6-2600	2165.0	542.2
pH	7.2-9.1	8.2	0.6	7.2-8.4	7.9	0.3	7.63-8.7	8.3	0.4
Ammonium (mg/L NH4)	0.1-6.4	3.4	2.2	0.7-1.2	0.9	0.2	0.7-5.3	2.9	1.5
Sodium (mg/L Na)	37.4-72.3	51.4	11.4	17-51	35.2	11.3	47.1-68.5	54.4	7.7

Potassium (mg/L K)	2.4-10.3	6.3	2.9	1.3-3.8	2.7	0.9	5.7-15.4	10.0	4.0
Calcium (mg/L Ca)	155.0-254.0	194.3	20.6	68.2-412.8	219.6	115.2	118-328	221.0	68.9
Magnesium (mg/L Mg)	39.0-69.0	55.9	9.6	7.2-17.0	10.3	2.9	38-72	59.1	11.7
Total Iron (mg/L Fe)	0.6-1.3	1.0	0.3	0.3-0.7	0.5	0.2	0.6-0.8	0.7	0.1
Manganese (mg/L Mn)	0.0-0.1	0.0	0.0	0.1-0.3	0.2	0.1	0.0-0.1	0.0	0.0
Chloride (mg/L Cl)	36.1-67.0	52.5	12.9	14.7-24.5	19.0	3.6	28.5-56.4	44.1	9.3
Nitrate (mg/l NO_3)	18.0-39.2	28.6	7.4	11.2-28.3	19.9	5.0	23.4-32.6	27.5	3.6
Chromium (mg/L Cr)	0.0-0.1	0.0	0.0	0-0.2	0.1	0.1	0-0.1	0.0	0.0
Copper (mg/L Cu)	0.7-1.8	1.2	0.3	0-0.1	0.0	0.0	0.1-1.2	0.8	0.5
Nitrite (mg/L NO_2)	0.1-0.2	0.1	0.0	0.1-0.7	0.4	0.2	0-0.4	0.2	0.1
Alkalinity (mg/L $CaCO_3$)	265.0-425.0	329.1	46.7	117.4-274.3	200.6	46.3	270-1450	919.8	513.3
Carbonate (mg/L $CaCO_3$)	1.0-3.6	2.3	0.9	2.6-8.2	5.2	1.6	0.301-23.9	15.7	7.1
Bicarbonate (mg/L HCO_3)	323.3-471.2	406.1	47.4	56.3-346.2	233.3	89.4	175.3-828.7	657.5	135.6
Sulphate (mg/L SO_4)	281.2-431.5	381.0	44.0	56.3-876.4	388.2	284.7	125.7-322.4	247.6	76.1
Phosphate (mg/L PO_4)	1.1-1.7	1.4	0.2	0.7-1.6	1.0	0.3	0.74-1.72	1.2	0.4
Total Coliform (cfu/100 mL)	500-3100	2060.0	834.3	500-1000	740.0	177.64	600-7300	4650.0	2526.43
E.coli (cfu/100 mL)	200-1500	910.0	378.4	200-400	320.0	91.89	200-3300	2137.5	1210.59

True color (Chromaticity) in TCU	4.2-15.6	11.8	3.9	1.8-5.1	3.3	1.1	9.7-19.3	13.2	3.6
Turbidity in NTU	1.6-5.6	3.3	1.2	1.0-1.7	1.4	0.2	2.3-8.8	6.3	2.7
SAR (Sodium Absorption Ratio)	0.7-1.1	0.8	0.2	0.4-0.8	0.6	0.1	0.6-1.0	0.9	1.5

cfu = Colony Forming Units; TCU=True Color Units; NTU=Nephelometric Turbidity Units.

Table 4. Levels of parameters found in samples from streams/river channels, seepage/runoff, and FS (untreated) collected from Mekelle municipality between May 15 and June 20, 2020 (n=23)

Parameter	**Stream/river channel (n=12)**			**Seepage/runoff (n=6)**			**Faecal sludge (n=5)**		
	Range	Mean	St. Dev	Range	Mean	St. Dev	Range	Mean	St. Dev
Salinity (mg/L Sal)	0.7-2.4	1.2	0.6	1.1-2.1	1.5	0.4	2.5-3.7	3.0	0.5
Dissolved Oxygen (DO mg/L)	0.6-11.4	5.3	3.4	4.6-10.7	7.7	2.2	1.0-1.8	1.4	0.4
Biochemical Oxygen Demand (BOD) (mg/L)	415-1313	898.3	260.3	11.5-1683	1373.2	180.4	1185-1413	1292.0	82.2
Chemical Oxygen Demand (COD) (mg/L)	826-2753	1867.8	519.5	2424-2824	2630.0	148.4	2290-2831	2555.6	195.7
Fluoride (mg/L F^-)	0.7-1.3	1.0	0.2	0.5-0.7	0.6	0.1	1.0-1.2	1.1	0.1

Total Hardness (mg/L $CaCO_3$)	582.5-990.8	697.8	107.7	796.7-968.6	875.9	62.6	786.2-967.5	852.1	70.3
Total Dissolved Solid (mg/L)	1003.4-3144.8	1729.8	691.0	1561.71-1928.2	1740.2	125.1	2865.3-3772.4	3317.5	386.5
Electrical Conductivity (µS/cm)	1407-4410	2425.7	969.0	2190-2698.5	2437.2	173.7	4068.7-5290	4687.7	542.4
pH	8.0-9.2	8.8	0.4	7.9-9.0	8.5	0.4	7.0-8.1	7.6	0.5
Ammonium (mg/L NH4)	3.5-7.2	4.8	1.2	3.0-4.1	3.6	0.4	3.1-4.2	3.7	0.4
Sodium (mg/L Na)	37.4-89.3	58.5	16.9	64.5-96.3	77.1	11.8	81.8-97.4	89.5	6.1
Potassium (mg/L K)	6.6-130.5	34.2	43.5	39.4-96.4	64.6	21.9	133.0-1679.6	423.0	244.2
Calcium (mg/L Ca)	140-288	173.9	19.1	280-532.8	294.6	66.0	231-301.5	245.9	18.3
Magnesium (mg/L Mg)	48-66	58.8	6.2	51-86	70.2	13.6	55-82	69.0	10.0
Total Iron (mg/L Fe)	0.5-1.1	0.8	0.1	0.7-1.0	0.8	0.1	0.8-1.0	0.9	0.1
Manganese (mg/L Mn)	0-0.1	0.0	0.0	0-0.1	0.1	0.0	0.1-0.14	0.1	0.0
Chloride (mg/L Cl)	35.9-82.8	56.7	14.9	61.83-89.4	75.6	10.2	71.6-98.2	85.3	10.5
Nitrate (mg/l NO_3)	19.3-43.7	29.0	7.7	30.6-61.5	51.5	11.2	39.2-56.2	47.5	6.7
Chromium (mg/L Cr)	0.03-0.08	0.0	0.0	0.04-0.08	0.1	0.0	0.05-0.09	0.1	0.0
Copper (mg/L Cu)	0.8-1.7	1.1	0.2	0.7-1.1	0.8	0.1	0.6-1.2	0.9	0.2
Nitrite (mg/L NO_2)	0-0.3	0.1	0.1	0.2-0.4	0.3	0.1	0.05-0.12	0.1	0.0
Alkalinity (mg/L $CaCO_3$)	125-1490	374.9	379.1	635-1036	886.0	152.0	1060-2465	1986.6	546.5

Carbonate (mg/L $CaCO_3$)	1.72-110.88	17.3	30.1	33.99-68.5	53.5	12.5	2.04-4.06	3.1	0.7
Bicarbonate (mg/L HCO_3)	283-1117.7	408.0	131.7	694.2-1027.4	885.6	132.4	993.2-2007.3	1377.3	361.2
Sulphate (mg/L SO_4)	249.5-391.6	348.2	50.6	276.3-336.7	300.5	22.7	229.7-325.4	268.2	36.2
Phosphate (mg/L PO_4)	0.7-1.6	1.1	0.2	0.9-1.2	1.0	0.1	1.1-1.5	1.3	0.1
Total Coliform (cfu/100 mL)	1800-10500	3516.7	2373.66	7100-12400	9266.7	1840.29	3900-7500	5560.0	1381.3
E.coli (cfu/100 mL)	800-5300	1900.0	1513.57	4200-5600	4950.0	543.14	1200-3100	2080.0	712.04
True color (Chromaticity) in TCU	9.6-18.6	14.2	2.6	7.0-9.2	8.3	0.8	14.3-18.2	16.3	1.5
Turbidity in NTU	1.2-8.1	4.1	2.2	2.6-5.1	4.0	0.9	7.5-9.0	8.3	0.6
SAR (Sodium Absorption Ratio)	0.7-1.5	1.0	0.3	0.9-1.4	1.1	0.2	1.2-1.4	1.3	0.1

cfu = Colony Forming Units; TCU=True Color Units; NTU=Nephelometric Turbidity Units.

Evaluation of sanitation challenges facing Mekelle municipality

Review of existing policies, strategies, regulatory frameworks as well as participatory stakeholder workshops and discussions revealed that various institutions are currently engaged in WASH in Mekelle city. The main institutions include federal and regional as well as city council level department offices and non-governmental organizations (Table 5).

Table 5. Summary on the roles and responsibilities of various institutions involved in WASH.

Institution	**Role/Responsibility**
Ministry of Water and Irrigation of Ethiopia	Setting of national policies for the water supply sector in Ethiopia.
Ministry of Health of Ethiopia	Setting of national policies for sanitation and hygiene in Ethiopia.
Tigray Bureau of Water Resources	Responsible for investment planning and development of water resources of the region and provision of technical assistance to service providers. Also responsible for developing legislations, institutional frameworks and monitoring and evaluation systems for the region.
Tigray Bureau of Health	Through the regional health partners' forum and regional sanitation technical working group it supports the different actors in the implementation of sanitation and hygiene.
Mekelle City Administration through	Responsible for planning and managing city water supply systems including setting management teams

its Mekelle Water Supply and Sewerage Service Office	as well as approving investment plans and tariff adjustments. It includes the supply of potable water and the provision of wastewater/sludge disposal service.
Hygiene and Sanitation branch of the Mekelle City Health Office	In charge of administering sanitation facilities and promoting hygiene education in Mekelle.
Sanitation and Hygiene Department of the Municipality	
Donors and NGO's supporting the WASH program such as: World Bank, Africa Development Bank, UNICEF, Relief Society of Tigray, USAID.	Provision of various types of support: budget subsidy, community mobilization, capacity building, stakeholders training, provision of transport facilities and material resources.

Note: the Bureau of Education and the Environment Authority are also involved in water and sanitation promotions (though not fully engaged in sanitation service provision of Mekelle municipality).

From participatory stakeholder workshops, focus group discussions as well as participatory field evaluations, various challenges/barriers were identified which were categorized into the following: technical/technological, social, environmental, institutional/political and financial issues as summarized below (Table 6).

Table 6. Summary of the major challenges/knowledge gaps related to WASH in Mekelle city.

Category	**Gaps/Challenges**
Technical and technology challenges	▪ Shortage of skilled professionals who could properly understand the behaviors of waste/wastewater and their management solutions including the study, design and construction of different waste management solutions that considers the dynamic waste-environment-infrastructures-human interactions. ▪ Lack of data which could be used for proper planning, design, construction and maintenance of sanitation facilities. ▪ Shortage of equipment and facilities that could help for characterization of waste/wastewater, level of contamination and its oval impact. ▪ Limited knowledge on technology options related to waste management (including circularity) and lack of proper follow-up and technical support for existing sanitation facilities.
Social challenges	▪ Lack of knowledge and in some cases resistance to accept waste management as an instrument for promoting human and environmental health. ▪ Lack of awareness and knowledge on the possible contamination of water due to improper management of waste and use of OD practices: this is especially the case for religious institutions who advocate for the use of spring water as "holy water" for the treatment of their patients though samples from such water sources are found to have high level of E.coli counts.

Environmental challenges	▪ Lack of understanding on the impacts of improper waste management on the environment (including soil and water). ▪ Lack of understanding on the dynamic interactions among urban infrastructures and waste and their relation to urban hazards (flooding, climate change, etc.).
Institutional, governance and regulatory challenges	▪ Lack of integration and coordination among the different institutions involved in sanitation including overlaps or gaps in their roles and responsibilities. ▪ Institutional instability: there has been several changes in the names and/or structures of organization mandated to water resources management, and this is contributing to professional instability. ▪ Existing policies, strategies, regulatory frameworks were developed based on top-down approach; not encouraging and promoting locally adoptive solutions to WASH challenges. ▪ Water bureau lacks proper institutional set-up particularly in view of delivering its appropriate support in the urban water supply and sanitation services. ▪ WASH stakeholders working in the region do not have a common working and supporting modalities; the steering committee is not effective and/or active. Except the major donors, others lack clarity with their mandates and responsibilities.
Financial issues/ challenges	▪ Shortage of finance to construct, maintain and manage sanitation facilities. ▪ Absence of incentives for private sector businesses involved in water and sanitation through proper value chain development.

	▪ Shortage of finance to purchase field and laboratory equipment and facilities related to waste characterization and evaluation.

Water source and septic tank connectivity

As outlined in section 2.2.5, six different interaction scenarios were monitored in the field (Scenarios 1-6) and summarized below:

- ***Scenario 1: Septic tank downstream of shallow well***: In this case (Fig 8), in the months of Aug to Jan 2021/22 the groundwater level was found to rise close to the surface and the level of the septic tank contents. Outside of these months, the faecal sludge level in septic tank was at a higher elevation as compared to the groundwater level. From the liquid level measurements it can be noted that under dry season conditions, septic tanks were more likely to leach into the wells, while during the wet season, well waters were more likely to flow through the saturated natural media (soil and weathered rock) into septic tanks.
- ***Scenario 2: Septic tank upstream of groundwater source***: In this scenario (Fig 9), the groundwater level was below the faecal sludge level in septic tank throughout the year. The septic tank recharged the groundwater well all year round (in dry and wet season).
- ***Scenario 3: Septic tank in close proximity to stream****:* In this case (Fig 10) the faecal sludge level in septic tanks was found to be at higher elevation as compared to the stream bed. The maximum flood level in the stream (during rainy season) was recorded to be at lower elevation than the faecal sludge level. As a result, the septic tank contents leached (recharged) the stream throughout the year.
- ***Scenario 4: Groundwater source upstream, but in close proximity to a perennial stream****:* In this scenario (Fig 11), the groundwater level in the well was found to vary

with season: in the months June to February the water table was at higher elevation than the stream bed level and hence the well leached its contents into the streams. In the months March to June the water table was below the stream bed level and hence the stream recharged the wells.

- ***Scenario 5: Spring at downstream but close to septic tank:*** In this case (Fig 12) the faecal sludge level was at higher elevation than the spring discharge level and hence the septic tank recharged the spring all year round.
- ***Scenario 6: Septic tank at downstream of groundwater well but adjacent to stream***: In this scenario (Fig 13) in the months September to November the groundwater level raised to the surface and recharged the septic tanks as well as the stream. In the other months of the year the septic tank recharged the well. Moreover, during the dry season (February to June) the stream recharged the well. During flood season the stream recharged the groundwater well.

Fig 8. *Scenario 1- Depth of septic tank contents (from surface) with respect to ground water level (GWL) and month at site 1. FSL= Faecal sludge level for site 1.*

Fig 9. *Scenario 2- Septic tank located upstream of well: in dry season as well as during wet season septic tanks recharge the wells. FSL-2: Faecal sludge level of site 2; GWL= groundwater level for site 2.*

Fig 10. *Scenario 3-Septic tank located close (e.g. 18.2m) to streams and septic tanks recharge the streams/river channels throughout the year. FSL-3: faecal sludge level for site 3; STB-3: stream bed level for site 3; MFL-3: maximum flood level for site 3.*

Fig 11. *Scenario 4-Wells located at upstream but close to stream/river channel (e.g. 26.4m): in wet season the wells recharge the streams and during dry season streams/river channels recharge the wells. GWL-4: groundwater level for site 4; STB-4: stream bed for site 4; MFL-4: maximum flood level for site 4.*

Fig 12. *Scenario 5-Spring located at lower elevation but close (e.g. 30m) to septic tank: the septic tank recharges the spring throughout the year. FSL-5: faecal sludge level for site 5; SPL-5: spring level for site 5.*

Fig 13. *Scenario 6-Seepage/runoff at downstream but close to septic tanks: the septic tank recharges the seepage/runoff zones throughout the year. GWL-6: groundwater level for site 6; FSL-6: faecal sludge level for site 6; STB-6: stream bed for site 6; MFL-6: maximum flood level for site 6.*

The above monitored scenarios and interactions between shallow wells, springs, septic tank contents and streams/river channels highlight some of the ways in which contaminants including pathogens can be transmitted and controlled within the environment. The effect of leaching/recharge from septic tanks to groundwater wells, streams/river channels, springs etc. could be an opportunity to enhance water and wastewater availability for irrigation and environmental management with due consideration that the quality is within the allowable limit as recommended by WHO [83] and outlined above in section 3.5.3. The interactions monitored and the observed effects also indicate the applicability and hence the need for further promotion of the concept of land treatment defined by Crites et al. [104] as “the controlled application of wastewater onto the land surface to achieve a designed degree of treatment through natural physical, chemical and biological processes within the plant-soil-water matrix”.

Existing practices and potential for circular economy in Mekelle

As reported by Halog & Anieke [105] in municipal areas and in cities, the government plays a vital role in circular economy transition which includes: (a) minimizing pollution loads in urban areas and assisting communities affected by mismanaged wastes in particular, and (b) supporting treatment of wastewater and the water (recycling) so it can be used for irrigation purposes.

Existing practices which support the circular economy show that there are already some examples of good practice in Mekelle including promotion of urban agriculture (food crops (vegetables and fruits), livestock feed, cultivation of ornamental trees, and production of organic compost (e.g. Fig 14). In few cases, urine has been used to improve soil condition and to support biofuel production. In several locations especially those close to streams/river channels and in low-lying areas where there is good potential for shallow groundwater resources, innovative households have developed new shallow wells and are providing services (selling water) to neighboring households. As confirmed through ground water level monitoring, some of these wells are recharged from streams/river channels and influenced by septic tanks.

Fig 14. *Examples of practices related to circularity in Mekelle: (a) gully affected area converted into an area for ornamental tree growth with water from untreated stream/river channel, (b) vegetables grown with water from a stream/river channel, (c) livestock feed production with seepage/runoff wastewater leaching from faecal sludge drying bed, and (d) youth collecting solid waste (plastic) for reuse from a blocked box culvert with solid waste.*

The current conflict and associated crisis are forcing people, especially the urban poor, to seek alternative livelihoods to survive. This study identified the following emerging trends in water, wastewater and land utilization as well as circular economic initiatives in Mekelle:

- Extensive urban agriculture development - especially cultivation of vegetables, field crops with some ornamental trees and fruits (irrespective of the available land area);
- Use of organic compost and urine for soil enhancement – as there is critical local and global shortage of widely used chemical fertilizer.
- Critical water shortages in the city and increasing demand from urban agriculture is aggravating the shortage of potable water. Hence a new trend is emerging in the use of multiple water sources including boreholes, springs, harvested rainwater (rainy season), greywater, drainage waters, streams/river channels and the construction of shallow hand-dug wells. While this use of multiple water sources needs to be promoted and strengthened, close attention needs to be paid to the quality requirements for the various purposes. However, the emergence of new wells and water supply service providers can drive increased water demand for various purposes (households, livestock and irrigation). This calls for the implementation of effective water management and

monitoring of water quality deterioration and associated health risks, along with groundwater surveillance to avoid over abstraction.

- Identification and utilization of new spaces, such as the sides of streams/river channels, roadsides, for urban agriculture deters open defecation as well as other antisocial waste disposal practices. The comparative assessment of poorly-managed versus well-managed streams/channels and embankments (Table 7) suggest that the well-managed surface waters have multi-dimensional advantages over poorly managed ones including multiple economic and environmental benefits. This calls for a new shift in urban development that aims at utilizing banks of streams/river channels for various circular economy activities as well as environmental enhancement.
- Promotion of reuse and recycling activities in Mekelle, resulting from conflict-related shortages of money and goods – this has increased number of people collecting plastic materials (e.g. plastic water bottles, plastic bags, etc) for reuse and organic materials (grasses, fruit remains, etc.) for the production of compost. There is a need to support such initiatives not as a temporary alternative for livelihood but as a long-term solution for sustainable (circular) waste management.

Table 7. Results of the assessments of seven streams/river channels and embankments with different levels of management.

Parameter	**Poorly-managed streams/river channels (n=3)**	**Well-managed streams/river channels (n=4)**
Stream/river channel length	0.5-1.4km	0.3-0.8km

Stream/river channel channel width	55-87m	35-120m
Stream/river channel depth	3-5m	2-6m
Ownership and management	▪ Publicly owned and unprotected ▪ OD and solid waste dumping sites	▪ Privately owned and protected ▪ No OD or solid waste dumping sites
Land management condition	▪ Active gully erosion and bank collapse ▪ No structures that enhance soil and water conservation	▪ Stabilized streams with different treatment methods (check-dams, retaining structures) to avoid gully erosion and bank collapse ▪ Structures that enhance soil and water conservation
Economic benefits	Not used for economic activity	Used for various economic activities: ▪ Urban agriculture such as field crops, vegetables, fruits, etc. ▪ Private hand-dug wells developed at the sides of river channels/streams for service provision to local communities.

N= number of streams. Note: In addition to the above observed advantages, treated/well managed streams/river channels are expected to have positive effects on downstream areas.

Implications of promoting circular economy on climate change adaptation and mitigation in urban and peri-urban areas

Urban systems interact with climate systems in multiple, dynamic and complex ways [106]. Climate change can have direct impacts on the functioning of urban systems, while the nature of those systems plays a substantial role in modifying the effects of climate change [107,108]. According to Dodman et al. [109], observed and expected impacts from the main hazards identified for cities, settlements and infrastructure due to climate change include: temperature extremes, flooding, water scarcity and security, as well as other hazards such as landslides. As reported by Lin et al. [110], sustainable urban development has been implemented worldwide in response to a range of problems, such as urban sprawl, pollution, traffic congestion, economic decline in developed countries, and rapid urbanization in developing countries. In view of these, the promotion of circular economy in Mekelle city and in other similar areas is believed to play a role for reducing climate change related challenges. There is therefore a need to promote urban agriculture, greenery area development along streams/river channels and open spaces, use of municipal waste water for productive purposes (irrigation and enhanced groundwater recharge), and production of bio-fuels/bio-fertilizer as part of integrated urban development.

Conclusion

Our study has revealed that hydrogeological and geotechnical factors need to be given due considerations in waste management as well as design and construction of WASH facilities. In the case of Mekelle city, our study show that, the different underlying geology confers variable properties in relation to their permeability, engineering properties and the movement of water (surface and sub-surface): (a) the fractured dolerites, limestones (within the Agulae shale or

Antalo limestone formation) as well as the interface between unconsolidated sediments and underlying rocks have relatively higher permeability; (b) the presence of shale as intercalations within the Agulae shale and Antalo limestone retards vertical flow of subsurface fluids; (c) the low permeability nature of the dominant soils in Mekelle city and its surrounding areas coupled with the construction activities (buildings, roads, etc) favours more runoff and hence associated hazards such as flooding; and (d) the high free swell property of the soils is expected to have an effect on the design and construction of shallow foundations including sanitation and drainage systems.

The municipality of Mekelle relies on groundwater from different aquifer sources and from surface waters impounded by the Gereb Segen dam. Water from shallow open hand-dug wells, springs, and streams/river channels are also commonly used for multiple purposes. Our water quality analysis revealed different levels of contamination with municipal waste:

- Open hand-dug wells are contaminated with pathogens due to combinations of factors (e.g. shallow water levels, lack of protection (unsealed well head/apron) and leaching from overflowing septic tanks, etc).
- Boreholes on the other hand were found to be relatively less contaminated, likely to be because the well fields are located in less urbanized areas, characterized by deeper water levels, protected/closed wells, and underlying geology (shale layers as intercalations in the multi-layer aquifers) that reduces vertical transmission of contaminants.
- Springs and streams/river channels were found to be contaminated because of different factors such as: (a) the overflowing of faecal sludge from sanitation facilities (e.g. septic tanks, drying beds), (b) release of greywater waste from washing into streets/roads, (c) uncontrolled dumping of solid municipal waste on streets, roadside ditches, (d) blockages of hydraulic systems (roadside ditches,

culverts and bridges), and (e) blockage-related overflow from contaminated urban drainage systems.

Assessment of sanitation and waste management issues revealed that although sanitation coverage has increased over the last 10-15 years, contamination is associated with several processes and factors including: (a) attitudes and cultural issues related to open defecation practices in open spaces, streams and river channels, (b) poor design and operational problems with onsite septic tanks and faecal sludge drying beds, (c) sustainability and management problems of sanitation and drainage facilities. Moreover, the interactions with surface and sub-surface water as well as their associations with solid waste is affecting sanitary water quality in Mekelle. It is therefore important to promote sanitation and waste management with due understanding of the dynamic interactions between waste, environment, infrastructures and humans.

Our study has identified key opportunities for further upscaling and promoting the circular economy and environmental protection involving urban agriculture, horticulture, arboculture and greenery space development, waste separation at source, organic compost development and small business development involved in waste (solid and liquid) management. The use of urban water and wastewater for irrigation and for other uses is reliant on the evaluations of the quality requirements for their respective uses especially for unrestricted irrigation.

The implication for further upscaling of such practices to other urban and semi-urban areas is believed to be high as most of the urban and peri-urban areas in Tigray are dominated by shallow unconfined aquifers (mainly unconsolidated deposits and weathered rocks) with small urban agriculture practices, though are challenged by a shortage of water. Similar to that of Mekelle, waste management in these areas is generally poor. The concept of circular economy is therefore believed to be applicable to other urban and peri-urban areas of Tigray.

Implementation of sustainable waste management in Mekelle requires a paradigm shift in the way municipal waste is perceived and mitigation interventions are implemented. It is recommended that urban water supply and sanitation management focusses on interventions over the entire urban water cycle; from the way water is used (and reused); to the greater application of natural systems for water and wastewater treatment. This calls for an integrated and dynamic approach to water and waste management which involves: (a) water and wastewater quality monitoring, suitability evaluations and use for different purposes; (b) promoting value-chain oriented circular economy with waste (liquid and solid); (c) design and implementation of proper institutional arrangements and regulatory frameworks.

Supporting Information

The following supporting information is available:

- S1 Fig. Population dynamics of Mekelle city.
- S2 Fig. Hydrometeorology (rainfall and Potential Evapotranspiration (PET)) (mm) of Mekelle city
- S3 Fig. Water and sanitation services and overall coverage for Mekelle city for the year 2020.
- S4 Fig. E.coli concentrations (cfu per 100 mL) in the different water and faecal sludge samples.
- S1 Table. Description of soils and rocks in Mekelle city and its surrounding areas
- S2 Table. Sampling and laboratory tests results of soils and weathered rocks in Mekelle city and its surrounding areas.
- S3 Table. Spring record and characteristics (13 springs) in Mekelle and its surrounding areas.

- S4 Table. Results of the quality tests of water samples from hand-dug wells (HDW) in Mekelle city and its surrounding area.
- S5 Table. Results of the quality tests of water samples from boreholes (BH) in Mekelle city and its surrounding area.
- S6 Table. Results of the quality tests of water samples from springs (SP) in Mekelle city and its surrounding area.
- S7 Table. Results of the quality tests of water samples from streams/river channels (ST) in Mekelle city and its surrounding area.
- S8 Table. Results of the quality tests and reliability analysis of water samples from seepages/runoff (SE) in Mekelle city and its surrounding area.
- S9 Table. Results of the quality tests of faecal sludge (FS) samples from Mekelle city and its surrounding area.

Author contributions

- Conceptualization and methodology: all authors.
- Analysis and Investigation: Kifle Woldearegay, James Ebdon, Diogo Gomes Da Silva.
- Original draft preparation: Kifle Woldearegay, James Ebdon, Diogo Gomes Da Silva.
- Writing, review and editing: Kifle Woldearegay, James Ebdon, Diogo Gomes Da Silva.
- Final review: all authors.
- All Authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by Economic and Social Research Council (ESRC), UK, for funding this research through a grant agreement: *ES/T008113/1*.

Acknowledgment

The first author is highly indebted to Prof. Lyla Mehta for her relentless support and encouragement during this research work. We would like to thank the Economic and Social Research Council (ESRC), UK for funding this research. The following organizations are acknowledged for all the support they have provided during the research work: Mekelle University, Tigray Bureau of Water Resources, Tigray Bureau of Health, Mekelle City Municipality Office, Mekelle Water Supply and Sewerage Office, and Tigray Environment Agency. We are grateful to all the stakeholders, experts and decision makers who participated in this project. The content of this paper is solely the responsibility of the authors and does not necessarily represent the official views of the financiers and organizations who supported this research.

Declaration of conflicting interests

The authors declare that they have no conflict of interest with respect to the research, authorship, and/or publication of this article.

References

1. WHO & UNICEF. Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities. New York: United Nations Children's Fund (UNICEF) and World Health Organization, 2019.
2. UN DESA. The Sustainable Development Goals Report: A Roadmap out of Crisis. United Nations publication issued by the Department of Economic and Social Affairs (DESA), 2022; ISBN: 978-92-1-101448-8.

3. Mitlin D (2015). Will urban sanitation “leave no one behind”?. *Environment and Urbanization*, 2015; *27* (2), pp.365-370.

4. McFarlane R, Horwitz, P, Arabena K, Capon A, Jenkins A, Jupiter S, et al. Ecosystem services for human health in Oceania. *Ecosystem Services, 2019; 39*, p.100976.MCM (Mekelle City Municipality) (2019). Annual performance report of the year 2019 and plan for 2020. Mekelle. 42pp.

5. Allen A, Dávila J D, Hofmann P. The peri-urban water poor: citizens or consumers? *Environment and Urbanization*, 2006; *18*(2), 333–351. https://doi.org/10.1177/0956247806069608

6. Mehta L, Marshall F, Movik S, Stirling A, Shah E, Smith A, Thompson J. Liquid Dynamics: challenges for sustainability in water and sanitation, STEPS Working Paper 6, 2007; Brighton: STEPS Centre.

7. Mehta L, Movik S. Liquid dynamics: challenges for sustainability in the water domain. *Wiley Interdisciplinary Reviews: Water*, 2014; *1*(4), pp.369-384.

8. Mehta L, Karpouzoglou T. Limits of policy and planning in peri-urban waterscapes: The case of Ghaziabad, Delhi, India. *Habitat International*, 2015; *48*, pp.159-168.

9. Nelson KL, Murray A. Sanitation for unserved populations: technologies, implementation challenges, and opportunities. *Annual Review of Environment and Resources*, 2008; *33*, pp.119-151.

10. Willetts J, Halcrow G, Carrard N, Rowland C, Crawford J. Addressing two critical MDGs together: Gender in water, sanitation and hygiene initiatives. Pacific Economic Bulletin, 2010; 25(1), 162–176.

11. Kvarnström E, McConville J. September. Sanitation planning-a tool to achieve sustainable sanitation. In Proceedings of the International Symposium on Water Supply and Sanitation For All, 2007; 27-28 September 2007.

12. Mara DD. Sanitation for all in periurban areas? Only if we use simplified sewerage. Water Science and Technology: Water Supply, 2005; 5(6), pp.57-65.

13. Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, Vol 114, 2016; P. 11-32, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2015.09.007.

14. Nikiema J, Cofie O, Impraim R. Technological options for safe resource recovery from fecal sludge. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE), 2014; 47p. (Resource Recovery and Reuse Series 2). doi: 10.5337/2014.228.

15. Otoo M, Drechsel P (Eds.). Resource recovery from waste: business models for energy, nutrient and water reuse in low- and middle-income countries. Oxon, UK: Routledge - Earthscan. 2018; 816p.

16. Gebrezgabher SA, Meuwissen MPM, Kruseman G, Lakner D, Oude Lansink AGJM. Factors influencing adoption of manure separation technology in The Netherlands. J Environ Manage, 2015; Mar 1;150:1-8. doi: 10.1016/j.jenvman.2014.10.029. Epub 2014 Nov 22. PMID: 25460418.

17. Otoo M, Drechsel P, Hanjra MA. Business models and economic approaches for nutrient recovery from wastewater and fecal sludge. In Drechsel, P.; Qadir, M.; Wichelns, D. (Eds), Wastewater: Economic asset in an urbanizing world, 2015; pp. 247-268.

18. Murray, A. & Buckley, C. (2010). Designing reuse-oriented sanitation infrastructure: the design for service planning approach. In *Wastewater Irrigation and Health, 2010.* Routledge; pp. 329-344.

19. Heymans C, Birhane G, Defere E, Eales K. Improve Urban and Small Towns Sanitation Services Delivery in Ethiopia: Messages and Lessons from Cities, Towns and the National Policy Dialogue. International Bank for Reconstruction and Development/The World Bank, 2017; A Synthesis Report. 55pp.

20. Tadesse T, Ruijs A, Hagos F. Household waste disposal in Mekelle city, Northern Ethiopia. Waste Management, 2008; 28: 2003–2012. doi:10.1016/j.wasman.2007.08.015.

21. Meinzinger F, Oldenburg M, Otterpohl R. No waste, but a resource: Alternative approaches to urban sanitation in Ethiopia. Desalination, 2009; 248: 322–329. doi:10.1016/j.desal.2008.05.071.

22. Tadesse T. Environmental concern and its implication to household waste separation and disposal: Evidence from Mekelle, Ethiopia. Resources, Conservation and Recycling, 2009; 53: 183-191.

23. Lohri RC, Camenzind EJ, Zurbrügg C. Financial sustainability in municipal solid waste management – Costs and revenues in Bahir Dar, Ethiopia. Waste Management, 2014; 34: 542–552.

24. Nigussie A, Kuyper TW, de Neergaard A. Agricultural waste utilisation strategies and demand for urban waste compost: Evidence from smallholder farmers in Ethiopia. Waste Management, 2015; 44: 82–93. http://dx.doi.org/10.1016/j.wasman.2015.07.038.

25. Damtew YT, Desta BN. Micro and Small Enterprises in Solid Waste Management: Experience of Selected Cities and Towns in Ethiopia: A Review. Polymer Journal, 2015; Vol. 1.

26. Girma Y, Terefe H, Pauleit S. Urban green spaces use and management in rapidly urbanizing countries: The case of emerging towns of Oromia special zone surrounding

Finfinne, Ethiopia. Urban Forestry & Urban Greening, 2019; 43: 126357. https://doi.org/10.1016/j.ufug.2019.05.019

27. Berhe AA, Aregay AD, Abreha AA, Aregay AB, Gebretsadik AW, Negash DZ, et al. Knowledge, Attitude, and Practices on Water, Sanitation, and Hygiene among Rural Residents in Tigray Region, Northern Ethiopia. Journal of Environmental and Public Health, 2020; Article ID 5460168, 9pp. https://doi.org/10.1155/2020/5460168.
28. Astatkie H, Ambelu A, Beyene EM. Sources and level of heavy metal contamination in the water of Awetu watershed streams, southwestern Ethiopia. Heliyon 7, 2021; e06385. https://doi.org/10.1016/j.heliyon.2021.e06385.
29. Wakejo WK, Meshesha BT, Habtu NG, Mekonnen YG. Anthropogenic nitrate contamination of water resources in Ethiopia: an overview. Water Supply, 2022; 22 (11), 8157. doi: 10.2166/ws.2022.377.
30. Tibebu S, Worku A, Shebeshi A, Kassahun E. Assessment of Liquid Waste Handling Practice of Addis Ketema and its Impact on Shankela River, Addis Ababa, Ethiopia. European Journal of Environment and Public Health, 2022; 6 (1), em0097. e-ISSN: 2542-4904.
31. Abera KA, Gebreyohannes T, Abrha B, Hagos M, Berhane G, Hussien A, et al. Vulnerability Mapping of Groundwater Resources of Mekelle City and Surroundings, Tigray Region, Ethiopia. Water, 2022; 14, 2577. https://doi.org/10.3390/w14162577.
32. Beker BA, Kansal ML. Complexities of the urban drinking water systems in Ethiopia and possible interventions for sustainability. Environ Dev Sustain., 2023; https://doi.org/10.1007/s10668-022-02901-7
33. ECSA (Ethiopian Central Statistical Agency). Population projection for major towns and cities of Ethiopia, 2019; Addis Ababa, Ethiopia.

34. TBoP (Tigray Bureau of Planning). Annual report on the performance of Tigray region for the year 2020, 2021. Mekelle. 23pp.

35. Alemayehu T, Mebrahtu G, Hadera A, Bekele DN. Assessment of the impact of landfill leachate on groundwater and surrounding surface water: a case study of Mekelle city, Northern Ethiopia. Sustain. Water Resour. Manag., 2019; 5, 1641–1649. https://doi.org/10.1007/s40899-019-00328-z.

36. Gebreyohannes F, Gebrekidan A, Hadera A, Estifanos S. Investigations of Physico-Chemical Parameters and its Pollution Implications of Elala River, Mekelle, Tigray, Ethiopia. Momona Ethiopian Journal of Science (MEJS), 2015; V7 (2): 240-257,CNCS, Mekelle University, ISSN:2220-184X http://dx.doi.org/10.4314/mejs.v7i2.7.

37. Tekle KA, Yoshida I, Harada M. Nitrate Concentration in Drinking Groundwater Wells of Mekelle, Ethiopia. Journal of Rainwater Catchment Systems, 2004; 10 (1): 1-5. doi https://doi.org/10.7132/jrcsa.KJ00003257771

38. Zenebe GB, Hussien A, Girmay A, Hailu G. Spatial analysis of groundwater vulnerability to contamination and human activity impact using a modified DRASTIC model in Elalla-Aynalem Catchment, Northern Ethiopia. Sustain. Water Resour. Manag., 2020; 6, 51. https://doi.org/10.1007/s40899-020-00406-7.

39. MoWI (Ministry of Water and Irrigation). Report on water supply coverage of cities and towns in Ethiopia, 2017. Addis Ababa. 46pp.

40. ENMSA (Ethiopian National Meteorology Service Agency). Daily rainfall data for Illala station, 2019; Mekelle, Ethiopia.

41. Berhane G. Engineering geological and Geotechnical investigations of Mekelle area. Tigray, Northern Ethiopia. M. Sc. Thesis Addis Ababa University, 2002, Addis Ababa. 163 pp.

42. Getahun E. Engineering geological and Geotechnical mapping of Northern part of Mekelle town, Northern Ethiopia. MSc. Thesis, Mekelle University, 2011, Ethiopia. 125 pp.

43. Woldearegay K. Geohazards in selected towns of Tigray, Ethiopia. A paper presented at a conference "Geohazards and development challenges in Sub-Saharan Africa", 2015, Addis Ababa, Ethiopia.

44. Foster SSD, Morris BL, Chilton PJ. Groundwater in urban development- a review in the linkages and concerns. In: Ellis, J.B. (ed) Impacts of urban growth on surface water and groundwater quality. IAHS Publication, 1999; 259: 3-12.

45. WWDE (Water Well Drilling Enterprise). Well completion report on Aynalem wells, 1998; Addis Ababa, Ethiopia.

46. Kessler J, Oosterbaan R. Determining hydraulic conductivities of soils. In: Drainage principles and applications. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1974; Vol. 16 (III): 253-296.

47. Hazen A. Discussion of "Dams on Sand Foundations" by A.C. Koenig, Transactions, ASCE, 1911; 73, 199-203.

48. Riggs CO. Chapter 15. Soil exploration at contaminated sites. In: Daniel D.E. (ed.). Geotechnical Practice for Waste Disposal, 1993. Chapman & Hall, London. ISBN 0 412 35170 6.

49. Issa SO, Khera RP. Geotechnology of Waste Management; PWS Publishing, 1998: Boston, MA, USA, 1998.

50. Allen A. Containment landfill; the myth of sustainability. Eng. Geol. 2001; 60: 3–19.

51. Yılmaz A, Atmaca E. Environmental geological assessment of a solid waste disposal site: a case study in Sivas, Turkey. Environ Geol, 2006; 50: 677–689. DOI 10.1007/s00254-006-0241-1.

52. Arjwech R, Somchat K, Pondthai P, Everett M, Schulmeister M, Saengchomphu S. Assessment of Geological, Hydrogeological and Geotechnical Characteristics of a Proposed Waste Disposal Site: A Case Study in Khon Kaen, Thailand. Geosciences, 2020; 10, 109. doi:10.3390/geosciences10030109.

53. Carevi´c I, Sibinovi´c M, Manojlovi´c S, Bato´canin N, Petrovi´c AS, Sreji´c T. Geological Approach for Landfill Site Selection: A Case Study of Vršac Municipality, Serbia. Sustainability, 2021; 13, 7810. https://doi.org/10.3390/su13147810.

54. Berhane G, Ayenew T. Soil and Rock characterization in the Mekelle area, Northern Ethiopia. International journal of earth science and engineering, 2010. Volume III, No. 6, pp. 762-774.

55. Gebrekrstos K. Investigation in to Engineering properties of Mekelle soils. M. Sc. Thesis. Addis Ababa University, 2005, Addis Ababa. 69 pp.

56. TBoWR (Tigray Bureau of Water Resources). Annual performance report for the bureau of water resources for 2006 and plan for the year 2007, 2017; Mekelle. 21pp.

57. MWSSO (Mekelle Water Supply and Sewage Office). Annual performance report on water supply service of Mekelle for the year 2022, 2022. Mekelle. 15pp.

58. Meinzer OE. Outline of groundwater hydrology with definitions, water supply paper 494, 1923; USGS, 71pp.

59. Inversin AR. Micro-hydropower source book. A practical guide to design and implementation in developing countries. NRECA (National Rural Electric Cooperative Association) International Foundation, 1986; Washington DC. 285pp.

60. MoWR (Ministry of Water Resources). Annual performance report for the year 2000 and plan for 2001, 2000. Addis Ababa. 61pp.

61. MoWR (Ministry of Water Resources). Annual performance report for the year 2005, 2006. Addis Ababa. 37pp.

62. MoWI (Ministry of Water and Irrigation). Report on water supply coverage of major cities in Ethiopia, 2015; Addis Ababa. 37pp.

63. MWSSO (Mekelle Water Supply and Sewage Office). Annual performance report of the water and sewage office for the year 2020 and plan for 2021, 2021; Mekelle. 24pp.

64. MCM (Mekelle City Municipality). Annual performance report of the year 2020 and plan for 2021, 2020; Mekelle. 31pp.

65. MCM (Mekelle City Municipality). Annual performance report of the year 2019, 2019. Mekelle. 26pp.

66. MCM (Mekelle City Municipality). Annual performance report of the year 2021, 2021. Mekelle. 26pp.

67. MWSSO (Mekelle Water Supply and Sewage Office). Annual performance report and plan for the year 2020 and plan for 2021, 2020; Mekelle. 12pp.

68. MWSSO (Mekelle Water Supply and Sewage Office). Annual performance report on water supply coverage of Mekelle for the year 2019, 2019; Mekelle. 16pp.

69. TBoWR (Tigray Bureau of Water Resources). Annual performance report of the bureau of water resources for the year 2018, 2018; Mekelle. 27pp.

70. TBoWR (Tigray Bureau of Water Resources). Annual performance report of the bureau of water resources for the year 2020, 2020; Mekelle. 16pp.

71. TBoWR (Tigray Bureau of Water Resources) (2021). Annual performance report of the bureau of water resources for the year 2021, 2021; Mekelle. 14pp.

72. MHO (Mekelle Health Office). A short report on the sanitation and hygiene condition of Mekelle city, 2018. Mekelle. 14pp.

73. Gagan M, Amit C, Avinash K, Ajendra K. Impact of industrial effluent on ground water and surface water quality-A case study of Dhampur region (UP), India. J. Chem. Pharmaceut. Sci. 2016; 9 (2), 709–713.

74. Hussien A. Hydrogeology of the Aynalem well field, Tigray, Northern Ethiopia. Unpublished MSc thesis, Addis Ababa University, 2000; Addis Ababa. 103 pp.
75. Eaton AD, Franson MAH. Standard methods for the examination of water & wastewater. 21st ed., 2005; Centennial ed. / Washington, DC, American Public Health Association.
76. Chapman D, Kimstach V. Chapter 3. Water Quality Variables. Chapter of book “Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring”. Second Edition. 1996; Deborah Chapman (Ed.). Published on behalf of WHO by F & FN Spon. UNESCO/WHO/UNEP, ISBN 0419215905(HB) 0419216006(PB). 651pp.
77. ISO 5815-1. Water quality - Determination of biochemical oxygen demand after n days. International Organization for Standardization, 2003; Switzerland. 22pp.
78. APHA (American Public Health Association). Standard Methods for the Examination of Water and Wastewater, 17th ed., 1989; Washington, D.C.
79. Jasim SY, Saththasivam J, Loganathan K, Ogunbiyi OO, Sarp S. Reuse of Treated Sewage Effluent (TSE) in Qatar. J. Water Process Eng., 2016; 11, 174–182.
80. Linsley RE, Franzini JB, Freyberg DL, Tchobanoglous GT. Water-Resources Engineering. Fourth Edition. 1992; McGraw-Hill, New York.
81. Fetter CW. Applied hydrogeology, 4th ed., 2001; Merrill publishing .Co. USA.
82. WHO (World Health Organization). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda, 2022, Geneva.
83. WHO (World Health Organization). Guidelines for the safe use of wastewater, excreta and greywater, 2006. Geneva.

84. USDA (U.S. Department of Agriculture). Diagnosis and improvement of saline and Alkaline soils. Agriculture handbook 60, 1954; L.A. Richars Editor, Washington, D.C., 160pp.

85. Wilcox LV. Classification and Use of Irrigation Waters, U.S. Department of Agriculture Circ. 969, 1955.

86. Beyth M, Shachnai E. Hydrogeology of Mekelle area. Hydrogeological Note 1970/1, Geological survey of Ethiopia, 1970; Addis Ababa.

87. Chernet T, Eshete G. Hydrogeology of the Mekelle area, Ethiopian Institute of Geological Surveys, Ministry of Mines and Energy, 1982; Addis Ababa.

88. EGS (Ethiopian Geological Survey). Hydrogeological map of Northern Ethiopia, EGS, 2002. Addis Ababa.

89. Zeray T. Evaluating the potential of the Aynalem well field for the conjunctive use of surface and groundwater. MSc. Thesis, Mekelle University, 2007; Ethiopia. 126pp.

90. EGS (Ethiopian Geological Survey). Geological map of Mekelle basin (Sheet ND 37-11). Geological Survey of Ethiopia, 1971. Addis Ababa, Ethiopia.

91. TBoWR (Tigray Bureau of Water Resources (2006). Status of Mekelle water supply system, Mekelle, TBoWR, 2006. 33pp.

92. TBoH (Tigray Bureau of Health) (2018). Annual performance report of the Tigray Bureau of Health for the year 2017. TBoH, 2018, Mekelle. 27pp.

93. TBoH (Tigray Bureau of Health) (2022). Report on the status of sanitation and hygiene of major towns in Tigray region. TBoH, 2022; Mekelle, 21pp.

94. TBoH (Tigray Bureau of Health) (2019). Annual report on the status of sanitation and hygiene of Tigray region. TBoH, 2019; Mekelle, 46pp.

95. WHO & UNICEF. Progress on household drinking water, sanitation and hygiene 2000-2020: Five years into the SDGs. Geneva: World Health Organization (WHO) and the United Nations Children’s Fund (UNICEF), 2021; Licence: CC BY-NC-SA 3.0 IGO.
96. MCM (Mekelle City Municipality) (2022). A short report on status of Water, Sanitation and Hygiene in Mekelle city. MCM, 2022, Mekelle. 17pp.
97. Pincus LI. Practical Boiler Water Treatment, 1962. McGraw-Hill, New York.
98. Alemayehu T, Leis A, Dietzel M. Environmental isotope and hydrochemical characteristics of groundwater in central portion of Mekelle sedimentary outlier, northern Ethiopia. Journal of African Earth Sciences, 2020; 171: 1-10. https://doi.org/10.1016/j.jafrearsci.2020.103953.
99. Gehm HW. Neutralization with up-flow expanded limestone bed. Sewage Works J., 1944; 16:104.
100. Reidl AL. Neutralization with up-flow limestone bed. Sewage Works J., 1947; 19:1093.
101. Rose C, Parker A, Jefferson B, Cartmell E. The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. Critical Reviews in Environmental Science and Technology, 2015; 45 (17), 1827–1879. https://doi.org/10.1080/10643389.2014.1000761.
102. Chapman D, Kimstach V. Selection of Water Quality Variables. Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environment Monitoring, Chapman Edition, 2nd Edition, 1996; E and FN Spon, London, 59-126.
103. Wilcox (1955) Wilcox, L.V. (1955) Classification and Use of Irrigation Water. US Department of Agriculture, Circular 969, Washington DC.
104. Crites RW, Meyer EL, Smith RG. Process Design Manual for Land Treatment of Municipal Wastewater. U.S. Environmental Protection Agency, 1981. EPA 625/1-81-013.

105. Halog A, Anieke S. A Review of Circular Economy Studies in Developed Countries and Its Potential Adoption in Developing Countries. Circular Economy and Sustainability, 2021; 1:209–230. https://doi.org/10.1007/s43615-021-00017-0.

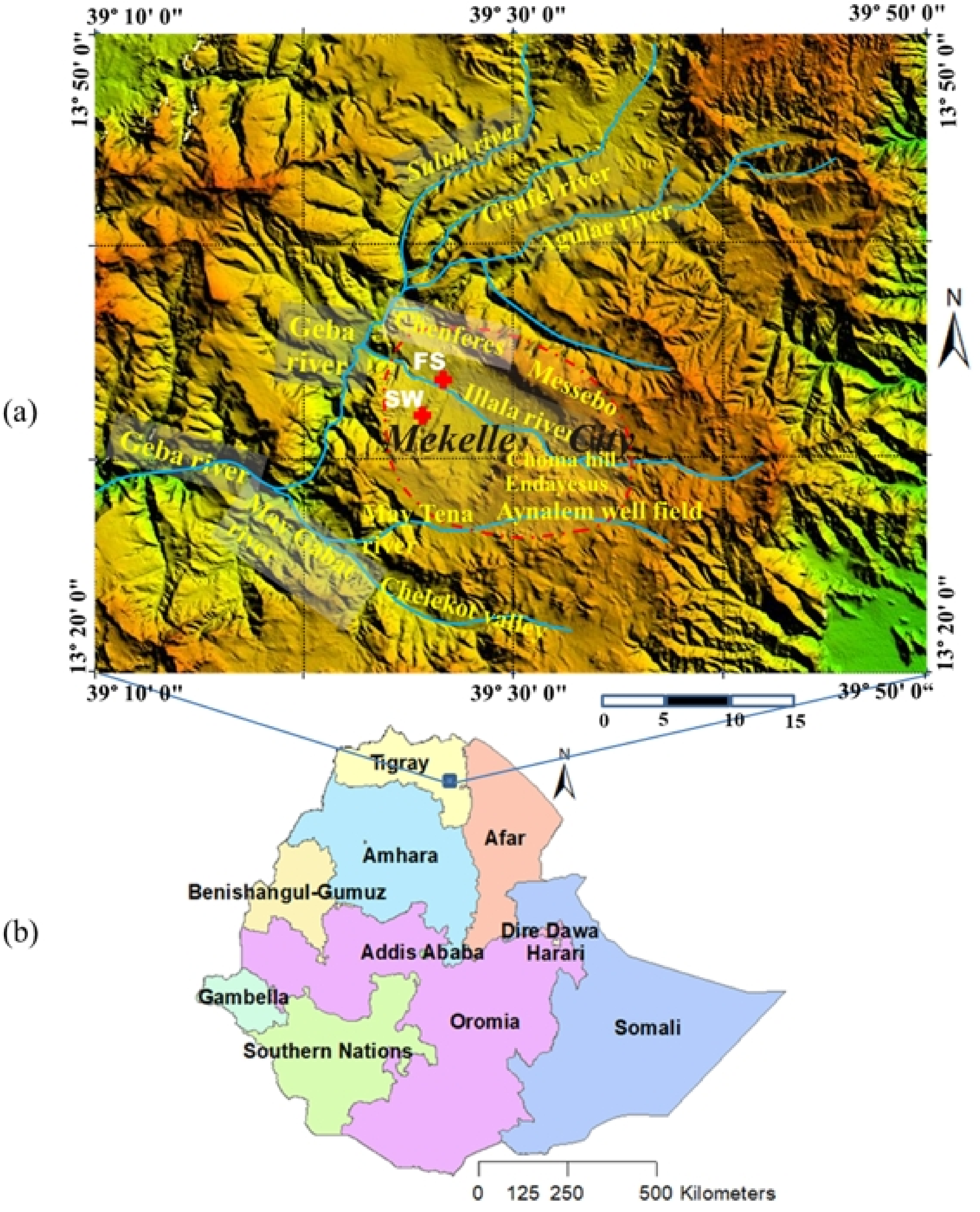
106. Doblas-Reyes FJ, Sörensson AA, Almazroui M, Dosio A, Gutowski WJ, Haarsma R, et al. Linking Global to Regional Climate Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, 2021; Cambridge, United Kingdom and New York, NY, USA, pp. 1363–1512, doi:10.1017/9781009157896.012.

107. Frank B., Delano D. & Caniglia, B. (2017). Urban Systems: A Socio-Ecological System Perspective. Sociology International Journal. 1.10.15406/sij.2017.01.00001.

108. Smid M, Costa AC. Climate projections and downscaling techniques: a discussion for impact studies in urban systems, International Journal of Urban Sciences, 2018; Taylor & Francis Journals, vol. 22(3), pages 277-307, July.

109. Dodman D, Hayward B, Pelling M, Castan Broto V, Chow W, Chu E, et al. Cities, Settlements and Key Infrastructure. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, 2022; Cambridge, UK and New York, NY, USA, pp. 907–1040, doi:10.1017/9781009325844.008.

110. Lin SH, Huang X, Fu G, Chen JT, Zhao X, Li JH, Tzeng GH. (2021). Evaluating the sustainability of urban renewal projects based on a model of hybrid multiple-attribute decision-making. Land Use Policy, 2021; 108, 105570.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Suluh river
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Illala river
Mekelle City
Choma hill
Endayesus
Aynalem well field
May Tena river
Geba river
May Gabat river
Chelekot valley
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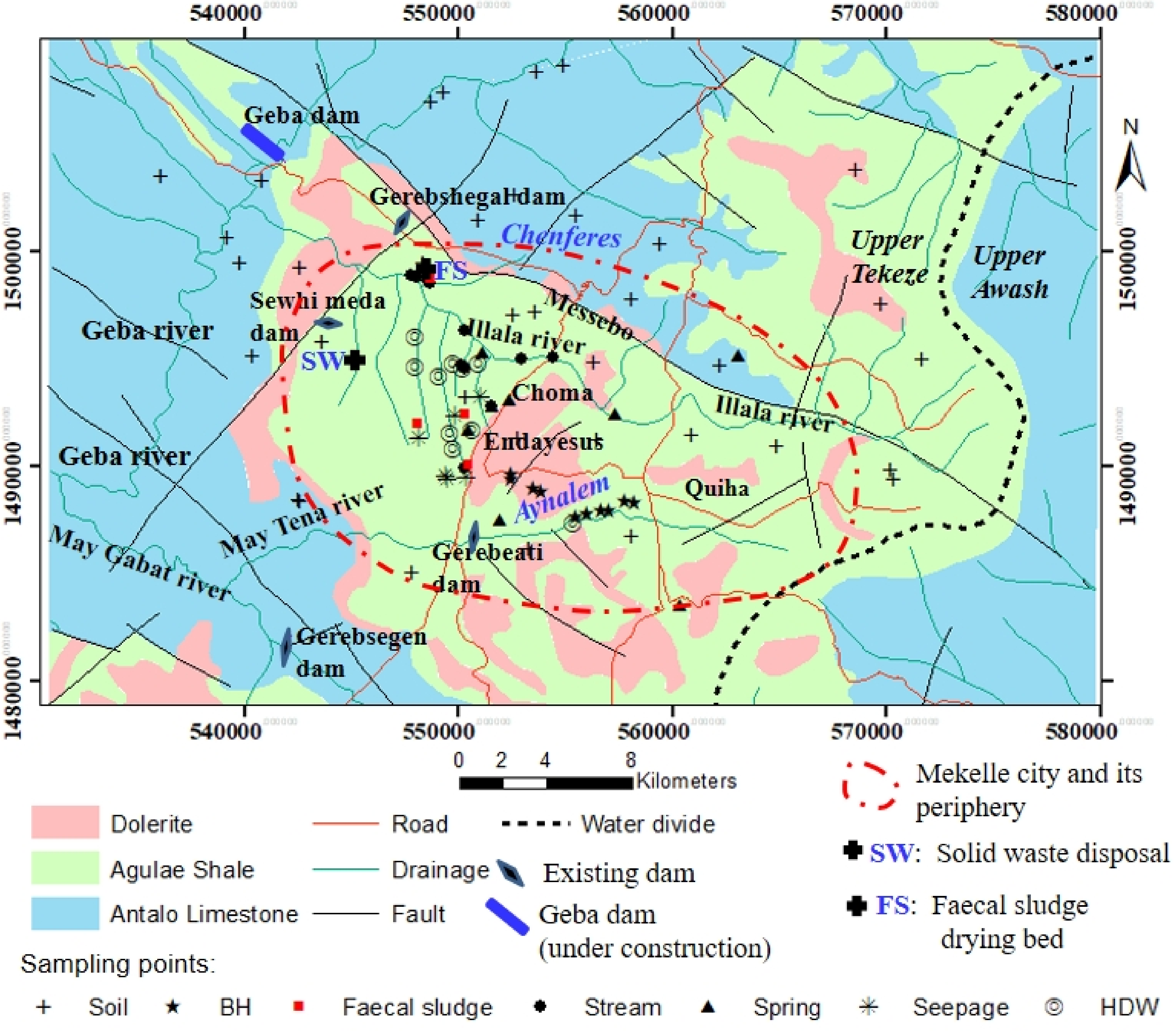
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Quiha
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Agulae Shale
Antalo Limestone
Road
Drainage
Fault
Water divide
Existing dam
Geba dam (under construction)
Mekelle city and its periphery
SW: Solid waste disposal
FS: Faecal sludge drying bed
Sampling points:
+ Soil
★ BH
■ Faecal sludge
● Stream
▲ Spring
✳ Seepage
◎ HDW


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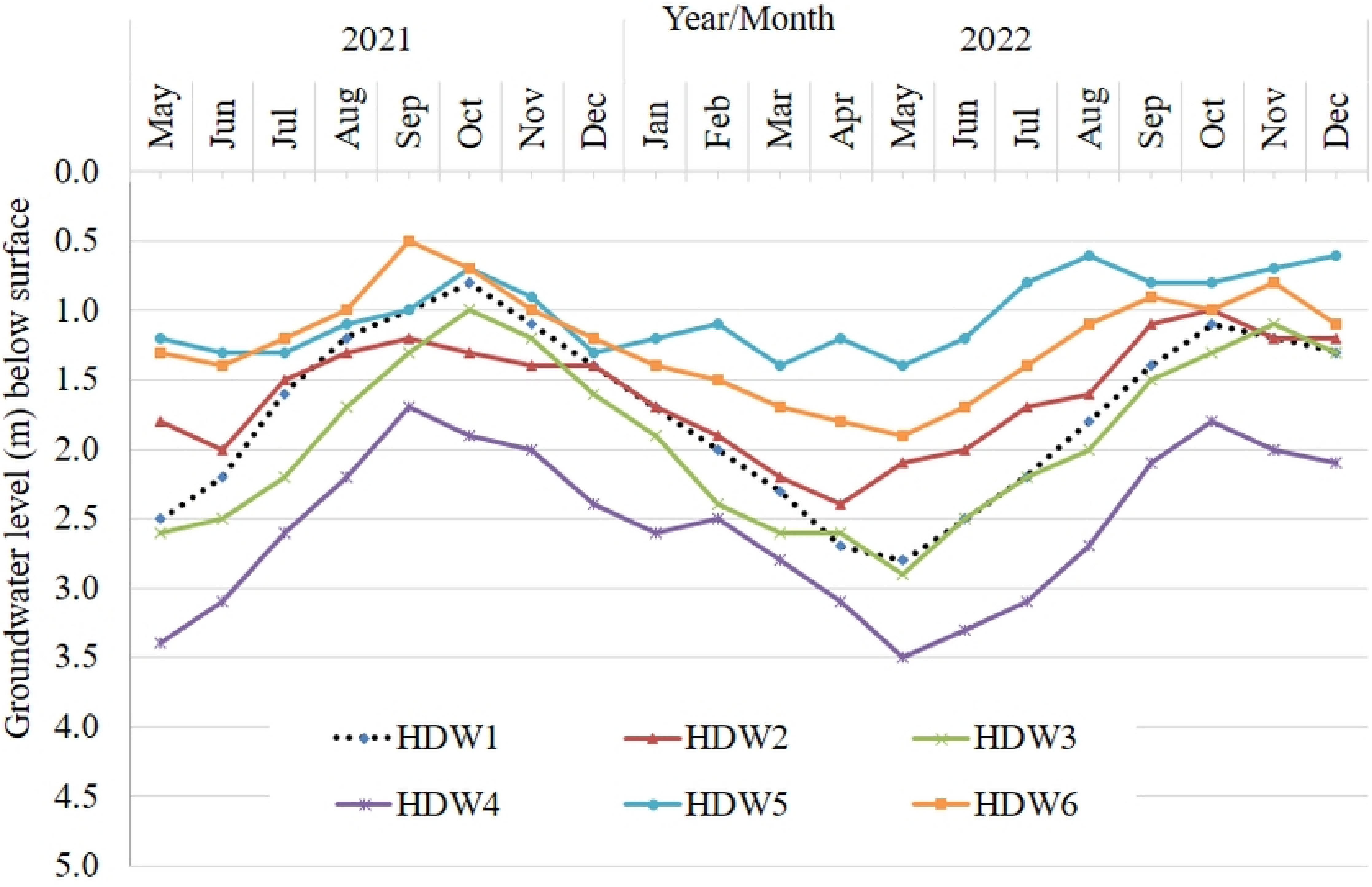
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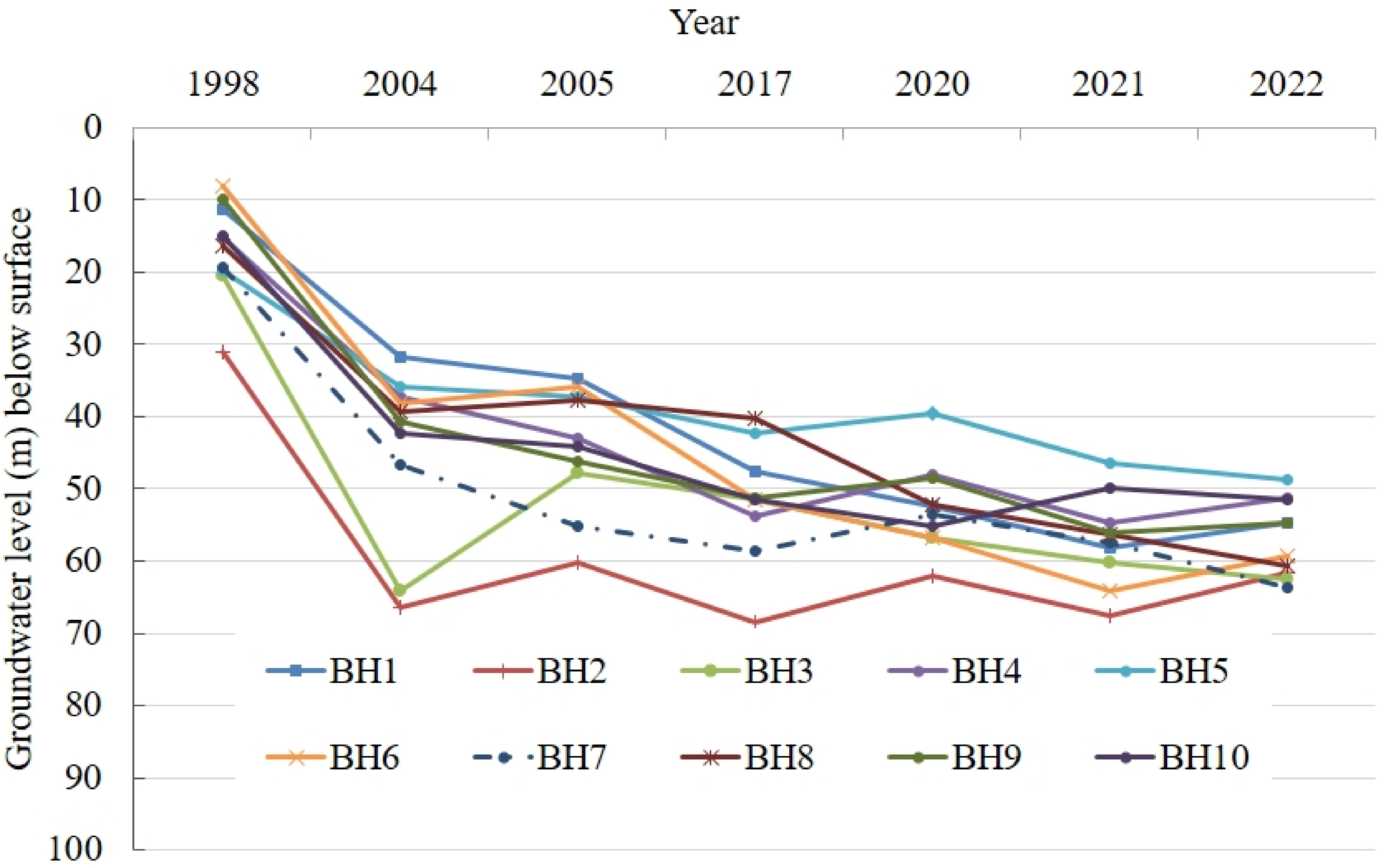
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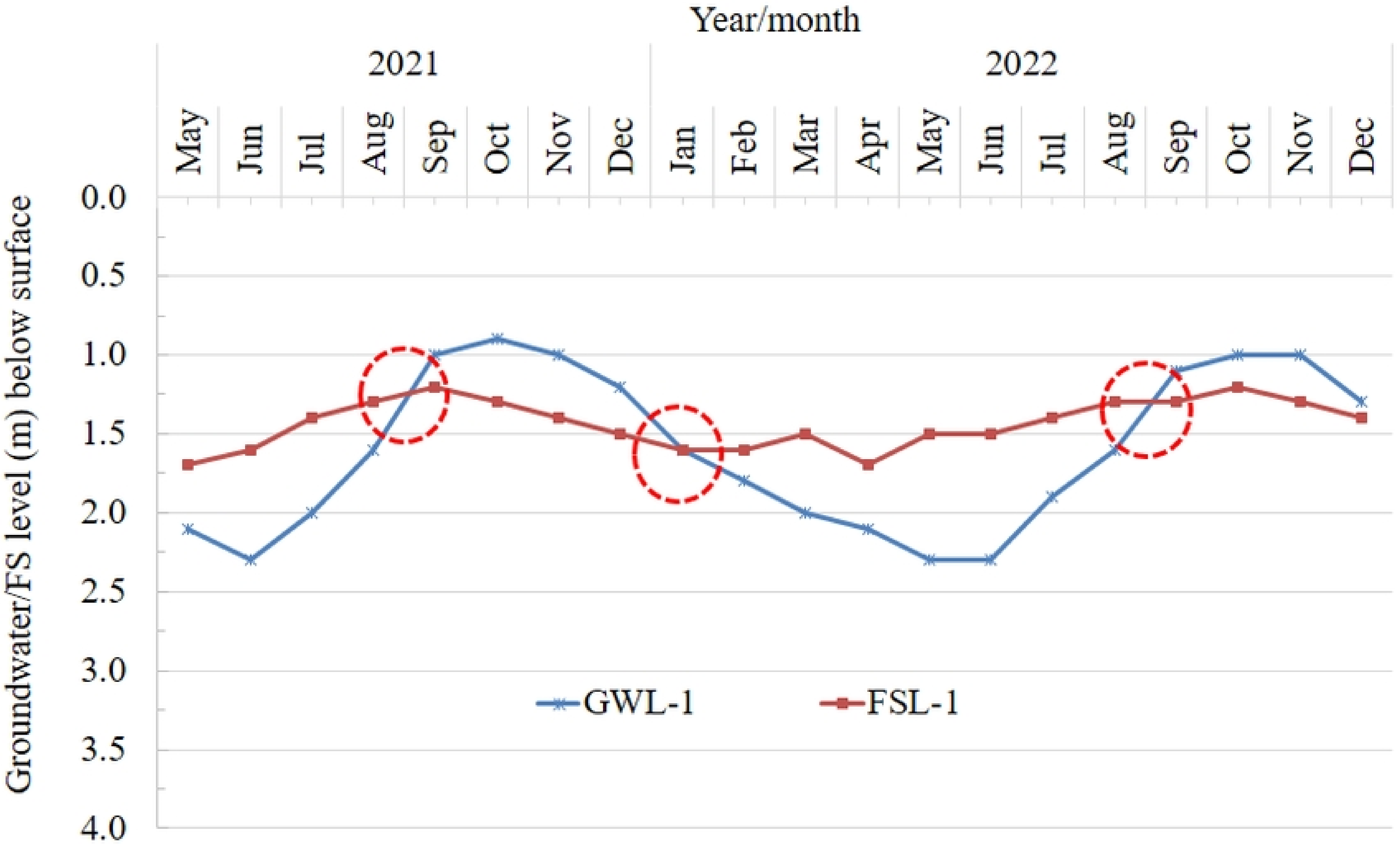

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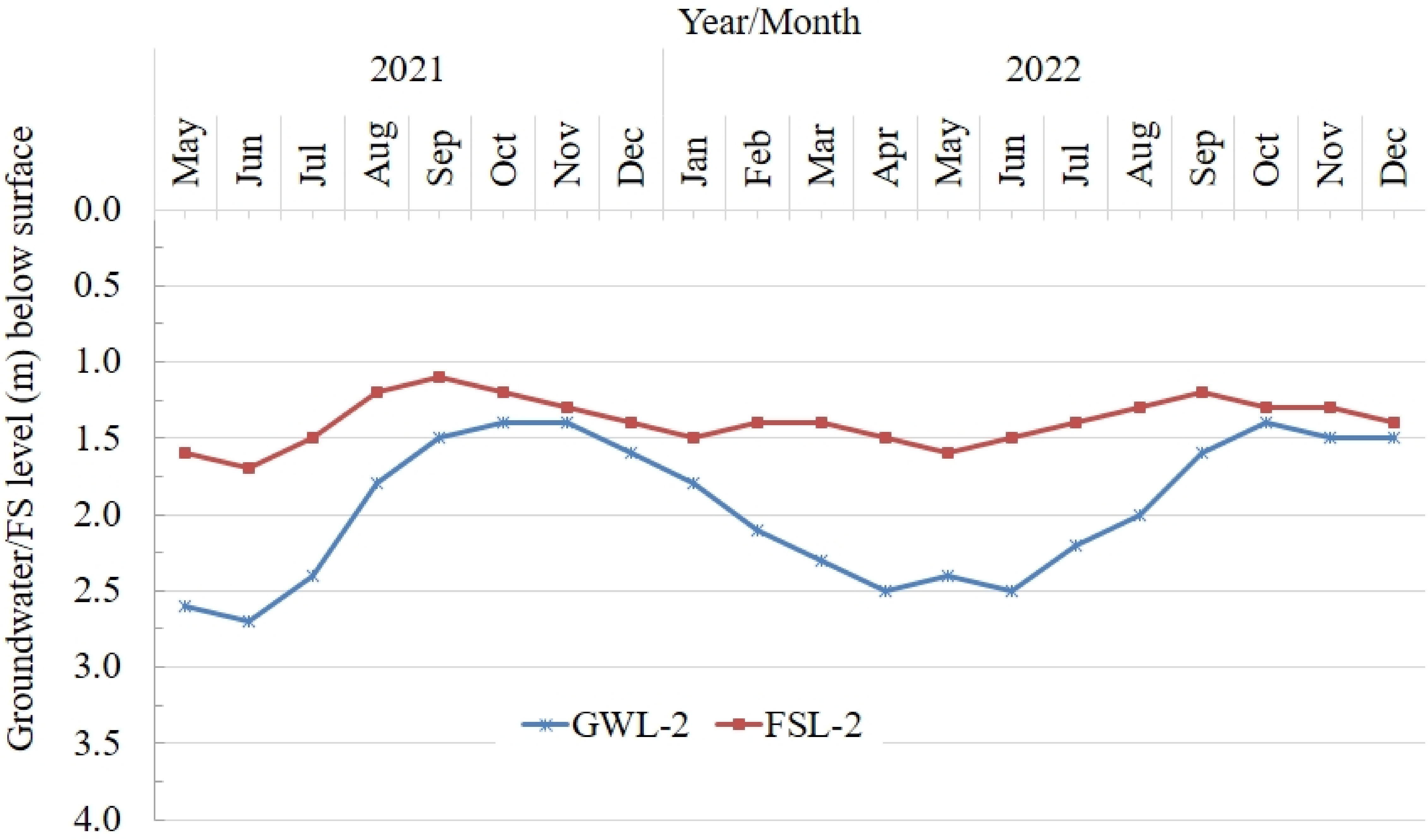
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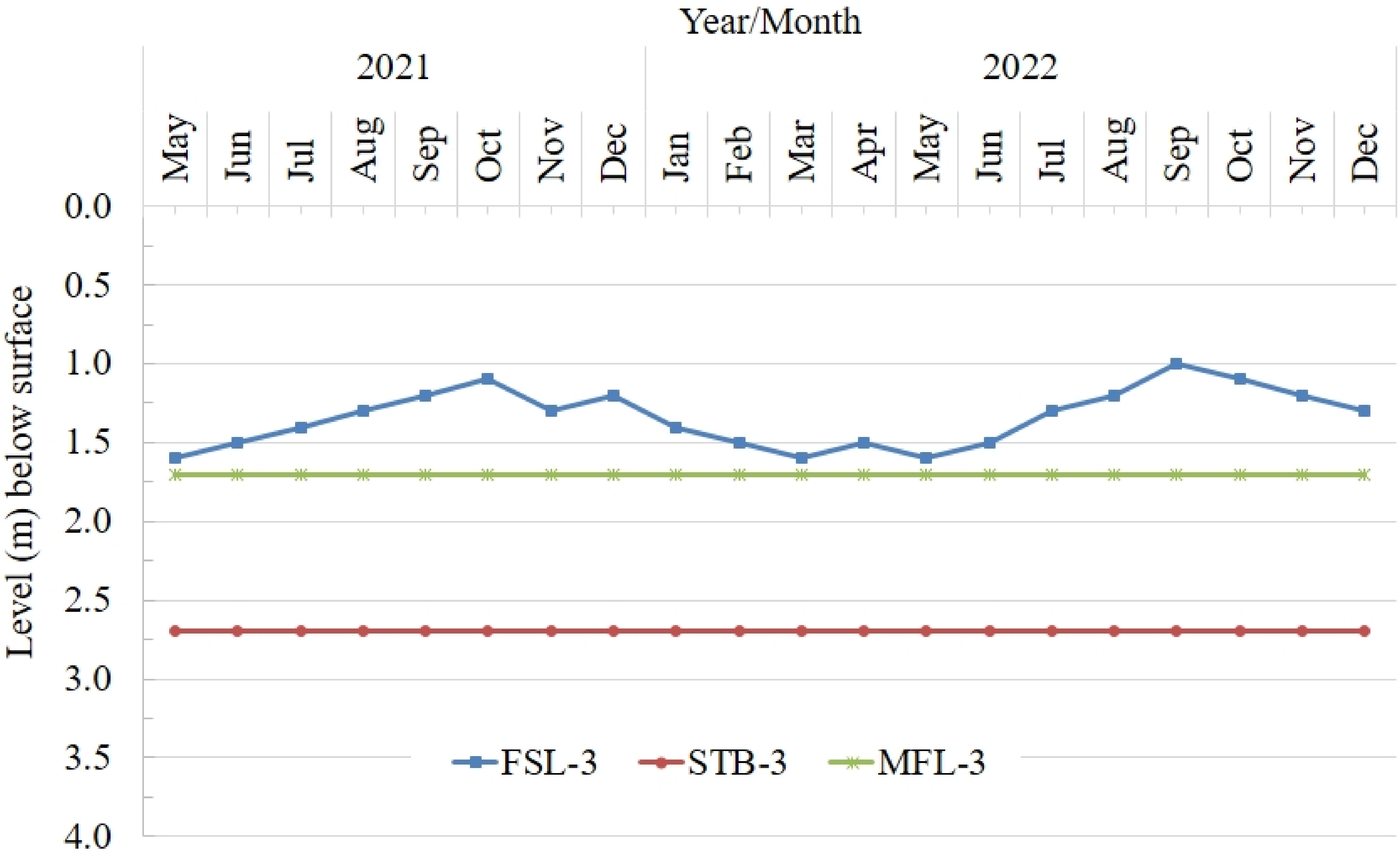
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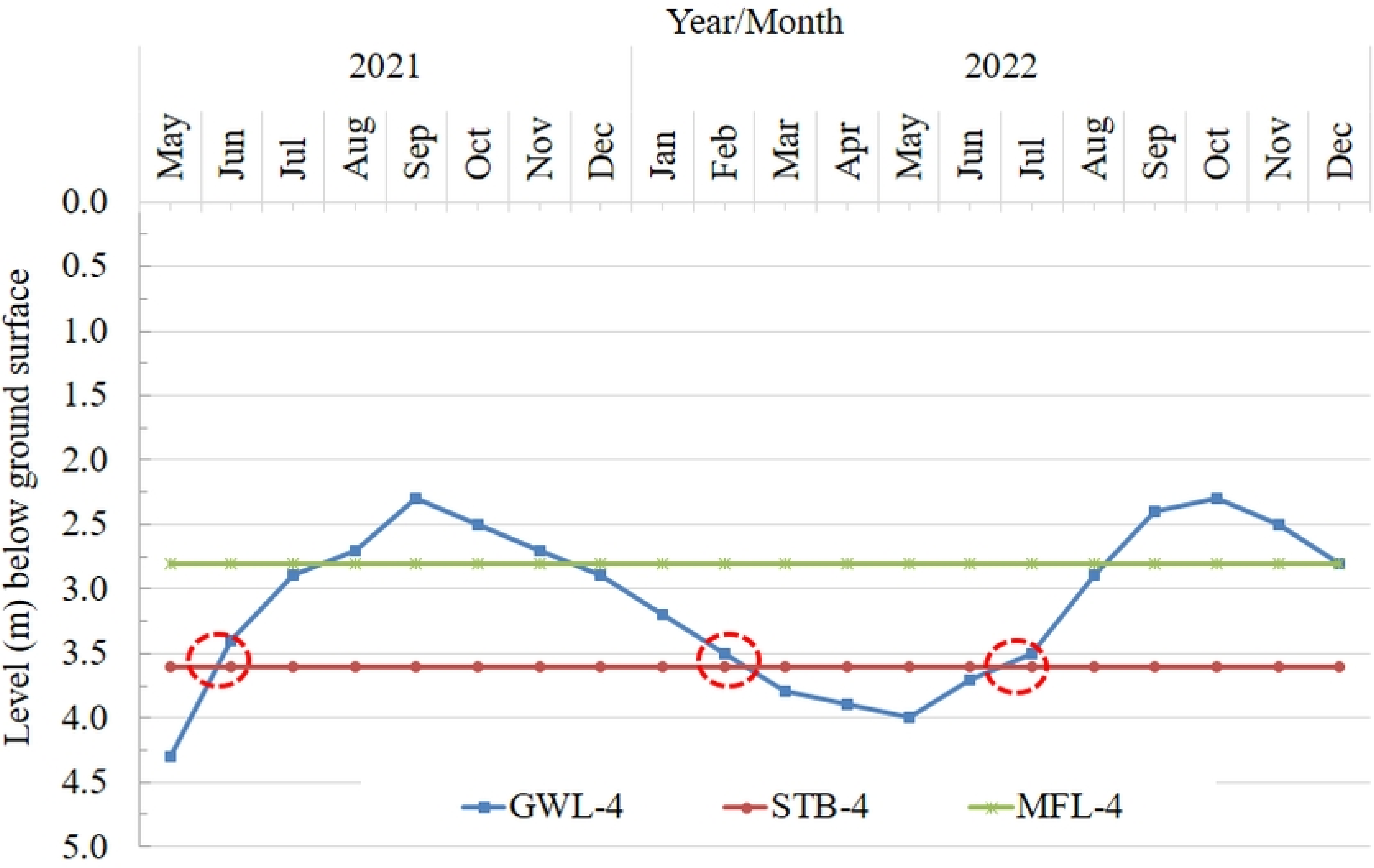
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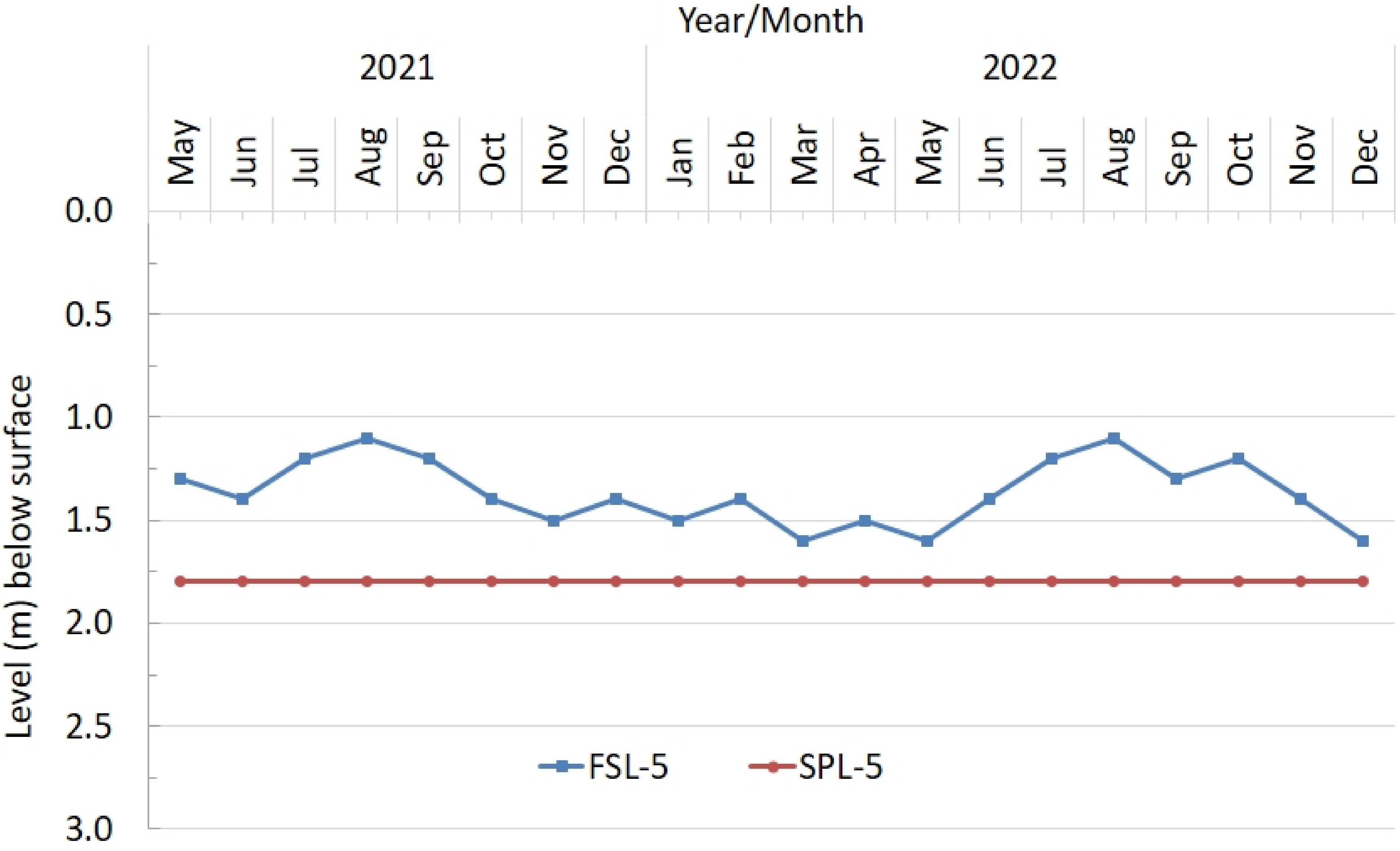

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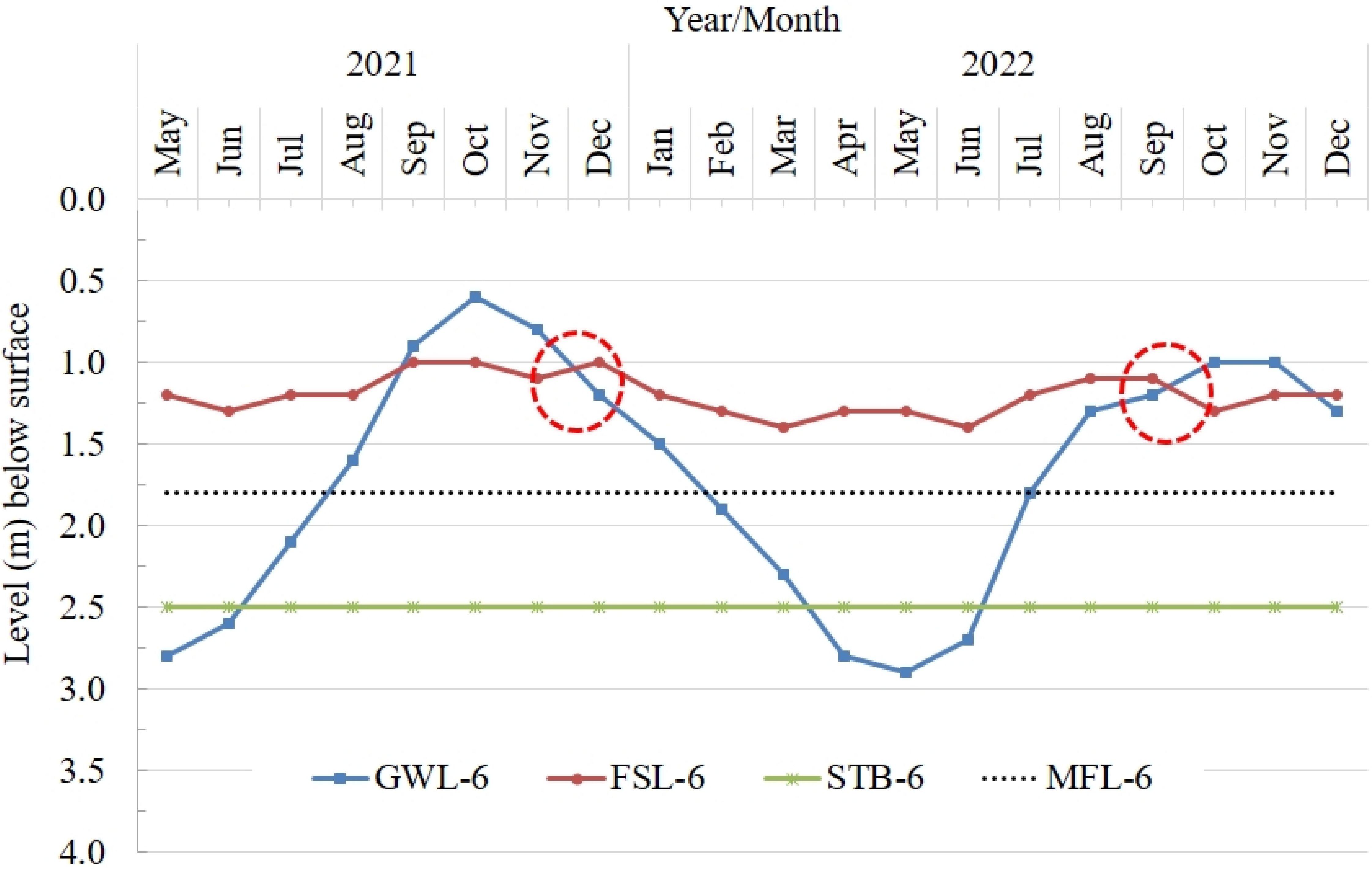
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Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Level (m) below surface
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
GWL-6
FSL-6
STB-6
MFL-6


(a)
(b)
(c)
(d)