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CHALLENGES OF GROUNDWATER DEVELOPMENT FOR TOWNS AND BIG CITIES WATER SUPPLY IN RIFT VALLEY AREAS

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ABSTRACT

The experiences of the last 30 years developed an understanding in the Addis Ababa Water Utility that groundwater sources are not fully dependable for such a big city. Notwithstanding this, additional wells and well-fields are being developed especially in the last 10 years to meet the ever increasing demand. The Akaki well-field was initially designed for an abstraction rate of up to 35,000 m3/day for 20 years until 2020 though the current abstraction rate is nearly ten-fold. The current developments are only demand driven irrespective of safe and sustainable utilization. What is making things worse is the rise of other water competing demands for irrigation projects in adjacent well-fields. The present water supply coverage of the Addis Ababa city is not more than 50%. The situation in other urban centers in the Upper Awash basin is not different. Conceptual modelling, time series well water level measurements and operational assessments showed that the aquifer systems are not uniform and dotted with many volcanic flow barriers; there is sharp decline of water table (up to 70 meters since 2000) in some well-fields and the decline is propagating upstream of the Akaki well-field. Moreover, the excessive and uncontrolled pumping is impacting regional groundwater table. Topographic and technical issues are hampering upstream water distribution, and the once exemplary hundreds of wells are now abandoned. The frequent tapping of thermal and high fluoride water is another complication. Unless proper intervention is devised, grave environmental problems are likely to come in the near future.

Contribution/Originality: This study is one of the few studies which investigated the time series well water evolutions in the Upper Awash and Akaki catchments and well water operational difficulty in Akaki catchment.

1. INTRODUCTION

The Upper Awash River Basin is located in central Ethiopia on the western edge of the Main Ethiopian Rift (MER). The basin is the most densely populated and industrialized regions of the country. It has emerging towns as well as small, medium and large cities. Ginchi, Holeta, Addis Alem, Olonkomi, Burau, Legetafo-Legedadi, Sendafa, Sebeta, Asgori, Teji, Tefki, Bishoftu, Dukem, Tole, Tulu Bolo and Mojo are some of the small and medium towns which have 15,000 to 100,000 inhabitants. The biggest urban center in the basin is the capital Addis Ababa City and the seat of the African Union hosting around 4,794,000 people [1]. The Akaki Catchment is situated to the north east of the Upper Awash basin and it is the place where Addis Ababa city is located.

Except Addis Ababa and Tulo Bolo, all the other towns get their water supply fully from groundwater. Even 65% of the water supply to Addis Ababa city is coming from groundwater [2]. For the city of Addis Ababa, the contribution of groundwater has been increasing from 10% some 15 years ago to the current 65% due to population pressure, rapid urbanization and inability to construct additional reservoirs to tap surface water sources.

The remaining 35% of the water supply to the city is coming from two dams namely, Gefersa (30,000 m^3 per day) and Legedadi (195,000 m^3 per day) [2]. Construction of additional surface water reservoirs has been hampered by fund limitation, environmental and social issues.

Despite conjugative use of surface and groundwater and the continuous groundwater-based funding of the sector for the last 15 years, the Addis Ababa city's water supply coverage cannot be raised more than 50%. To cover the deficits and cope up with the increasing water demand, the utility has been developing well fields in old (Akaki) and new (Legedade, Ayat and Sebeta) wellfield areas.

In spite of these endeavours, now competition for water supply is emerging between surrounding towns and the city and between surrounding irrigation schemes and the city's sources. Majority of the existing and planned water supply sources of the city are located outside the city's periphery where the corresponding authorities have different plans and priorities.

On top of these, the existing dams are being silted up and the pocket wells and well fields are rapidly depleting. Review of the last 30 years' groundwater level measurements in the Akaki wellfield showed that water level decline in the major well field ranges from 50 meter in the centre to 90 meters towards the boundary.

Groundwater development in Akaki catchment is in its third and probably towards peak stage though there may be a few years until all the catchment is dotted with maximum depth wells. The first stage of development was until the beginning of 1930's where springs and hand dug wells were the major sources to the city of Addis Ababa [3].

A major shift to surface water occurred between 1940 to mid-1970's and two dams were constructed that temporarily quietened groundwater development. The second phase exploration of relatively deeper groundwater started in the 1980's that culminated in the implementation of Akaki well field in early 2000. A sub component of this phase included the development of wells up to 250 meters deep all over the Akaki catchment until 2009.

The current phase is the third stage where well depths of as deep as 700 meters are being drilled. Development and transmission of well water from Adda and Becho plains to Addis Ababa is complicated both technically and socially.

With regard to the Akaki catchment, despite the seemingly promising potential, the frequent tapping of thermal and fluoride rich well waters below 500 meters' depth in the major source areas; fast declining of well yields from initial hundreds of litres per second to a half in just a couple of years, the risk of contamination with town waste effluents and the soaring demand of the city may gradually force the utility to look for an additional surface water source. There is also a huge disparity between hydrogeological conditions on one hand, and operational feasibilities and socio-environmental circumstances on the other hand.

In connection with the aim of this study, it is intended to give first-hand information on the challenges of supplying big cities with groundwater in Upper Awash and Akaki catchments and draw the attention of all stakeholders to find alternative solution for the looming water supply problem. To study these, conceptual modelling of the aquifer systems, monthly water level measurements and assessment of the water supply current operation were assessed.

2. MATERILAS AND METHODS

2.1. Scope of the Study

Currently, transient groundwater flow modelling and management study is going on the Upper Awash Basin and Akaki Catchment where all of the developments mentioned under Section 1 are located. The aim of the modelling is to visualize the temporal response of groundwater flow to stresses, understand the behaviour of flow terms and propose development plans. Hence, some of the data used in the modelling and the analysis results are used in this study.

Reviews were conducted on several studies conducted mainly related to groundwater development. Among others, the most important ones are [4-12]. Except the study by Water Works Design and Supervision Enterprise [11]; Water Works Design and Supervision Enterprise [12] nearly all of the previous studies focused on the shallow, perched and fractured aquifers with a depth of less than 250 meters. The works of Water Works Design and Supervision Enterprise [11]; Water Works Design and Supervision Enterprise [12] explored the groundwater occurrence up to 700 meters. These data assisted in conceptualizing the aquifer systems in both basins, preparing cross-sections, and formulate groundwater levels shown in section 3.1.

Additional reviews also included other geological, hydrogeological, and inter-basin groundwater transfer studies conducted by different authors [13-16]. These researchers from universities are less related to actual groundwater developments but their input was important in the study area conceptualization. Furthermore, the Geo-matrix [8]; Seureca [9] studies were helpful in understanding the operational difficulty of well management (section 3.3)

On top of these, time series recharge and abstraction rates (section 3.1.5), monthly and long-time groundwater levels (section 3.2) are collected and operational cases studies are documented. Some results of the groundwater flow modelling (section 3.1.5) are included to conceptualize the hydrogeological framework.

The objective of this study is the thus to identify the extent and sizes of the aquifer systems, assess long term and seasonal variation of groundwater tables and review operational feasibility of the groundwater fields. The study tries also to show the major challenges of groundwater development in the area.

2.2. Site Description

The Akaki catchment covers a total area of 1,464 km^2 and is located in the northeastern edge of the Upper Awash Basin which in turn is situated at the western edge of the Main Ethiopian Rift. The former catchment is bounded within 8^0 46'to 9^0 14' N latitude and 38^0 34' to 39^0 04' E longitude. The northeastern, northern and northwestern volcanic mountain ranges widely form the watershed divide of the Akaki and Awash basins with Blue Nile river basins. The city Addis Ababa covers most of the central and northern portion of the Akaki catchment Figure 1.

The Upper Awash basin, on the other hand, is bounded with a series of volcanic mountains that demarcate watershed divides with the adjacent basins. The basin is located in the western edge of the Main Ethiopian Rift (MER) and lies between longitudes 37^0 57' 06 and 39^0 17' 24" East and latitudes 8^0 09' 02 and 9^0 18' 12". The basin shares borders with Middle Awash Basin in the East and South East, the Gibe Basin in the West and South West, the Blue Nile basin in the North and North West and the Rift Valley Lakes basin in the South.

Both catchments form down sloping terrains that drop thousands of meters to the south and south east towards the rift floors. This gradient favors the occurrence of many springs at different elevation and develops relatively shallow groundwater level in the Adaa and Becho plains Figure 2.

The landforms of both catchments are the results of different episodes of Cenozoic volcano-tectonics, denudation and later erosion. It is because of these that the basins are marked by different size volcanic peaks, caldera and crater sinks. The mountainous areas in the northern portion of both basins are characterized by ragged, sloppy and deeply weathered and fractured volcanic formations which favored formation of dense drainage networks.

Demographically, both basins are the densely populated and highly industrialized areas of the country. For instance, the population of Addis Ababa city has grown from 392,000 in 1950 to 4,793,699 in 2020 [1]. Moreover, around 12.3 million people reside in the Upper Awash Basin which is 12% of the country's population living in nearly 1% of the area.

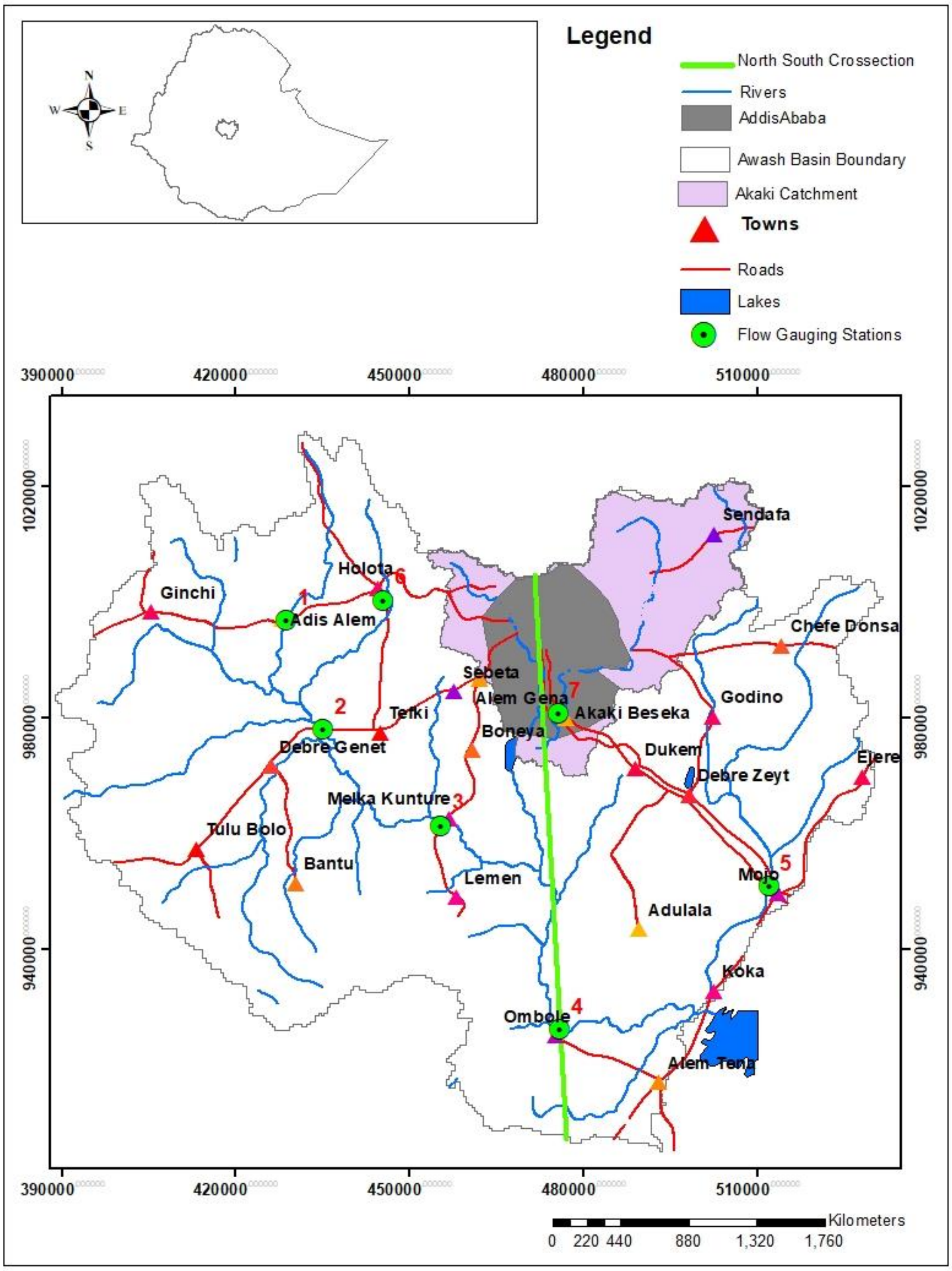

Figure-1. Location map of the study areas.

Source: Extracted from ARC GIS map of Ethiopia and Arc SWAT watershed delineator, Assefa Eyassu, 2020.

With regard to the geology of both catchments, it is manifested by Pre-Rift, Syn-Rift and Main Rift Volcanic Units [15, 17-20]. Hydro-geologically, in this study, these are categorized into two litho-stratigraphic units as pre-rift Ethiopian Volcanic Plateaus and the Main Rift Volcanic Units.

The Pre-Rift units are Upper Oligocene to Late Miocene plateau flood basalts and shield volcanos whereas Main Ethiopian Rift Volcanic is expressed by Late Miocene, Pleistocene to Holocene products of volcanic rocks of welded to partially welded pyroclastic flows with basalt, rhyolite and trachytic lava domes. Young central volcanoes are the manifestation of the Main Rift Units.

The rainfall patterns of the study areas are distinguished by two separate seasonal climatic displays: the rainy season which stretches from June to September, contributing much of the annual precipitation and the dry period which embraces the month from October to May with a minimal rainy time in March and April well understood for its inconsistency.

Temperature and rainfall show strong altitudinal dependences. Precipitation decreases from North and North West to South and South East. The opposite happens to temperature. Mean annual temperature is about 15.7 C^0 in the highlands and around 22.3 C^0 in the rift floor. The average annual rainfall ranges from around 905.4 mm in the rift floor to 1,238.2 mm in the northern highlands [21]. Figure 1 displays the location of the two study areas, the Addis Ababa city and other towns. Table 1 below displays annual average precipitation and temperature for the study areas.

Table-1. Annual rainfall (mm/year) and Temperature (C^0) of Akaki and Upper Awash Basins.

Area		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov.	Dec	Total
Akaki Basin	Rain Fall	6.6	45.0	60.4	127.4	68.6	131.7	206.5	234.2	130.3	31.2	0.3	2.6	1044.7
	Temp	16.6	17.6	18.4	18.6	18.9	17.5	16.2	16.4	16.6	16.6	15.9	15.8	17.1
Upper Wash Basin	Rain Fall	18.4	22.6	59.3	66.3	68.8	124.6	239.0	237	113.6	28.0	18.8	15.1	1,011.1
	Temp	18.7	20.3	20.4	20.6	20.7	20.2	18.8	18.7	19.5	18.6	18.5	17.6	19.3

Source: Tenalem [21].

In addition to recharges from precipitation, there is also surface and groundwater influx from upstream highlands to the rift escarpment and floors. The study areas comprise both recharging and discharging zones. The promising rainfall and recharge conditions favored presence of at least ten perennial streams in the high and mid lands eight of which finally converge into Awash River in the rift floor before leaving the basin.

In connection with hydrochemistry, the water in the catchment passes through different hydro-chemical evolutions. Precipitated water infiltrates down by interacting with the different minerals mixing and evolving before it reaches the discharging zones along the flow paths. The hydrolysis reaction in the highlands results in silicate dissolution that frees up many of the major cations and anions. The water quality changes from Ca-Mg-HCO_3 to dominantly Na-HCO_3 type towards the rift. The salinity also increases towards the rift floor.

This weathering process creates thick and fertile soil mass that suits agriculture in the mid and low land areas of the study area. The main land use in the basins is controlled by intensively cultivated, moderately cultivated, open shrub land, open woodland, open grassland, urban area and water body.

2.3. Approach and Methodology

Several climatic, metrological, hydrological, hydrogeological, and geological information were collected and observations made to develop the preliminary conceptual view of the Upper Awash and Akaki basins. Some of the results of the previous studies on time series recharge assessment [21] and the ongoing transient modeling were used. Moreover, two types of temporal groundwater level data collection Figure 3 and Figure 5 were done to assess the temporal variability of the groundwater level. On top of these, cases on the operational difficulties of the borehole based groundwater developments are assessed.

The first method of temporal groundwater level monitoring comprised monthly well water level measurement conducted from July 2018 to June 2019 on wells which represented the existing wells in the Upper Awash and Akaki catchment. The second method is the review of water level measurements taken in 1990 and 2000 by BCOM-Seureca [6, 7] and 2018 by this study. On top of these, seasonal well abstraction data were collected for wells in both basins.

The data gathered on groundwater level, recharge, aquifer property and thickness, hydrogeology, study area geometry, aquifer boundary and flow directions helped to prepare the conceptual model and cross-sections across the two basins Figure 2. The study areas' boundaries were delineated by Arc SWAT watershed delineator.

Similarly, cross-section surface slopes were prepared by extracting XZ profile data from the 30m digital elevation model extracted from SRTM Digital Elevation Model.

To visualize the flow terms and water budget, Table 3 all the processed climatic, meteorological, hydrologic and hydrogeology data were simulated with the help of MODFLOW. The average recharge values estimated with the help of Hydrograph Separation, TIMESPLOT [21] and HBV models were an input to the model.

With regard to information on operational difficulties, different interviews and actual site observation Figure 4 were made on active and abandoned projects. The author was once an employee of the utility and had firsthand information.

In general, to assist the study, the aquifer systems of the two basins are conceptualized, monthly and long-time water level and abstraction rates are collected and operational case studies are documented. Some results of the groundwater flow modelling are included to illustrate the changes. Compilation and analysis of these data helped to understand the aquifer system behavior, piezo-metric fluctuations and operational challenges.

3. RESULTS AND DISCUSSIONS

3.1. Aquifer Conceptualization

Hydrogeology is far from being a quantitative science, hence, simplified representation or conceptualization of an aquifer system is needed to understand the hydrogeological units and groundwater flow systems. A conceptual model gives the basic constructed understanding of how systems and processes operate [22]. Preparation of a conceptual model includes assessment of the study area, determination of the boundary conditions, construction of cross-sections for the aquifer system, compilation and analysis of aquifer properties and estimation of stresses.

3.1.1. Study Area Delineation

The first step in conceptualization of a study area is demarcation of the study area from the surrounding groundwater system. As per Anderson, et al. [23] regional groundwater divides are typically found near topographic highs. Fortunately, the study areas are distinguished from adjacent basins by their distinct watershed and interaction with the adjacent northern basin is considered in the water budget. Upper Awash basin has clear topographic highs that separate it from adjacent Blue Nile, Ghibe, and Kesem River Basins.

Similarly, the boundary of Akaki catchment is clearly marked by surface water divides that identifies it from Upper Awash, Blue Nile and Kesem River basins. The remaining southern boundaries of both basins were demarcated by bounding the basins by the last stream network outlets. The watershed boundaries of both catchments were delineated by using Arc SWAT Watershed delineator by defining streams, stream networks, and stream outlets.

The general groundwater flow direction for Upper Awash basin is from West or Northwest to East whereas that from Akaki catchment is from North to South. There is a general understanding that groundwater is entering into both basins from adjacent Blue Nile basin [11, 13, 14, 16, 24]. Moreover, groundwater enters the model areas as base flow and outflows at eastern and southern boundaries from Upper Awash and Akaki basins, respectively.

3.1.2. Water Bearing Formations of the Study Area

Since 2007, the concept of presence of hydrogeological windows, through faults and fractures, or general rift-ward dipping has been gaining momentum. This window or dipping is assumed to channel groundwater from the adjacent Blue Nile Basin to the Upper Awash basin [11, 13, 16, 24]. Apart from these, in this study, the stratigraphic units of the study area are hydro-geologically divided into two main groups.

The first group is the Upper Oligocene to Lower Miocene Trap Series Basalt and Trachyte formations [25] which are sometimes termed as the uplifted Ethiopian Volcanic Plateau [20]. This unit forms the lower volcanic aquifer of the conceptual model Figure 2. The formation is thicker at the North and Northwest section of the study area otherwise it steeply dips into the rift floor.

The stratigraphic unit is down thrown by about 500 meter with respect to the Yerer Tullu Welwel volcano-tectonic lineament (YTVL) [20]. The formation is manifested by columnar basalts, weathered and fractured basalts, trachyte, ignimbrites and rhyolites. Transmissivity ranges are wide (1 to 266 m2/day) largely due to heterogeneity of the aquifer system and lineament density Andarge [13] and Tilahun [16]. Moreover, groundwater tables range from nearly 10 meter to more than 100-meter depending on geomorphology and fracturing.

Most of the wells in the study area are drilled along feasible sites where promising geomorphology, geologic structure and porosities are expected to prevail. Because of this, majority of the wells have good transmissivity and conductivity. However, in non-feasible rugged terrains and mountainous areas, hydraulic parameters are very small or close to zero. Many wells, drilled by Addis Ababa Sewerage Authority, in some non-feasible sites in the mountainous areas, proved this.

The Late Miocene (12 Ma) to recent age upper volcanic sequence [20] is considered as the second aquifer group and forms the upper aquifers of the conceptual model Figure 2. This category consists of wide range of aquifers. The main aquifers include (Scoriaceous) Basalt (with some trachyte and rhyolites) and Ignimbrite aquifer. From the plateau to the rift floor, the basalt gradually thins out and pyroclastic rocks (ignimbrite and tuff) gradually thicken. Thin paleo-sol layers between successive volcanic episodes and contact zones between different rocks also form water bearing zones.

The scoria and scoriaceous basalt mainly occur in Akaki, Dukem, Bishoftu and upper Modjo areas. This aquifer has thin intercalations of ignimbrite, tuff and paleo-sols. The unit is characterized by high hydraulic conductivity attributed to the high primary and secondary porosities associated with the lineament density. As per the recent 85 deep wells drilled in Akaki area (up to 600-meter depth), the transmissivity ranges from 65 to 18,700 m^2/day. The relatively shallow wells drilled between 1998 and 2000 had a transmissivity as high as 105,408 m^2/day [6].

The ignimbrite, tuff and ash formations of the Becho plain which are underlain by basaltic layers have a transmissivity value of between 17 to 120 m^2/day. Similarly, wells in the lower Adda plains have a transmissivity of 8 to 50 m^2/day. The lower Adda plains are situated at the centre of the rift floor and are constituted by ignimbrite, tuff and ash. The groundwater level in Becho plains are on average 10 meters but in lower Adda plains it ranges from 30 to 70 meters

3.1.3. Stratigraphy and Cross-Section

Conceptual modelling of groundwater flow systems requires projection of the geologic structures, hydrogeological characteristics and groundwater tables. Data from hundreds of wells with depths as deep as 800 meters are used in preparing hydro-stratigraphic units explained under section 3.1.2. Additional previous cross-sections done by Tsegaye, et al. [20] and Geological Survey of Ethiopia [18, 26] for different parts of Upper Awash Basin are used to develop the interpretation. Among the several cross-sections done during this study, the main alignment which portrays majority of the features of the basins is given below Figure 2.

3.1.4. Hydraulic Properties

Transmissivities of the different aquifers are shown under section 3.1.2. Hydraulic conductivities are the function of transmissivity and aquifer thickness, hence the values given in the mentioned section denote hydraulic conductivities.

Data base of wells has been organized for wells in Addis Ababa and Upper Awash basin by the Addis Ababa Utility and respective government water offices. There are more than 500 old shallow to medium depth wells drilled in Upper Awash basin over the last 50 years. Moreover, additional deep wells were drilled especially for

Addis Ababa city in the last 10 years. As per the information from these wells, hydraulic conductivity does not show change with depth both in Akaki catchment and upper Becho plains but show slight variation in lower Becho and Adda plains [11, 12].

With regard to storage terms, majority of the wells were pump tested without observation wells hence it is difficult to get sufficient values of specific yield and storage coefficient. However, there are a few wells pump tested with observation wells in Akaki catchment and projections were made by other previous authors for other areas. Storage terms account for the rate of amount of water stored or released from aquifer due to changes in hydraulic heads [27].

On the other hand, due to the interconnectedness of the aquifers, it is difficult to categorize aquifers into confined and unconfined layers. In such conditions, specific yield and storage coefficient are interchangeably used [23, 27-29].

In general, based on field data and previous studies, the storage coefficient values range from 0.6% to 2% with mean value of about 1% in Akaki wellfield and 0.01% and 1% elsewhere in Akaki catchment [6]. As per Water Works Design and Supervision Enterprise [11]; Water Works Design and Supervision Enterprise [12] estimated storage coefficients for Becho and Adaa is 0.15% and 0.25%, respectively.

3.1.5. Water Balance

A water balance estimation implies computation of the volume of water both entering and living the model area and includes the flow terms like river flow, fluxes, recharge, well abstractions, and flow across boundaries. Similarly, water budget indicates valuation of the discharge, recharge and water balance components.

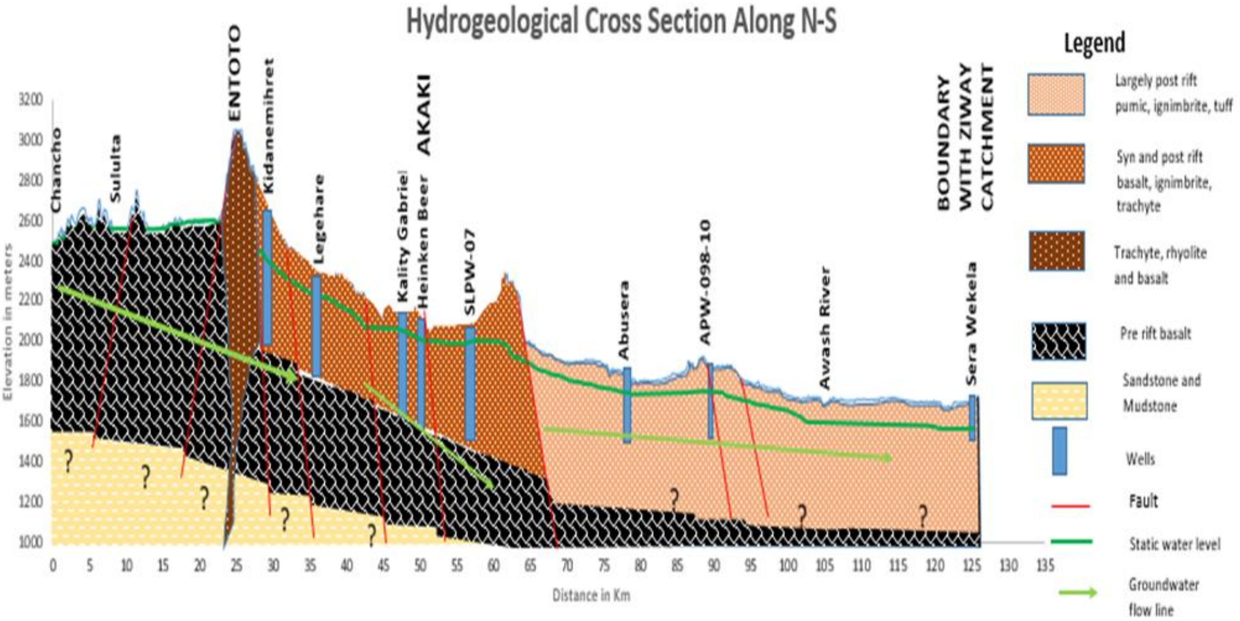

Figure-2. Hydro-stratigraphic cross-section of the Upper Awash and Akaki catchments from north to south.

The data for Table 2 was collected from time series recharge and discharge measurements conducted for the indicated months (section 2.3). The recharge values were the average of Hydrograph Separation, TIMESPLOT [21] and HBV recharge estimation methods (part of the ongoing PhD research). The abstraction wells in the Akaki well field were clustered into 437 whereas for Awash they were grouped into 576 wells Table 2.

Conceptually, water enters the model areas as recharge from rain fall, waste water from cities like Addis Ababa, lateral flow from adjacent basins and through riverbed depending on head differences. Water leaves the model area as outflow through boundaries, well abstractions, river base flows and evaporation. Groundwater storage changes by the difference between the inflows and outflows.

Table-2. Temporal recharge and discharge values for akaki and upper awash basins.

Month	Akaki Basin		Awash Basin	
	Recharge (mm/month)	Well discharge (M^3/day)	Recharge (mm/month)	Well discharge (M^3/day)
December	25.2	616,815	4.2	653,243
January	23.7		4.4	
February	21.9		4.1	
March	22.0		4.0	
April	21.5		3.8	
May	21.3		4.0	
June	23.3	412,110	4.9	435, 495
July	42.2		10.3	
August	73.4		22.4	
September	51.7		16.5	
October	29.2		8.1	
November	26.2		4.5	
Total	381.6		91.2	

Table 3 shows the water balance and budget obtained in the last (12th) period and last time step (48th) of transient modelling.

Table-3. Water budget for the two model areas from transient groundwater flow modelling for the 12th period and 48th time step of transient modelling.

Flow term	**In** (M^3/day)	**Out** (M^3/day)	**In-out** (M^3/day)
Akaki Catchment			
Storage	5.59E+05	5.45E+05	-1.34E04
Constant Head	9.63E+02	1.23E+05	-1.22E+05
Wells	3.01E+05	4.1E+05	-1.1E+05
Recharge	3.24E+05	0.00E+00	3.24E+05
River leakage	2.58E+05	4.83E+04	-2.25E+05
Head dep bounds	1.16E+04	9.5E+04	-8.36E+04
Sum	1.22E+06	1.22E+06	-2.2E+01
Discrepancy [%]	0.00		
Upper Awash Basin			
Storage	8.99E+05	5.44E05	3.54E+05
Constant head	3.4E+05	6.1E+04	2.78E+05
Wells	3.92E+05	3.39E+05	5.34E+04
Recharge	1.83E+06	0.00E+00	1.83E+06
River leakage	1.96E+05	6.93E+05	-4.96E+05
Head dep bounds	0.00E+00	2.02E+06	-2.02E+06
Sum	3.66E+06	3.66E+06	-2.48E+00
Discrepancy [%]	0.00		

3.2. Evolution of Groundwater Tables

Even though groundwater development has been going on for the last 50 years, relatively documented data is available only in Akaki well field area since 1990. Static water levels for old wells were documented by BECOM-Suerca for years 1990 and 2000 [6]. Moreover, measurements were done by this study in 20018 and 2019.

This groundwater evolution is shown below in Figure 3. The water level changes between 1990 and 2000 was less than 1 meter as there was no pumping of water in the wellfield. Even the level changes were minimal until 2009. Because until this time, daily abstraction in the well field was less than 40,000 m^3 per day. This discharge amount was in line with the maximum allowed safe yield from BCEOM— SEURECA SPACE JV [6] modelling result.

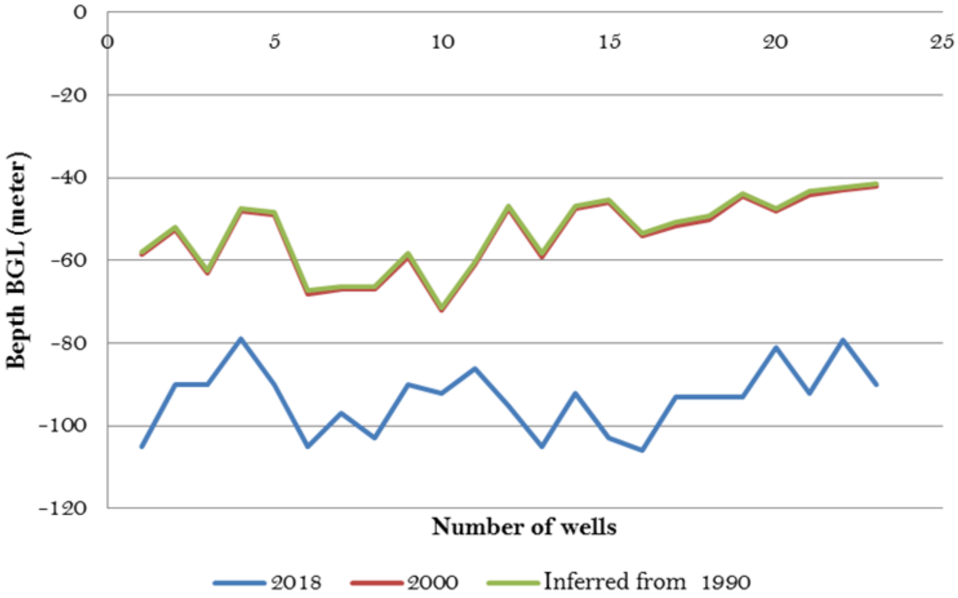

Figure-3. Drawdown Evolution for Old Akaki Wells in 1990, 2000 and 2018.

A drastic abstraction started in 2014 which resulted in sharp decline of groundwater. As a result, an average 50-meter decline in groundwater level occurred at the centre of the well field in 2018. The centre of the well-field is constituted by alluvial and fluvial sediments and it is the place where both Akaki rivers are merging. Away from the alluvial and fluvial sediments in to the scoria and scoriaceous basalt bed rock, the average decline goes above 70 years. The decline is due to abstraction rate of around 330,000 m^3/day since 2014.

As a result of excessive pumping, the minimum dynamic water level of the existing wells went down below 115 meters even in at centre of the wellfield. This kept more than 25 older wells out of service because their operable casing size was less than 100 meter deep. Figure 4 shows a sample of a well taken out of service due to well water level decline. The once exemplary project had to be totally replaced by new deeper wells in just 17 years.

Figure-4. One of the dismantled wells due to groundwater level decline.

In addition to static water levels, time series of water level data was measured in both catchments for about 13 months from July 2018 to July 2019. Considerable seasonal changes were observed in wells located in Akaki well field. Actually, the groundwater table continually decline due to high and persistent abstraction Figure 5. There is very slow decline in Legedade and Sendafa areas Figure 8 wellfields; and near steady state condition in Becho Figure 6 and Adda plains Figure 7.

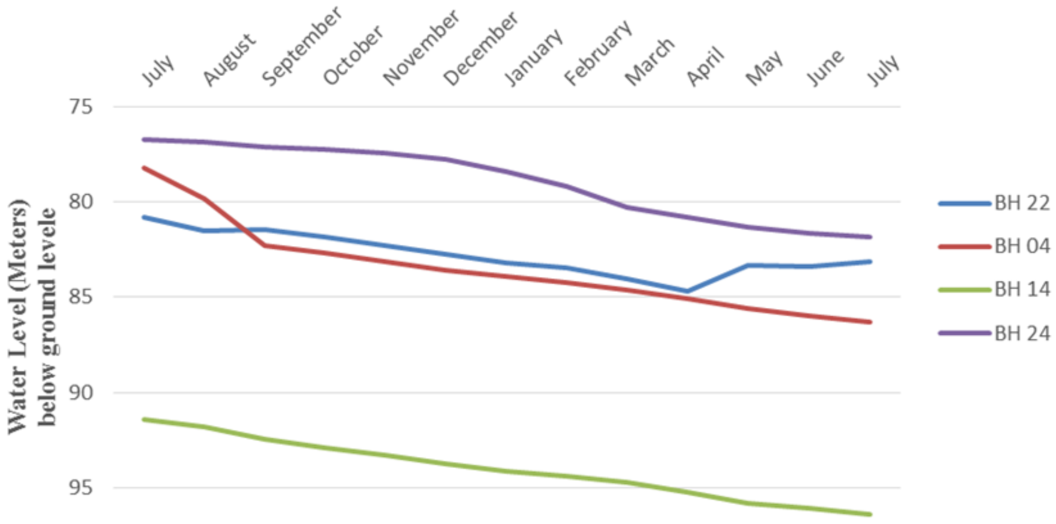

Figure-5. Time Series of water levels in the north of akaki well field, central upper awash basin.

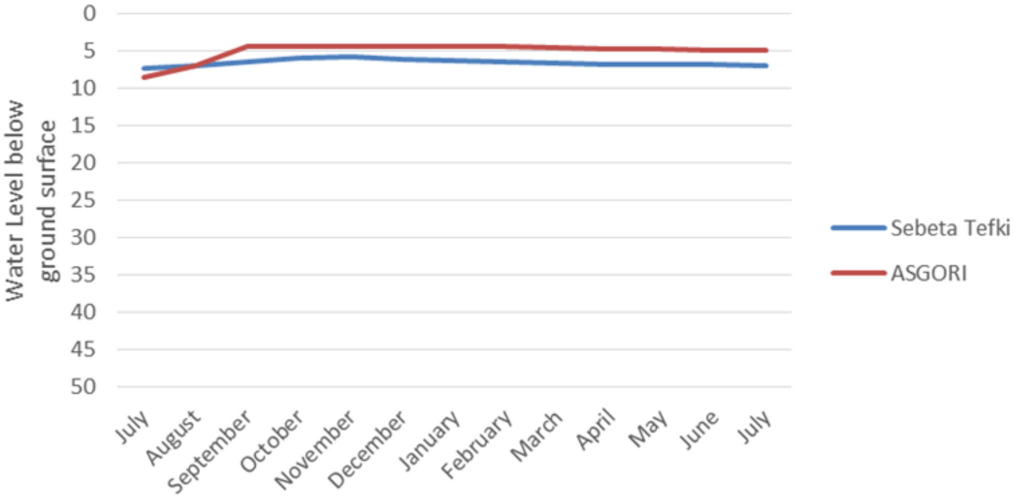

Figure-6. Time series of water levels in the west of upper awash basin.

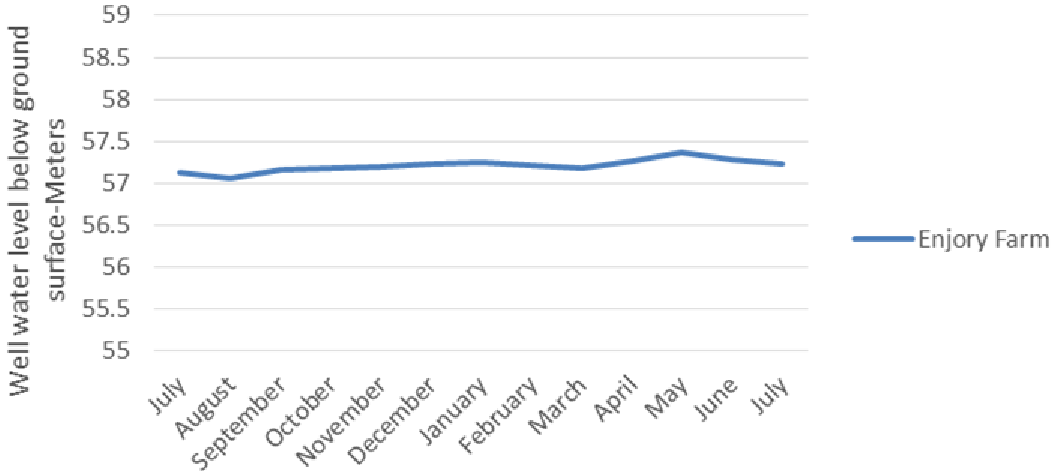

Figure-7. Time series of water levels in the south of upper awash basin.

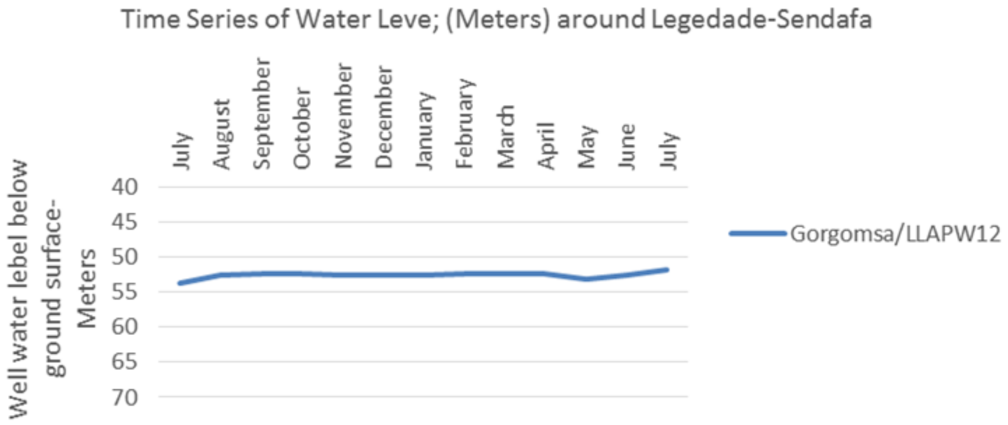

Figure-8. Time series of water levels in the west of upper awash basin.

The above water level data show only two seasons (one year). Several years' water level data are needed to show the complete picture of recurrent groundwater level fluctuations over prolonged climatic and metrological conditions. The following river flow recurrence data is analysed by base flow separation methods in an attempt to at least portray long period surface water level fluctuations and drought recurrences (Modified from Tenalem [21])

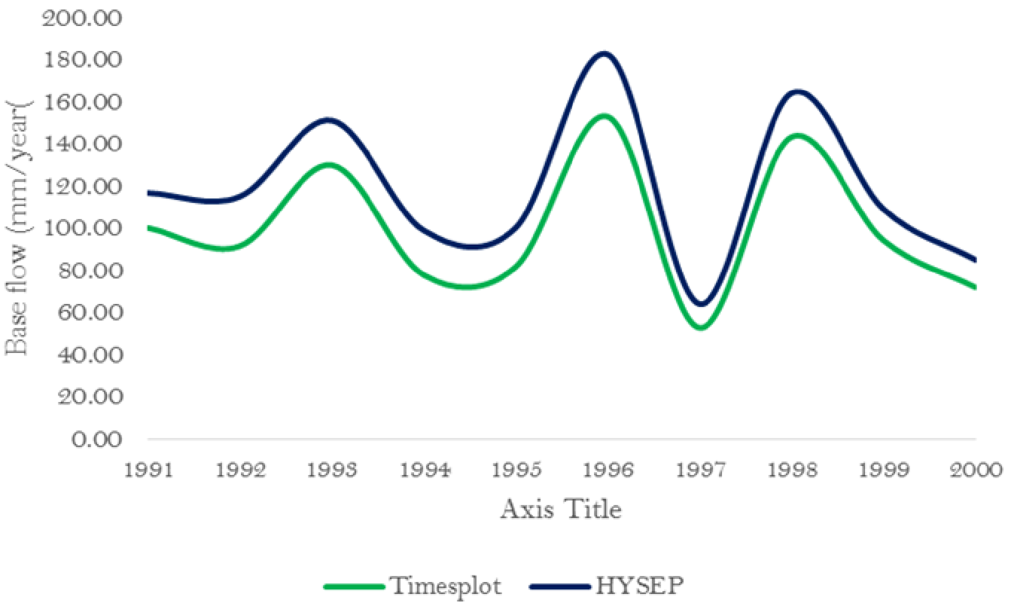

Figure-9. Evolution of base flow over the rives in Upper Awash Basin (mm/year).

Source: Modified from Tenalem [21].

3.3. Operational Difficulty

Many rural settlements and small towns use groundwater as their sole water supply in the study areas. The complexity of operating well based water supplies increases with increase of well numbers and topographic contrasts. No other town is suffering with such scenario more than the city of Addis Ababa. The city is abstracting water from hundreds of wells scattered all over the city and two adjacent well fields.

Actually, two-third of the well based water supply is coming from Akaki well field. But unlike other well locations, this well field is located at the southernmost downstream of the city. Hence, pumping well water up to the city re.

The city water supply utility is facing also other obstacles, like high operation and management cost, in running well based water supplies. But the major challenge occurs when the well or local groundwater level drops below the submersible pump positions. In such cases, infrastructures which costed millions of dollars' have to be sometimes abandoned.

For instance, the Akaki well field was initially designed for a daily abstraction of between 30,000 to 40,000 m^3/day for 20 years until 2020. During this phase, it was proposed that any abstraction above 70,000 m^3/day would impact regional groundwater conditions. Nonetheless, abstraction in excess of the design started long ago. The current abstraction of 330,000 m^3/day has already triggered the threshold and caused the abandonment of very sophisticated 25 wells Figure 4. quires relay pumping stations and continuous electric supply at each stations which is not always the case. While water supply from surface dams constructed in the 1940s and 1970s are still functional, many of the wells drilled far after them are abandoned and forced the utility to look for compensating wells. The human and logistical burdens of managing hundreds of scattered wells is expensive and complicated.

The utility is now unable to supply new industries and water demanding businesses. Hence, it is encouraging them to drill and develop their own wells. There are already hundreds of such wells drilled across the city. Moreover, there are more than 105 bottling plants in the Upper Awash basin with daily production of around 5,000 m^3 per day. They are planning to develop until the national demand is met which is around 42,000 m^3 per day. Many more boreholes are likely to be drilled in the coming years. These with the utilities intention to cover much of the 50% deficit with groundwater would undoubtedly impact the groundwater resource and worsen its operational difficulty. Gradual propagation of groundwater table decline to the Akaki catchment would in a near future stop majority, if not all, of the wells with a depth below 250 meters. In general, well based developments are flexible in space, fast to complete, low cost projects and best suited for small rural communities and rural towns. However, for a city like Addis Ababa, except using them as supplement and in a very peripheral or inaccessible areas, it is not sustainable to fully depend on them. In the last 10 years, the utility has aggressively invested hundreds of millions of dollars for a well based projects but could not bring sustainable supply apart from complicating the operation system. Hence, except using as conjunctive use with the surface water as a main source, there will be long term impact on the groundwater sources, even to the extent of influencing the underground pore pressure which in the end may cause cracks on infrastructures like roads and buildings.

4. CONCLUSION AND RECOMMENDATION

4.1. Conclusion

The aim of this study is to provide first-hand information on the challenges of supplying big cities with groundwater and draw the attention of all stakeholders to find alternative solution for the looming water supply problem. To study these, conceptual modelling of the aquifer systems was formulated; monthly water level measurements were conducted and current water supply operations were assessed. The stratigraphic units of the study area are hydro-geologically divided into two as the Upper Oligocene to Lower Miocene Trap Series Basalt and Trachyte formations and the Late Miocene to recent age upper volcanic sequence (scoracesous basalt, ignimbrite and tuff). The former unit is the base of the conceptual model and has high transmissivity as compared to the second unit. There is also groundwater influx from adjacent basins through faults, fractures and general rift-ward dipping. In connection with hydrochemistry, the hydrolysis reaction in the highlands results in silicate dissolution that forms Ca-Mg-HCO. This water quality gradually transforms to salty Na-HCOH type towards the rift. Despite the continuous groundwater-based funding of the sector for the last 15 years, the Addis Ababa city's water supply coverage cannot be raised more than 50%. However, this practice caused excessive pumping and abrupt groundwater decline to the extent of abandoning hundreds of shallow and medium depth wells. There is also high operation and management cost in running well based water supplies in contrasting topographic conditions.

The emergence of competition for water among surrounding cities and between community water supply and irrigation schemes is worsening the situation. In general, well based developments are flexible in space, fast to complete, low cost projects and best suited for small rural communities and rural towns. However, for a city like Addis Ababa, except using them as a supplement and in a very peripheral or inaccessible areas, it is not sustainable to fully depend on them. While water supply from surface dams constructed in the 1940s and 1970s are still functional, many of the wells drilled far after them are abandoned and forced the utility to look for compensating wells. The frequent tapping of thermal and fluoride rich well waters; the huge disparity between hydrogeological potentials and operational feasibilities; fast declining of well yields, the risk of contamination with town waste effluents and the soaring demand of the city may gradually force the utility to look for an additional surface water sources. Moreover, unless proper intervention is devised, excessive and uncontrolled abstraction may cause grave environmental problems in the near future

4.2. Recommendation

The present uncontrolled and massive well development and well water abstraction, especially in Akaki Catchment, shall be regulated. The Addis Ababa City utility shall seriously consider augmenting its water supply with additional surface water sources before it is too late in finding impounding areas.

Moreover, there shall be well monitoring system to be managed by, at least, Addis Ababa Water and Sewerage Authority. The well monitoring system shall be conducted in non-pumping wells distributed fairly on the source catchment.

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