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Original Research

Seasonal Behavior and Spatial Fluctuations of Groundwater Levels in Long-Term Irrigated Agriculture: the Case of a Sugar Estate

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Abstract

This paper presents results on the spatial and temporal fluctuations of the groundwater table depth (GWTD) at Wonji-Shoa Sugar Estate (WSSE). Accordingly, spatial maps of GWTD were produced in a GIS (ArcView 3.3) environment from 35 groundwater monitoring piezometers. Results of the study revealed that WSSE, after nearly 60 years of irrigation, is experiencing a serious waterlogging problem. The groundwater (GW) depth is extremely shallow (<1 m below ground) in most of the piezometers throughout the entire season and showed great spatio-seasonal variability. The rate of annual increment of GW rise, coupled with seasonal fluctuation, has obvious repercussions and grave consequences for the sustainability of WSSE in particular and to the region in general. Unless the potential causes for the rise of GWTD are identified soon and feasible corrective measures for mitigating GW rise are introduced, severe crises in the region are inevitable.

Keywords: groundwater monitoring, piezometers, mapping, groundwater fluctuation, waterlogging, water management

Introduction

Wonji-Shoa Sugar Esatate (WSSE) is one of the large-scale irrigation schemes within the Upper Awash River Basin (Ethiopia) established at the beginning of the 1950's. Its establishment in the basin marked the first era of large-scale irrigation development as well as domestic sugar production in Ethiopian history [1, 2]. It has a total irrigated area of about 7,620 ha (excluding the current project areas under expansion) and the factory has a total crushing capacity of 3,500 TCD (tons of cane per day). Sugarcane crop is mostly grown in the plantation.

For the last 60 years, WSSE has been producing sugar (white and brown) at the expense of unsustainable use of available land and water resources; currently faced with negative externalities. The main factor challenging the sustainability of the sugar estate is the rise of groundwater table depth (GWTD) to the crop root zone. The major cause for the rise of GWTD in the area is an intensive use of furrow irrigation system for long periods of time, coupled with poor drainage systems [3].

Groundwater (GW) rising to the crop root zone is one of the most unfavorable effects of irrigation projects, which occur slowly, and its problem tends to emerge over years [2, 4, 5]. The adverse impacts of shallow GWTD to human health, environment, and crop production are well documented by different (local and international) literatures [2,

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3, 5, 6-12]. Trend analysis made by Dinka and Dilsebo [3], for instance, indicated that the GW has potential to inundate Wonji plain and is anticipated to devastate production in the next 10-15 years. Hence, severe crises are inevitable in the area in the near future. The endangered sustainability of the sugar estate dictates the need to give due attention to appropriate water management systems.

GWTD is a dynamic variable [13], both in space and time [2]. Shallow GW levels tend to fluctuate at greater frequency and extent compared to deep ones [14]. GWTD can fluctuate daily, seasonally, annually, and over long periods of time in response to a variety of conditions (variation of precipitation, climate change, rate of irrigation, and pumping) [13]. The dynamics of GWTD are mostly a reflection of the GW system to external factors (climate and human activities) and often a hydrological indicator of the state of ecology of the region [15]. According to Akther et al. [16], GWTD rises due to increasing GW storage from different sources, such as infiltration from rainfall, recharge due to stream seepage, canal infiltration, seepage surface flow, etc.

In irrigated areas, observing, diagnosis, and mapping of waterlogged areas are mandatory for proper management of the valuable water and land resources [17]. Especially information related to the spatial and temporal variability of GWTD can be of great economic and environmental importance [11, 18]. Water managers, therefore, should be informed about the variation of GWTDs in both space and time [18]. Observing and evaluating GWTD in irrigation areas is important [8] in order to:

(i) observe changes of the GWTD due to excess rainfall and irrigation
(ii) determine the vulnerable areas or areas that are likely to be so
(iii) make proper irrigation planning
(iv) take the necessary precautions.

Thus, both time and spatial variability of GWTD should be studied jointly to understand the dynamic behavior of aquifer systems [19].

At WSSE, however, the spatial and temporal behavior of GWTD has not yet been studied in detail. The current situation urgently requires information about the prospective GWTD of the area across seasons and space so that appropriate and timely corrective measures can be adopted. The current study, therefore, aims to provide clear information about the status of GWTD of the area, its seasonal behavior, and spatial variability. Accordingly, the GWTDs were recorded systematically using a number of GW monitoring piezometers installed throughout the entire sugar plantation. Then, the spatio-temporal fluctuations of the GWTD were analyzed, assisted by a geospatial information system (GIS).

The Study Area

The study was conducted at Wonji-Shoa Sugar Estate (WSSE) within the Upper Awash River Basin, Central Rift Valley of Ethiopia. The study area (Fig. 1a and b) is situated 1,530 m above sea level in Wonji plain, bound by 8.43ºN latitude and 39.28ºE longitude. During the milling season, the sugar estate employs about 8,000 people. Moreover, more than 50,000 people (including employees, their families, and other residents) live in the region, generating their livelihood from the farm directly or indirectly. The soils of WSSE are of alluvial-coluvial origin developed under hot, tropical conditions. In general, plantation soils are categorized into light (course textured) and heavy (clayey black) soils; but predominantly (≈70%) clay type. Sugarcane is the most grown crop in the plantation, with a few crotalaria and haricot bean on heavy black clay soil during the fallow period.

Wonji plain is characterized by very flat and regular land having a small general slope (varying from 0.02-0.05%). This topographic characteristic of the plain is a bottleneck in the management of excess irrigation water and surface runoff (annual agricultural reports and our own observation by the first author in 2010). The area is sur-

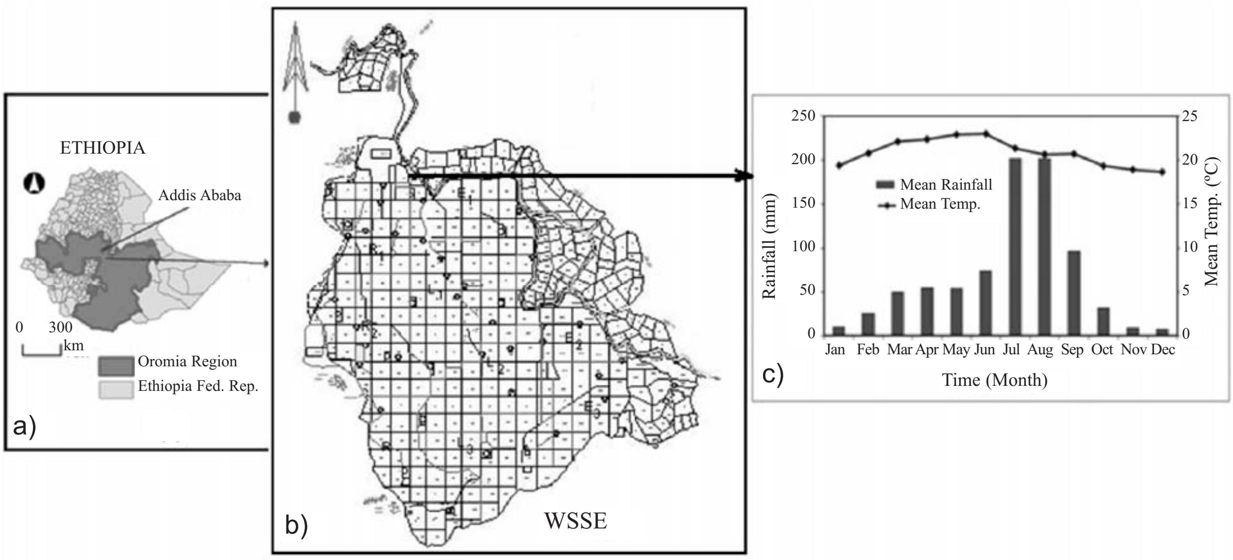

Fig. 1. Study area: (a) location of Wonji plain, (b) base map for WSSE, (c) mean precipitation and temperature of Wonji plain

rounded by hilly terrain, except in the southeastern part, where the terminal drain out-fall is located. Before the introduction of irrigated agriculture into the region, the Wonji area was rich in vegetation cover. Different categories of land use/cover (LUC) condition were present with a variety of animal and plant species. There has been big, unavoidable competition between grazing and agriculture in the past 5-6 decades. Changes in LUC (due to Koka Dam construction, irrigation development, settlement, etc.) have resulted in unwanted consequences: eviction of pastoralists from their wet grazing lands, conflicts between different societies (ethnic groups and clans), and drought insecurity due to loss of access to the river [2, 20-22].

Analysis of the long-term (1954-2010) weather data of Wonji Meteorological station indicates that Wonji plain is characterized by erratic rainfall distribution patterns, with average annual rainfall value of about 832 mm. The mean annual minimum and maximum temperatures of the area are 15.2ºC and 27.6ºC, respectively. The rainfall of the area exhibits considerable spatial and temporal (mostly seasonal) variations, where approximately 76% of the rainfall is concentrated in the main rainy (summer) season (June-September) (Fig. 1c). Sometimes there is an appreciable, but occasional rainfall in the month of March/April, accounting for about 10% of total rainfall. The other months are relatively dry. The occurrence of rainfall in the month of March/April is related to the Inter-tropical Convergence Zone (ITCZ) or monsoon winds coming from the ocean to dry lands in east Africa. The climatic condition of the study area is, in general, classified as subtropical monsoon /sub-humid/ according to Koppen, or semi-arid in the Thornthwaite classification system. That means the area is between the transitions of the semi-arid and dry sub-humid zones.

With exceptional supplemental water application depending upon rainfall magnitude, irrigation season normally starts in October and continues until June. The irrigation water is diverted to the estate from the Awash River (the only perennial river passing through Wonji Plain) using eight centrifugal pumps with combined capacity of 5.5 m^3/s. In addition, there are small pumps that irrigate the outgrower farmers' area. Since the pump operates continuously for 24 hrs and irrigation is carried out during the day, the pumped water from the river during the night is stored within night storage reservoirs. Field water application is through a block ended furrow irrigation system and the excess water is drained from the field through the network of surface drains.

Materials and Methods

Piezometer Installation and Monitoring

GWTD monitoring was carried out using piezometer tubes. A total of 35 new PVC tubes (ϕ = 80 mm and length = 2 to 3 m) were re-installed in September 2007 in order to characterize the seasonal behaviour and spatial variability of GWTD of the study area. The piezometers are all PVC tubes and fairly distributed in the area (Fig. 2). It should be noted that the outgrower farms are not considered in this study. Different sources of water (such as the Awash River, night storage reservoirs, irrigation canals, and drainage canals) were taken into consideration for the selection of piezometer sites. The PVC tubes were installed manually using auger tubes.

The locations (latitude, longitude and elevation) of each piezometer (Table 1) were registered using hand held GPS.

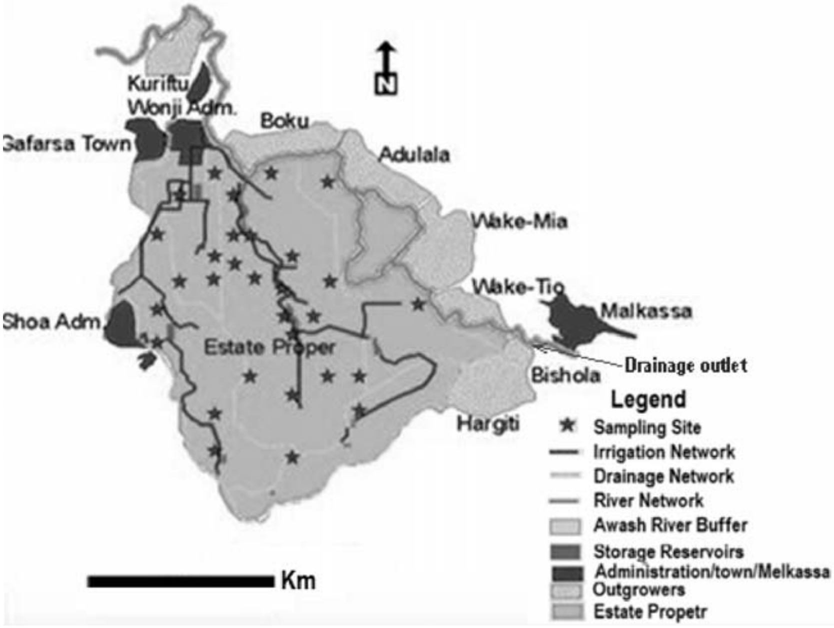

Fig. 2. Wonji-Shoa Sugar Plantation (estate proper and outgrowers) showing GW monitoring sites, storage reservoirs, networks of irrigation and drainage canals, administrative areas, and villages/towns. Note that there are seven outgrowers (Kuriftu, Boku, Adulala, Wake-Mia, Wake-Tio, Bishola, and Hargitti) managed by the farmers association supplying sugarcane to Wonji factory.

Table 1. Piezometer identification and coordinates.

Piezometer ID	Field No.	Coordinates (UTM)			Piezometer ID	Field No.	Coordinates (UTM)		
		X	Y	Z			X	Y	Z
1	16	524866	932771	1543	17	76	524263	928493	1539
2	18	526319	932772	1549	18	169	528851	933139	1542
3	166	527332	933381	1540	19	195	528908	930253	1541
4	123	525817	926426	1538	20	170	527861	932773	1541
5	177	529204	932575	1543	21	29	526320	931589	1543
6	182	528852	931591	1541	22	192	529205	930983	1539
7	101	526741	927510	1539	23	22	525427	933612	1546
8	202	528754	929424	1541	24	178	526739	931590	1549
9	99	525816	927510	1539	25	184	527895	930993	1541
10	131	529681	926517	1537	26	69	525815	929422	1540
11	25	524261	933379	1539	27	127	527897	926958	1540
12	105	528855	927511	1539	28	238	531086	926519	1538
13	41	525814	930992	1541	29	198	527899	925156	1538
14	189	527895	930993	1541	30	48	524868	930251	1536
15	159	525818	925365	1538	31	82	527896	928495	1540
16	52	526739	930252	1542	32	WRS	524502	934429	1543

X – longitude, Y – latitude, Z – altitude, UTM – Universal Transverse Mercator, Piezometer ID – given after field No.

GW depth monitoring commenced in 2007, just after piezometer tube re-installation, and continued until 2009; with the monitoring frequency of two readings per month. The monitoring period is representative of the water cycle for the whole year in recent time. Water levels were monitored using a graded contact gauge that provides sound and light signals when it touches water in the tube. Care was taken to collect the GW levels in all tubes within a minimum possible time.

An attempt also was made to collect secondary data from different sources. Topographic plantation base maps and meteorological data were collected from the database of Wonji Research Station (WRS), sugar estate, friends, and researchers. The previous GW records (1999-2005) were obtained from the database of WRS. The Digital Elevation Model (DEM) (90 m^2 resolution) was downloaded from Shuttle Radar Topography Mission (SRTM) [23].

Data Analysis and Mapping

The DEM was processed in ArcGIS (Ver. 9.2) for the study and the surrounding area, assisted by topographic and plantation base maps. The piezometer readings were analyzed in an excel spreadsheet to monthly, seasonal, and

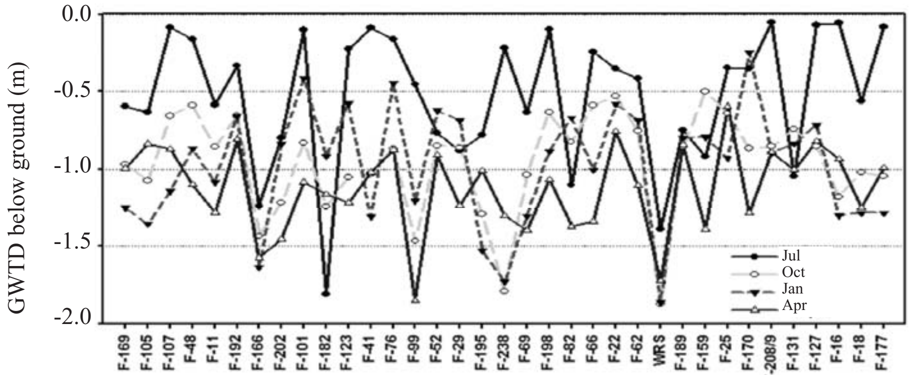

Fig. 3. Seasonal and spatial variation of GWTD for all piezometers (2007-09). Piezometers are labeled by the field number of the plantation. WRS refers to the piezometer installed at Wonji Research Station.

annual values for each piezometer. Any missing data were filled by regression analysis since the GWTD of the area, as reported by Dinka and Dilsebo [3], have strong spatial autocorrelation. Then, the extent of waterlogging was mapped from point-monitored data showing the piezometric surfaces. The spatio-seasonal maps of GWTD were produced in ArcView (Ver. 3.3) using the Inverse Distance Weight (IDW) interpolation technique. With the help of these maps, detailed explanations were provided regarding the waterlogged condition of the area for each of the four Ethiopian seasons (winter, autumn, summer, and spring) represented by four months (January, April, July, and October), respectively.

The seasonal responses of GWTD to rainfall excess were analyzed based on the accumulated monthly residual rainfall (AMRR) [3, 24]:

$$AMRR_t = \sum_{i=1}^{t} \left(M_{i,j} - \bar{M}_j \right)$$

...where: $M_{i,j}$ – rainfall (in mm) in month i (a sequential index of time since the start of data set), which corresponds to the j^{th} month of the year, $\bar{M}_j$ – mean monthly rainfall for the j^{th} month of the year, and t – month since the start of the data set.

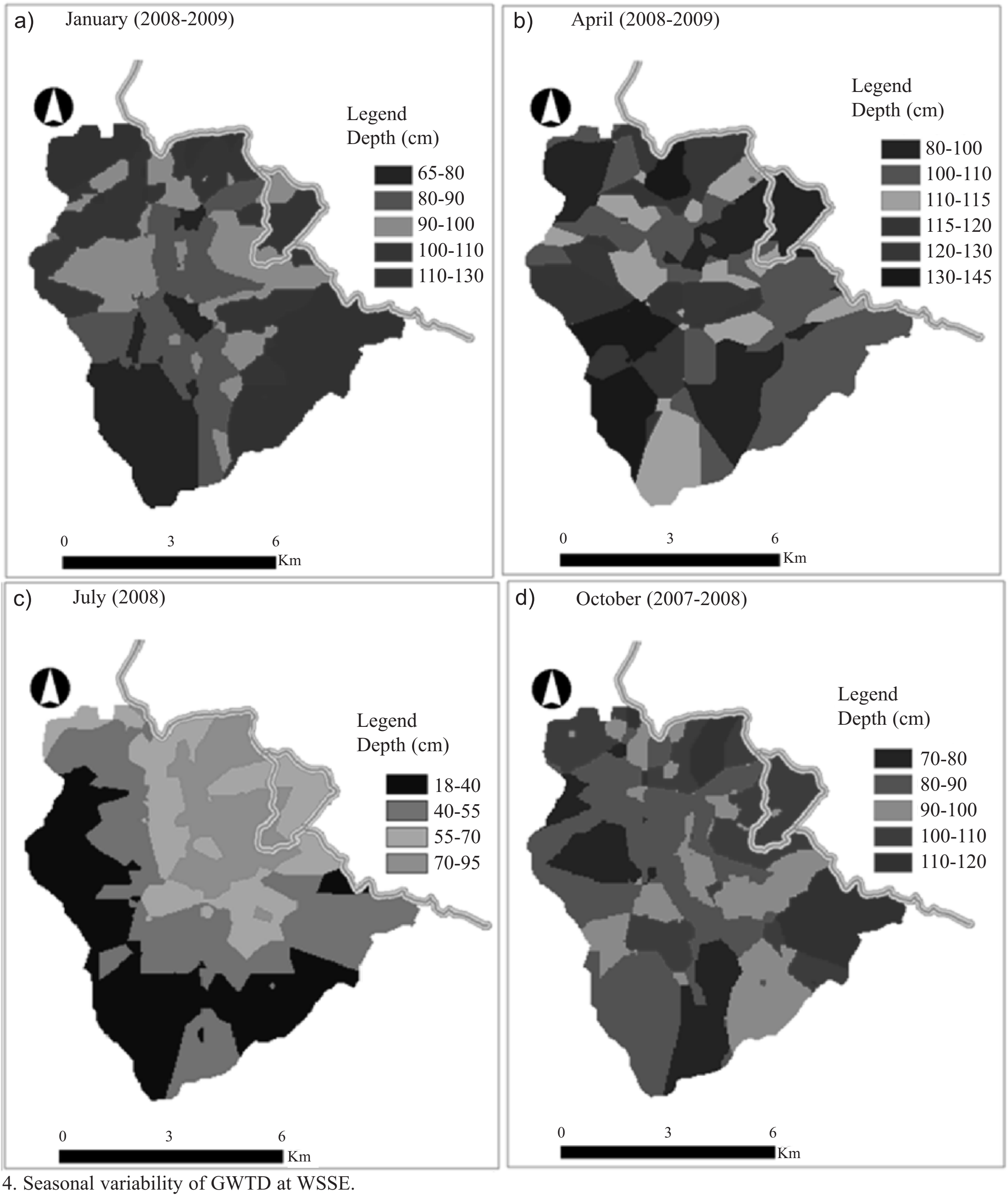

Fig. 4. Seasonal variability of GWTD at WSSE.

Results and Discussion

Spatial and Seasonal Variability of Groundwater Table Depth

The seasonal mean monthly GWTD responses of the 35 piezometers, installed at different parts of the plantation fields, were recorded over the monitoring period and plotted in sigma plot as shown in Fig. 3. From the plot, it is possible to envisage the status of GWTD and its seasonal fluctuation in recent time (2007-09). The GWTD varies from 0.05 m (July) to 1.85 m (April). During July (summer), most of the piezometers (except F-82, F-166, F-182, and WRS) have very shallow GWTD (<1.0 m) below the ground. In the same period, only piezometer F-182 has GWTD below the critical level (1.5 m) recommended for sugarcane crop [5]. In general, the GWTD of the area is very shallow and showed great seasonal and spatial variability.

Building on the piezometer readings, the spatio-seasonal maps of GWTD for the study area, produced in the GIS environment are presented in Fig. 4. From the figure, it is possible to envisage the status and seasonal fluctuation of GWTD values. Bellows, a detailed explanation regarding the extent of GWTD for the considered four seasons, are provided. The explanations were mostly based on the effects of rainfall (amount and distribution pattern) (Fig. 1c), excess irrigation, and surface runoff coming to Wonji plain (now onwards throughout this document, the term runoff is used instead of surface runoff) (Fig. 5b). This is set in relation to the poor drainage system and very flat topography (Fig. 5a) of the plantation area.

Season 1: Winter (January)

The GWTD is in the range of 0.70 to 1.30 m, with average value of 0.98 m (Fig. 4a). As per the individual piezometers (Fig. 3), the GWTD varies between 0.25 m and 1.90 m. About 53% of the plantation areas have GWTD less than 1.0 m. The northwestern and southeastern parts of the plantation have relatively deep GW depths, whereas the central, southern, and southwestern parts have very shallow GW depths (Fig. 4a), which is in line with the topographic feature (Fig. 5a) and stream network (Fig. 5b) of the area. The borders (except southern and southwestern), unlike summer and spring seasons (Fig. 4 c-d), have relatively deeper GW depths compared with the central parts. From July to January, the GWTD value lowered significantly (≈ by 1.0 m) in some fields (16, 18, 41, 107, 177 and 238); whereas other fields (29, 52, 82, 131, 159, 170 and 182) showed a slight increment (Fig. 3).

Winter season is the dry period in the study area, characterized by minute rainfall (Fig. 1c). Hence, the plantation area is not under the influence of direct rainfall and runoff. The possible sources for GW recharge are excess irrigation, plus seepage from the Awash River, irrigation, and drainage canals, and night storage reservoirs. Owing to this fact, a significant reduction in GW levels has been inevitable during this period, which is actually not the case. This is mostly due to the poor performance of irrigation and drainage systems of the area. However, it is important to note that the minimum GWTD significantly increased (from 0.18 m to 0.65 m), with the exception of southern and southwestern sides, in those border fields with very shallow GWTD during the main rainy season (Figs. 4 a and c). The southern and southwestern parts remained shallower owing to their lower altitude (Figs. 4a and 5a).

Season 2: Autumn (April)

The water table continued to decrease, but its magnitude is similar to that of the winter season. The GWTD is in the range of 0.80 to 1.50 m (Fig. 4b), with average value of 1.15 m below the ground. GWTD depth is relatively deeper in this season compared with all the other seasons.

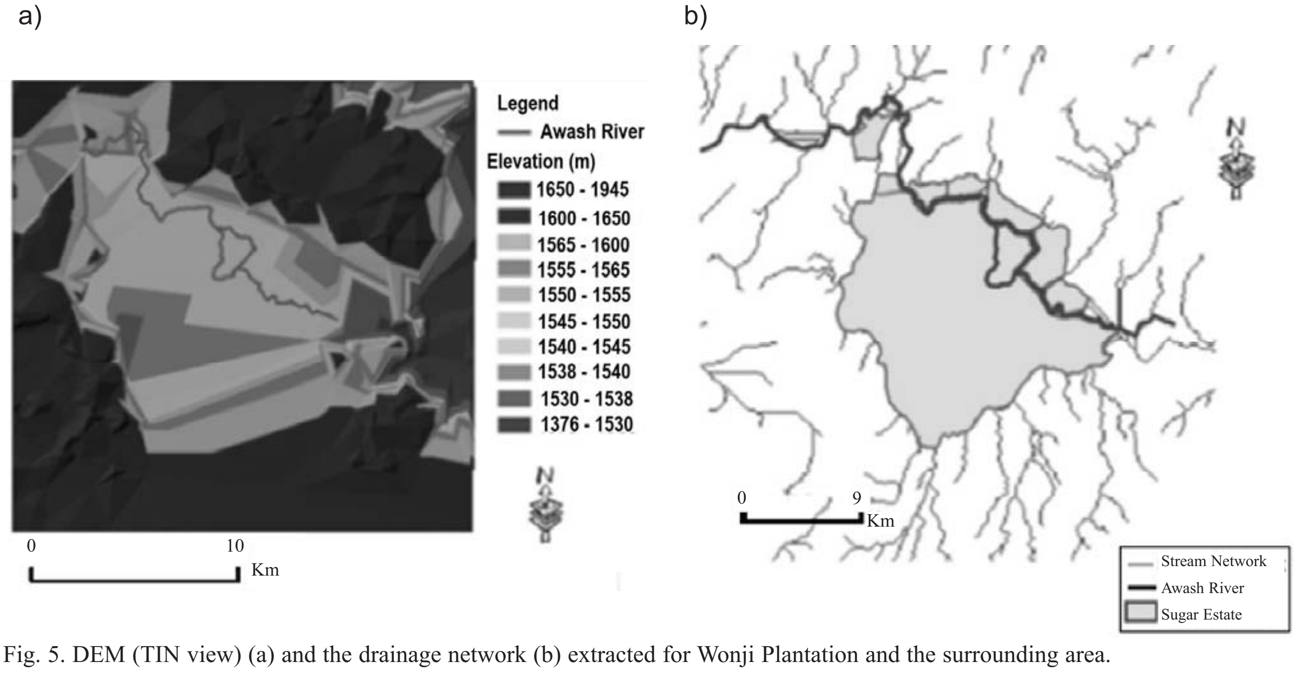

Fig. 5. DEM (TIN view) (a) and the drainage network (b) extracted for Wonji Plantation and the surrounding area.

About 80% of the plantation fields have GWTD greater than 1.0 m. Only 10% of the plantation has GWTD greater than 1.5m and found to be safe from significant yield reduction. The north and southwest areas have relatively deep GWTDs; whereas the southern, eastern, northwestern, and northeastern parts of the plantation have relatively shallow GWTDs (Fig. 4b), which is in line with the topography and stream network of the area (Fig. 5). During this season, very few fields (107, 159, 170, 189 – most of them are in southwestern part), showed significant reduction in GWTD (Fig. 3) compared to the preceding (winter) season.

The current period, like autumn and winter, is irrigation season, just prior to the summer (main rainy) season. During this season, the sugar estate had difficulty in getting enough water for their crops; thus, sugarcane plants usually showed signs of wilting (moisture stress). The peak crop water demand and significant reduction of Awash River flow are the main reasons for the shortage of water at WSSE during this season; the later one is a major concern for sustainability of irrigation development in the Awash Basin, in general. The water shortage in the Awash River Basin, during the season was due to the harsh climatic conditions (high temperature, high ET, more sunshine hours, high humidity, low rainfall) and the peak water demand in the basin. Climate change is expected to reduce water availability in the future.

Although this season is characterized by a small but occasionally appreciable amount of rainfall (Fig. 1c), it is compensated by the peak crop water demand, high ET, and reduced water application rates due to water shortage. As a result, similar to winter season (Fig. 4 a-b), the effects of direct rainfall and the incoming runoff on GWTD fluctuation are also minimum in this period. A careful perusal of Fig. 4b shows that the western and southwestern parts of the plantation have relatively deeper GWTDs compared to the other areas. These areas had relatively shallow GWTDs compared to other parts during the summer and spring (Fig. 4, c-d). This means that the GWTD would have decreased even more had there been well-controlled water management (i.e., efficient irrigation and drainage practice) in the area.

Season 3: Summer (July)

The GWTD during this season is in the range of 0.18 to 0.95 m, with average value of 0.53 m below the ground surface (Fig. 4c). Almost more than half of the plantation has GWTD less than or equal to 0.50 m. Almost all parts of the cane plantation fields are critically waterlogged (GWTD <1.0 m) during this season. According to Fig. 3, more than 85% of the piezometers have GWTD less than 1.0 m below ground. This implies that the period is characterized by severe waterlogging conditions in the area (see Fig. 4c) whereby GWTD as low as 5 cm below the ground surface has been recorded in some fields (16, 48, 41, 76, 101, 107,127, 177, 198, 208/9) during GWTD monitoring. Most plantation fields have shown an extremely high rise in GWTD compared to the preceding winter and autumn seasons (Fig. 3 and 4). This means that the response of the GW level to rainfall is quick and significant.

Border fields in the west, south, east, southeast, southwest, northwest, and northeast sides, which accounts for about 65% of the plantation area, have very shallow (<0.55 m) GWTDs. These areas of the plantation, as discussed earlier, have relatively deeper water tables during winter and autumn (Fig. 4 a-b). Furthermore, these areas, as shown in the stream/runoff network of the area (Fig. 5b), are known to receive high magnitude of runoff coming from the surrounding plateaus. From this result, it could be concluded that there is a change of GW flow pattern in this period, from the borders toward the central part of the plantation; thereby disturbing the normal drainage system of the area since water is usually drained toward the southwest (Fig. 2). This condition is especially challenging to water managers of the sugar estate.

Season 4: Spring (October)

This period is the beginning of the irrigation season, following the main rainy season. The GWTD is in the range of 0.70 to 1.20 m (average ≈ 0.95 m) below the ground surface (Fig. 4d). Almost 70% of the plantations have GWTD within 1.0 m and hence are critically waterlogged. The GWTD was slightly reduced compared to the previous summer season. Northeastern, eastern, and southeastern sides have relatively deeper GWTD compared with the other parts of the plantation fields. During this period, the border fields with very shallow GWTDs during the previous (summer) season and the central fields along the ex-Awash route continued to have relatively shallow GWTDs. However, it is important to note that the same border fields (16, 41, 76, 99, 101, 107, 123, 177, 208/9, 238), with very shallow GWTD during the summer season (Fig. 3), have shown greater reduction of GWTD (>0.5m) compared to the other parts (0.3-0.4 m) (Fig. 4). This shows that the GWTDs of the area would have been reduced significantly if drainage systems (particularly border drains) were effective. This ineffectiveness of the drainage system of the area, as discussed earlier, has an adverse effect on the GWTD condition during the subsequent periods (winter and autumn). Furthermore, it is logical to suggest from the results (Fig. 3 and 4) that the GW flow pattern returned back to its normal flow direction (toward the south and southeast) in this period, which was interrupted during summer (July, toward the center). That means the normal GW flow direction starts in October and continues until June.

Effects of Rainfall on the Rise and Variability of GWTD

Fig. 6a shows a graph of mean monthly rainfall (characterized by AMRR) and GWTD fluctuation for the period of January 1999 to December 2005. This figure illustrates the effects of extreme rainfall events and its stochastic behaviour (max. and min.) on the regimes of GWTD records of the study area. Fig. 6b illustrates the temporal variability of the mean GWTD values for the average piezometer records (2007-09). As shown in the bar-chart plot, the GWTD of the area is shallower in summer season, followed by spring, winter, and autumn.

The GW level is highly variable, mostly following rainfall magnitude and distribution patterns (Fig. 6a). Post-2002, however, the monthly and annual GW level fluctuations were relatively reduced irrespective of the rainfall magnitude and distribution pattern (Fig. 6a and Table 2). These characteristics of GW level fluctuations are evidence of other factors than rainfall, for the GWTD rise and fluctuation in recent years (post-2002). In the same period, the values of average annual GWTD showed a slight increment (Table 2).

Despite the above fact, as evident from Fig. 6b, rainfall is playing a leading role on the rise and variability of GWTD of the study area in recent time. The possible and convincing reason is due to the occurrence of an extreme climatic rainfall event in the area in 2008, which was an extremely wet period (strong La Niña) in the recorded history of the region (1954-2010). The highest average GW level change (rise of 0.9 m·yr^{-1}) in the history of the GWTD records (1998-2009) coincides with this extreme rainfall magnitude. The response of GWTD to this extreme rainfall event was rapid and significant.

Mean GWTD of the area increased abruptly by about 0.9 m within 2008 (Fig. 6b). This rapid rise of GWTD created a major concern for WSSE. The sugar estate, as observed by first the author during fieldwork in May 2009 and 2010, experienced the highest yield reduction since the inception of sugar estate because most of the fields were critically waterlogged. Waterlogging condition, in turn, resulted in late land preparation, cultivation, harvesting, and weeding operations. This condition has created awareness for the management of the sugar estate, for the first time, to start a rehabilitation of irrigation and drainage systems.

Conclusions and Recommendations

This study result clearly revealed that GWTD at WSSE was extremely shallow, at all seasons, exceeding the critical depth (1.5 m) recommended for sugarcane. It was characterized by a rise during summer and spring, and a gradual decline in winter and autumn due to water uptake by plants, decreased rainfall, and increased ET and GW discharge to streams and wetlands. Consequently, the direction of GW flow pattern in the cane fields, as suggested earlier, is subject to change in summer and spring based upon the seasonal GWTD status and topography of the area.

The analysis further indicated that the highest average fall (≈ 0.46m) of GWTD observed during autumn (with highest water demand) was almost comparable with the highest average rise (≈ 0.5m) observed during summer (mainly rainy). Consequently, there was only a slight rise in the GWTD in the period. In post-2008 the rise of GWTD

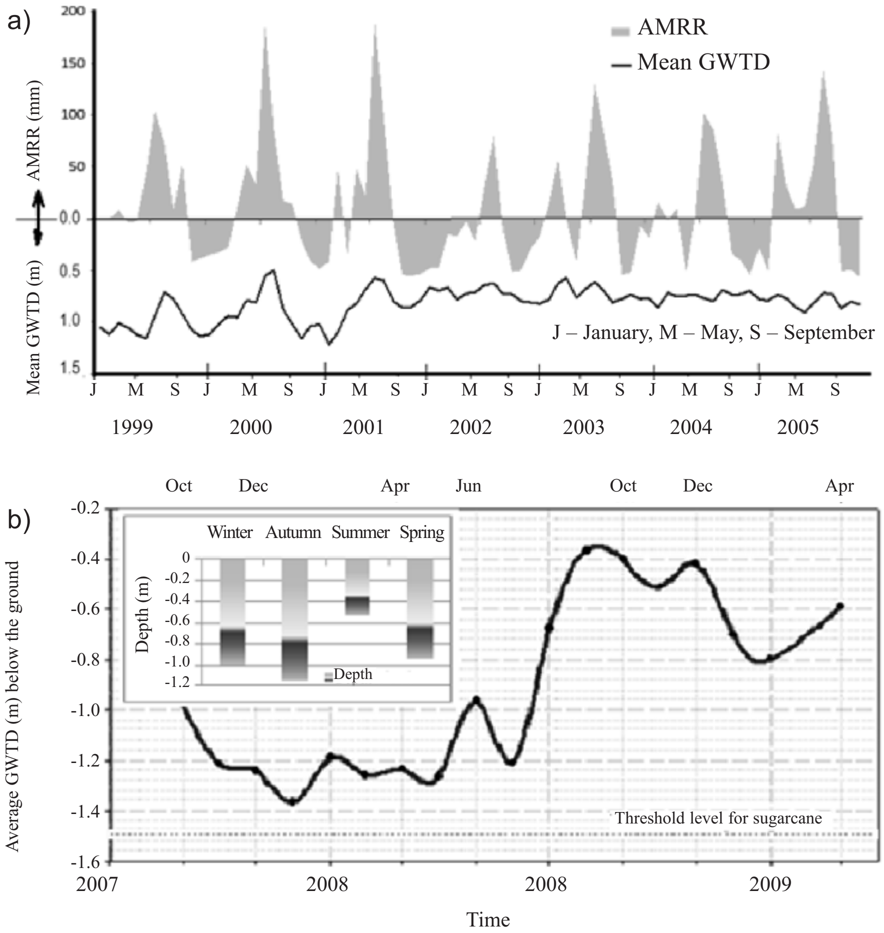

Fig. 6. a) The seasonal variability of mean GWTD as a function of AMRR (1999-2005); b) Hydrographs (GWTD vs time), and seasonal variability of mean GWTD (2007-09).

Table 2. Mean annual GWTD for some representative piezometers and rainfall (m) (1999-2005).

Piezometer No.	1999	2000	2001	2002	2003	2004	2005
44	-0.543	-0.360	-0.338	-0.323	-0.230	-0.195	-0.380
225	-0.371	-0.452	-0.452	-0.502	-0.360	-0.308	-0.587
134	-0.619	-0.663	-0.449	-0.182	-0.181	-0.178	-0.214
9	-0.458	-0.729	-0.763	-0.347	-0.338	-0.332	-0.341
101	-0.643	-0.619	-0.641	-0.538	-0.518	-0.504	-0.525
128	-0.680	-0.568	-0.855	-0.732	-0.647	-0.689	-0.690
166	-0.663	-0.648	-0.832	-0.554	-0.732	-0.981	-1.039
230	-1.912	-1.606	-1.184	-1.071	-1.326	-1.440	-1.429
214	-1.622	-1.362	-1.051	-1.022	-1.009	-1.001	-0.866
WRS	-2.568	-1.967	-1.946	-1.886	-1.886	-1.885	-1.947
Mean GW	-1.008	-0.897	-0.851	-0.716	-0.723	-0.751	-0.802
Mean Rainfall	0.382	0.624	0.620	0.359	0.669	0.579	0.700

Piezometer numbers are designated based on field number.
"-" negative sign indicates that it is below the ground surface.

during the rainy season was not compensated by the fall of GWTD during the non-rainy periods. This is mostly due to the failure of the surface drainage system of the area to drain excess water from the fields.

Although the root cause for the rise in GWTD of the study area is not yet fully identified, the current study clearly indicates that the recharge from direct rainfall on the plain and runoff from surrounding escarpments are the main causes responsible for the rise and fluctuation of GWTD. The evidence is three-fold:

(i) the water-table is shallower during the rainy (non-irrigation) period than in the irrigation period
(ii) the shallowest GWTD (<0.55 m) was observed at the border areas during summer season, which has relatively deep GWTD during autumn
(iii) the quick response of the GWTD to the extremely high rainfall in 2008 and the resulting significant rise of the GWTD.

The average annual rise of GWTD (0.9 m) observed in post-2008 was found to be greater than the total rise of GWTD observed in pre-2008 (between 1998 and 2008).

The authors would like to suggest that all the possible sources of GW recharge (such as rainfall, runoff, flooding, Awash river flow regime, irrigation return flows from fields, recharge from villages, seepage/leakage from night storage reservoirs and canals, inter-aquifer flows, rift system influence and climate change) could be possible causes for the rise of GWTD in the study area. Therefore, detailed investigations that include the entire possible causes of GW rise are highly recommended. Moreover, we recommend the adoption of a feasible management strategy to limit a further rise of GWTD in the area. One of the best strategies is the prevention of runoff coming to the plantation from the surrounding plateaus, especially from the western, southwestern and southern sides. This requires deepening and widening the border drains and creating the required slope for the drainage water to flow freely at the outlet point. Long-term over irrigation has a cumulative effect on the rise of the water table and can cause waterlogging and associated problems even if the border drains are effective in stopping the incoming runoff. Thus, efforts on the management of water resources, especially irrigation and drainage, in such areas are extremely important for the sustainability of irrigated agriculture.

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