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Status of Groundwater Table Depth Under Long-Term Irrigation in Wonji Plain: Concerns for Sustainability of Wonji-Shoa Sugar Estate, Upper Awash Valley, Ethiopia

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Abstract

The present study attempted to highlight the concerns of shallow groundwater table depth (GWTD) to the sustainability of Wonji-Shoa Sugar Estate (WSSE), Upper Awash Valley of Ethiopia. The recent magnitude and fluctuation of GWTD is mapped in ArcView GIS (using universal kriging technique) from the monthly GWTD monitoring data (2007-2009) using piezometer tubes. The study result clearly showed that the GWTD at WSSE was extremely shallow, showed great spatio-seasonal variability and rising trend; thus, threatening the sustainability of WSSE significantly. About 90% of the plantation fields have GWTD above the critical depth of 1.5 m below the soil surface and, hence, critically waterlogged. As a result, the estate is recently achieving only 55% of the production potential realized in the 1960s. Past trends indicate that the GW has the potential to inundate Wonji plain and is anticipated to devastate production during the next 10-15 years. Therefore, in order to sustain production system in the region, there is an urgent need to identify the possible causes of waterlogging and investigate the feasible remedial measures to combat its problems. The spatial mapping of GWTD with identified problematic areas, indicated in the current study, is believed to provide a tool for water management and, hence, crucial for the decision making and actions taking processes.

Keywords: shallow groundwater, piezometers, remedial measures, sustainability, waterlogging

1. Introduction

The rising food demands due to population pressure, increased frequency of drought and limited options for expansion of agriculture land have revealed the importance of irrigation development in Ethiopia. Irrigation development is being prioritized recently as one of the best alternatives for reliable and sustainable food security, income generation, livelihood improvement and development as a whole (Awulachew et al., 2007; Rufeis, 2008; Dinka, 2004, 2010a). The Government of Ethiopia gave priority for irrigation developments at various scales, especially in arid and semi-arid climatic regions. According to Awulachew et al. (2010) report, the country planned to increase the total area of irrigated land from the current 640,000 ha to 1.8 Mha in the near future. Accordingly, there is a massive irrigation development and expansion of the existing irrigation schemes.

The development of irrigated agriculture, if the water resource properly utilized and managed, has multi-directional benefits to economic development of the country. Equally, irrigation development also has negative consequences (e.g. environmental effects and social instability) if the irrigation water is not managed scientifically. For instance, most of the large-scale irrigated schemes in the Awash River Basin are affected by serious land degradation problems; mostly waterlogging and salinization. Extensive areas (> 20,000 ha) of irrigated lands in the Middle and Lower Awash Valleys (Amibara, Dofan, Dufti, Malka-Sadi, Malka-Warar, Matahara, etc) have been degraded due to over-irrigation and other forms of poor agricultural management (Alamirew, 2002; Awulachew et al., 2007; Girma & Awulachew, 2007) and the performances of the existing ones are not satisfactory (Dinka, 2012).

Groundwater table depth (GWTD) rising to the crop root zone is one of the most unfavourable effects of irrigation projects, whose problems tend to emerge over years (Esser, 1999). Different literatures (e.g., Kahlown & Azam, 2002; Asmuth & Knotters, 2004; Kahlown et al., 2005; Aslan & Gundogdu, 2007; Gundogdu & Guney, 2007; Dinka, 2010a) have well documented the adverse effects of shallow GWTD to human health, environment and crop production. Hence, it is a recognized fact that successful water management needs sufficient and reliable GW data. Water managers want to be informed about the status and variability of GWTD (Knotters & Bierkens, 2001) and the problems and prospects associated with shallow GWTD before it reaches irreversible stages.

Wonji-Shoa Sugar Esatate (WSSE) has been producing sugar for the last 60 years and is currently facing negative externalities. The main concern in the sugar estate, at present, is the rise of GWTD to the crop root zone and its associated problems; thus, challenging the sustainability of irrigated agriculture in the region. Sustainability in agricultural systems, according to (Pretty, 2008), incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods), and addresses many wider economic, social and environmental outcomes. Sustainable production refers to producing the maximum possible yield for the current generation from the available resources (land and water) without degrading the environment so that the future generation can meet their demands from the same resource. This concept of sustainable development was emerged popular since the Brundtland Commission Report (WCED, 1987).

The sugar estate has been experiencing great yield reductions in recent times (Dinka & Ndambuki, 2014), mostly because of waterlogging and its allied problems. Over the last decade, many researchers (Rahmeto Anito from 1998-2000, Habib Dilsebo from 2000-2005, Megersa O. Dinka from 2007-2010) have tried to address the GWTD of Wonji plantation by installing piezometers (Dinka & Dilsebo, 2010). Also, management of the sugar estate has been making various efforts to control the rise of GWTD in the past few years. Despite those efforts, GWTD continued rising and still impacting production and productivity. According to Dinka et al. (2013), the GWTD of the area has potential to inundate the Wonji Plain and devastate production in recent future (10-15 years). This indicates that the sustainability of the sugar estate is of great concern. The current study, therefore, aimed at mapping the GWTD with waterlogging class and then highlights the concerns of shallow GWTD to the sustainable production and productivity of WSSE in particular and to the region in general.

2. Overview of Wonji Plain

The study was conducted within Awash River Basin (*latitude: 8° to 12° N, longitude: 38° to 41.8° E, altitude: 250-3927 m.a.s.l*), Central Rift Valley of Ethiopia, in reference to WSSE (Figure 1). Awash Basin (Figure 1, Left) is bounded by Danakil depression in the north, Abbey basin in the west, Rift Valley Lakes (RVL) basin in the south, Wabe-Shebelle basin in the south-east and Somalia and Djibouti in the east. Awash River, the only perennial river in the Awash Valley, is the most important and utilized river basin in Ethiopia. The length of the main river is about 1,200 km. The river, after flowing about 250 km from its origin, enters into the Main Ethiopian Rift (MER). It originates from central Ethiopian highlands (Ankoobar in Ginchii area), west of Addis Ababa with an elevation of about 3927 m and flows towards north-east along the rift valley into the Afar triangle (with an elevation of 250 m), where it terminates in Lake Abhe on the Ethiopia-Djibuti border.

WSSE (Figure 1, Right) is situated (*8.43° N, 39.28° E, 1530 m.a.s.l.*) in the flood plain of Awash River, Wonji plain, Upper Awash Valley, Oromiya Regional State, just immediate downstream of Koka Dam at a distance of about 110 kms south east of the capital city. It is crossed by Awash River, which divides WSSE into west-bank and east-bank. The estate (including out growers) has a total area of about 8000 ha (excluding the current under expansion) and the factory has a total crushing capacity of 3500 TCD (ton of cane per day). The estate proper has about 6,100 ha of cultivated land and the remaining parts are occupied by residential area, factory, roads, canals and storage reservoirs. The estate proper is divided into nine management sections (refer the sections designated by R, L & E in Figure 2), each has its own section managers. Sugarcane is the most dominating crop grown in the plantation, with few crotalaria and haricot bean on heavy black clay soil during fallow period in the case of cane after fallow (CAF) system.

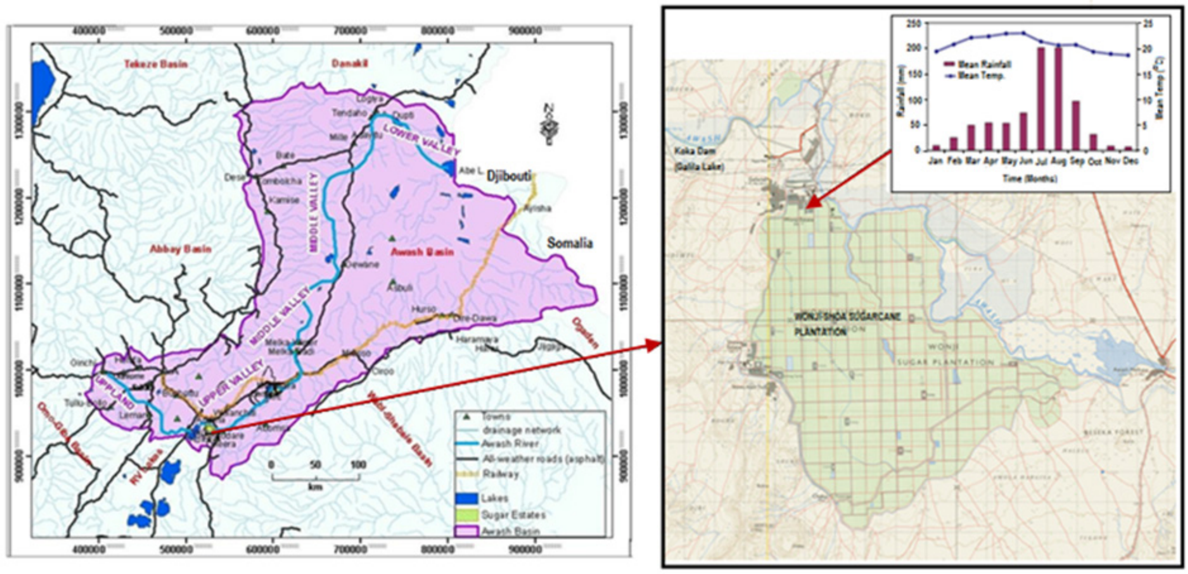

Figure 1. Study area Left: Awash river basin including its sub-divisions and bordering basins (Source: Dinka, 2010); Right: The location of WSSE and its climate

WSSE is one of the key and early large scale irrigation schemes in the Awash River Basin. Its establishment in the basin marked the first era of large-scale irrigation development and era of domestic sugar production in the Ethiopian history. According to the witness from indigenous people and others, the first modern and commercial large-scale irrigation system in Ethiopia was started at Wonji plain at the end of 1930 by Italians to grow sugarcane, during their second invasion of the country. This is evident from the Italian naming adopted up to date in WSSE (e.g., *'Mallang'* for furrow, *'Italian Canals', etc*) (Dinka, 2010a). The plain was a sparsely populated swampy area, and frequently affected by flooding (due to Awash River flow characteristics) and Malaria infestations.

Italians drained most of the Wonji swampland area in 1938 and then constructed long canals (currently named '*Italian canals*') and started growing sugarcane. Though certain group of people tried to continue using the farm after the evacuation of Italians from the country (1941), due to their defeat in the World War-II, they were unsuccessful and the farm was abandoned in 1946. In 1948, the Dutch Company named H.V. Amsterdam came to the area and started farming based on the agreement made with Hailasillasse-I regime by displacing the local indigenous people, Karayyuu (one of the semi-pastoralist Oromo tribe named Jillle) living in the Awash Basin. Wonji Factory was inaugurated and started producing the first bags of Ethiopian sugar in 1954 (March 20) (Dinka, 2004).

Wonji plain experiences bimodal and erratic rainfall distribution pattern. The long-term average annual rainfall is about 830 mm, mostly (≈76%) falling during the main rainy season (Jun-Sept) (Figure 1, right top). Temperature of the area (15.2–27.6 °C) is specifically suitable for sugarcane. The climate of the area is between the transition of the two zones: semi-arid to dry sub-humid. The soils of WSSE are of alluvial-coluvial origin developed under hot, tropical conditions. Texturally, the soil can be categorized into light (course textured) and heavy (clayey black) soils. The heavy clay soils (≈70%) are the dominant soil group in the plantation and characterized by inherent problems such as compaction, poor structure, shallow GWTD, etc. Consequently, these soils are regarded as problematic by plantation's agricultural managers. The geology of Woni plain is characterized by volcanic activities and rift tectonics, which is characteristics of the Main Ethiopian Rift (MER) (Dechasa, 1999).

A network of irrigation (≈280 km) and drainage (≈203 km) canals are used in the area. Irrigation water is diverted to the estate from Awash River using centrifugal pumps and then to masonry lined main canal. There are seven main and twelve tertiary night storage reservoirs distributed across the estate to store water during the continuous pump operation in the night time. Field water application is through block-ended furrow irrigation system and the excess water from the plantation fields are drained through the network of surface drains. The network of irrigation system consists of primary canals (480 m), secondary canals (≈76 km) and tertiary canals (≈203 km). There are also small canal structures (distribution tanks, flow divisors, road crossings, turnouts, canal falls, regulating, measuring, etc). Detailed description about the study area (location, topography, climate, soils, geology, land cover/use, irrigation water management) can be obtained from other publications (Dinka et al., 2013; Dinka & Ndambuki, 2014).

3. Materials and Methods

3.1 Data Collection

Fortnight GWTD of Wonji-Shoa sugarcane plantation (estate proper) was monitored through a network of piezometers (all PVC tubes: Φ = 80 mm and length = 2 to 3 m). The piezometer sites were selected purposively in order to cover the range of soil types, water sources (Awash River, Night Storage Reservoirs, Irrigation Canals and Drainage Canals) and topographic conditions; thus, fairly distributed all over the study area (Figure 2, Left). The PVC tubes were installed manually using auger tubes (Figure 2, Right). The piezometer locations (latitude, longitude, elevation) were registered using hand held Geographic Positioning System (GPS). GW depth monitoring was commenced (Oct 2007) just after piezometer tube re-installation and continued until July 2010; with the monitoring frequency of twice per month. Water levels were monitored manually using a graded tape that provides sound and light signals when it touches water in the tube. Of course, care was taken to collect the GWTDs in all the tubes in the minimum possible time.

In addition to GWTD monitoring using PVC tubes, an attempt was made to collect ancillary data from different sources through informal and formal discussions. The present and past conditions of the area were obtained from the elders of the indigenous people of the locality, researchers, previous reports and own personal observation during field visits. Meteorological data, topographic and digital plantation base maps were collected from the database of the sugar estate, friends and researchers. The plantation base map (CAD format) illustrating all the roads, irrigation and drainage networks, field plots and Awash River were collected from WSSE.

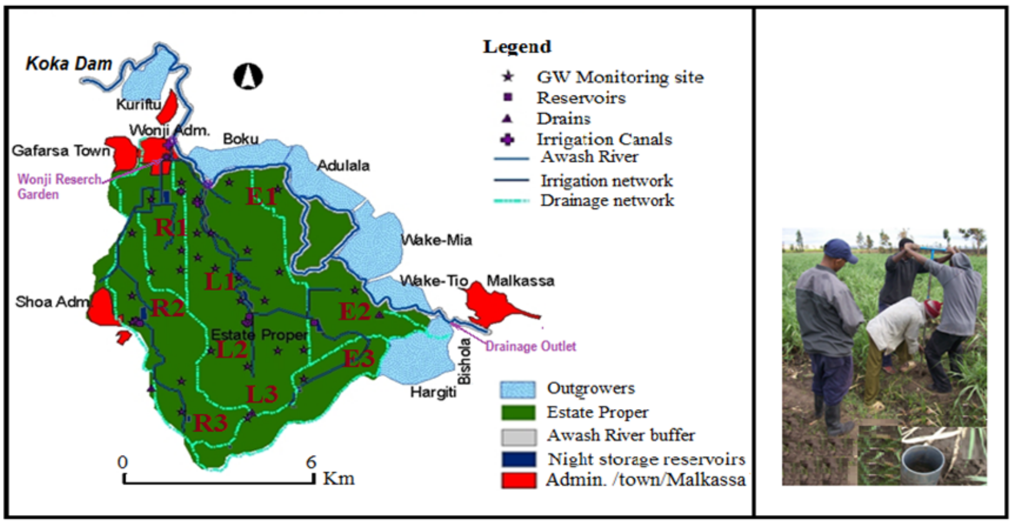

Figure 2. Left: Wonji-Shoa Sugar Estate (estate proper and outgrowers) showing GW monitoring sites, storage reservoirs, networks of irrigation and drainage canals, administrative areas, and villages/towns (Dinka & Ndambuki, 2014). Right: PVC tube manual installation at WSSE using auger tubes and the PVC after installation. *Note that R refers to Right section, L refers to Left Section and L refers to middle section*

3.2 Data Analysis and Interpretation

The observed GWTD values were analysed for monthly, seasonal and annual values in excel spreadsheet. In the present case study, the average GWTD maps were produced from the monthly observed GWTD point measurement data between 2007 and 2010 by the help of Universal Kriging (UK) technique available in ArcView (3.3) GIS software package, since the GWTD of the area exhibit normal distribution (Dinka et al., 2013). With the help of these maps, the waterlogged areas risky for sustainability of WSSE were delineated. Before performing kriging, the basics of geostatistical analysis (semivariogram model selection and model parameter estimation, Gundogdu & Ginley 2007) were made. Different reports (e.g., Kumar & Ahmed, 2003; Gundogdu & Ginley, 2007) clearly indicated that geostatistical (kriging) techniques provide a set of statistical tools for analyzing spatial variability and spatial interpolation. The underlying premise in geostatistics (kriging) is that the measured GWTD values can be used to estimate the values for the other areas where measurements were not made due to economic reasons. Such system is especially effective in areas where the GWTD show strong spatial autocorrelation.

Depending on the findings of this study, detailed explanations were provided regarding the concerns of shallow GWTD for the sustainability production and productivity of the sugar estate in particular and environment of the region in general. The ancillary information and the GWTD maps played a great role for the explanations. Since it is difficult to address all the possible effects of waterlogging, scientific suggestions were made depending on the prevailing actual condition of the area and other findings. However, an attempt was made to support most of the discussions by referring to other available reports (published and unpublished) from the area and elsewhere in the world.

4. Results and Discussion

Here, the status of the recent GWTD was presented from montghly groundwater monitoring data using 30 piezometers. Moreover, the trend in production and productivity of the sugar estate since its inception is presented briefly. Finally, implications of shallow water table to the sustainability of the region are presented.

4.1 Status of Groundwater-Table Depth

Figure 3 presents the spatial variability of GWTD values. The GWTD map and classes shown in Figure 3 was produced in ArcView GIS (3.3) using UK interpolation technique (quadratic drift model), which was established from the mean average GWTD values that were observed over the monitoring periods (2007-2010). The same figure at the right bottom presents the average annual trend rates (rise or fall) of GWTD for selected representative piezometers over the recorded period of 1998-2010. The areal coverage by each GWTD class are summarized in Table 1.

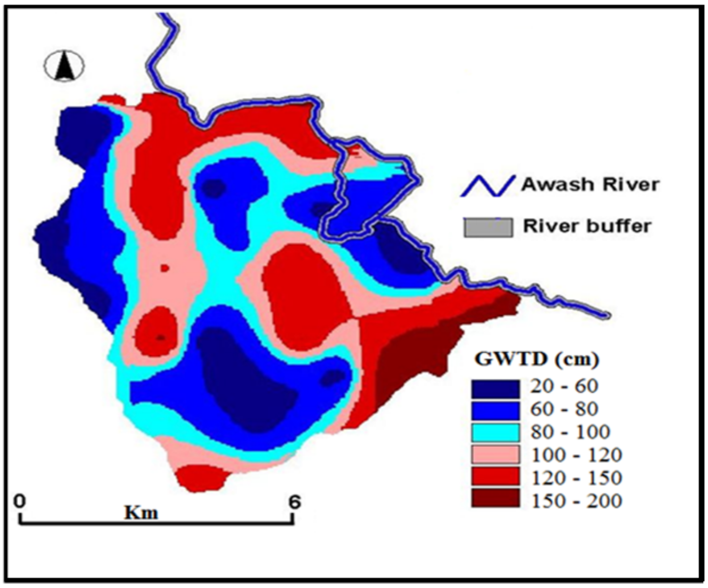

Figure 3. Delineated GWTD for WSSE (Estate Proper) for the average recorded period (2007-2010)

Table 1. Areal proportion of waterlogging class for sugarcane crop

S/N	Mean GWTD (cm)	Area Ha	Area %	Waterlogging Class Kahalown et al. (2005)	Waterlogging Class FAO/UNEP(1984)
1	20 – 50	915	15	Severe	Critical
2	50 – 100	3538	58	Critical	Critical
3	100 – 150	1037	17	Critical	Moderate
4	150 – 200	610	10	Moderate	Moderate

The delineated waterlogging condition (Figure 3 and Table 1) depict that the mean average GWTD of the study area ranged between 0.2 m and 2.0 m; thus, all plantation fields are classified to be shallow (i.e. waterlogged). Surprisingly, ninety percent of the area has average GWTD less than 1.50 m below the ground surface, hence, classified to be critically waterlogged since they are above the critical depth (1.5 m) recommended for sugarcane crop (Kahlown et al., 2005). Approximately, 10% of plantation fields have GWTD below the critical depth and 15% have extremely shallow GWTD (< 0.5 m). As per the FAO/UNEP (1984) guidelines (Masoudi et al., 2006), about 73% of the total plantation fields are critically waterlogged and the remaining proportions are moderately (potentially) waterlogged (1-3 m).

From Figure 3 (left), plantation sections experiencing critical waterlogging condition can be easily envisaged. The central (ex-Awash route) and southern parts as well as border areas (northwest, west, east and south) of the plantation were relatively very shallow (GWTD < 0.80 m). These areas were also identified as problematic fields by the management of the sugar estates (confirmed during the seminar presentation by the first author on water management to estate's professionals in 2009). Problematic fields, as per the agricultural management of the sugar estate, refers to those parts of the plantation fields that are heavy black clay soil type and affected by serious waterlogging, thereby creating problems for land preparation, harvesting and other mechanical operations.

Figure 4 presents the average annual trend rates of GWTD values. It is clear from Figure 4 (bottom) that most of the piezometers have showed a rising annual trend. The highest rise (15 cm) and highest fall (7.5 cm) occurred for piezometer installed in field 63 and 178/9, respectively. Surprisingly enough, both piezometers are situated near night storage reservoirs. Piezometer installed at field 178/9 is expected to have a rising trend since it is located near night storage reservoir. There is a higher possibility for seepage and deep percolation loss from night storage reservoirs of the area since they are earhen embankment type without lining.

As shown in the bar-chart plot of Figure 4 (top), the GWTD of the area is shallower in summer season, followed by spring, winter and autumn. Dinka and Dilsebo (2010) reported that most of the piezometers have showed great fluctuation and periodic response. The fluctuation is an indicator for the seasonal change in the direction of GW flow pattern in the study area, which strengthens study made by Dinka et al. (2013). Dinka et al. (2013) also stated that the direction of GHW flow pattern in the cane fields is subjected to change in summer and spring seasons depending upon the seasonal GWTD and topography of the area.

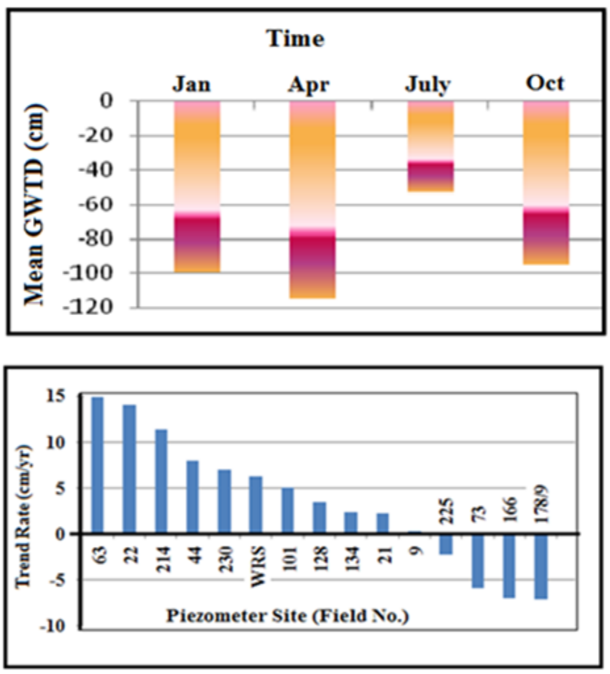

Figure 4. Top: Mean GWTD at different seasons; Bottom: Mean Annual trend rate (rise/fall) of GWTD for some representative piezometers over the recorded period (1999-2010)

4.2 Status of Production and Productivity

The status of waterlogging discussed earlier revealed the potential for significant yield reduction at WSSE. This is due to the fact that sugarcane yield is negatively affected when the GWTD rises above the critical depth (1.5 m) below the ground surface. The long-term average annual production (field cane and sugar yields) illustrated in Figure 5 confirms this argument. As expected, production and productivity of the area have reduced significantly in recent time (post-1990s). The maximum productivity attained during the 1960s has not been sustained in the past about 4-5 decades. As shown in bar chart of Figure 5, the highest yield (300 ton/ha) and lowest yield (110 ton/ha) were obtained in the 1960s and 1990s, respectively. Significant yield reduction is already happening due to the fact that the sugar estate is recently harvesting about 55% (≈163 ton/ha) of the created maximum potential yield in the 1960s. This yield reduction has significant economic losses (Datta & de Jong, 2002).

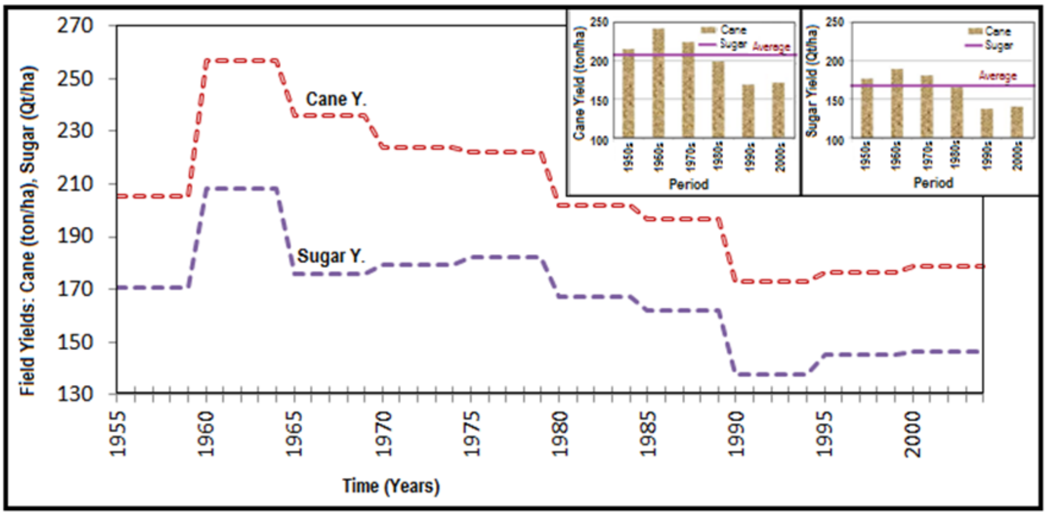

Figure 5. Long-term (1954-2010) average annual production at WSSE (*5-years moving average & decadal values*)

The status of GWTD, in the study area, has potential to cause further yield reduction and/or total devastation in the near future. Expecting the past rising trend amount 0.035 m/yr (Dinak & Dilsebo, 2010), the average GWTD below the surface in WSSE will become 0.3 - 0.5 m in the coming 10 -15 years. GWTD less than 0.5m is a very critical condition for sugarcane crop, and hence, the total devastation of the production, with no mitigation measures, may occur in the near future. Thus, it is logical to suggest that the sustainable production and productivity of WSSE, in Wonji plain, is under great risk due to waterlogging.

Different study reports (e.g. Wallender et al., 1979; Kahlown et al., 1998; Prathapar & Qureshi, 1999; Kahlown et al., 2005; Dinka, 2010a; Liu & Luo, 2011) have indicated that shallow GWTD is expected to contribute to the crop ET through capillary rise. A study made by Wallender et al. (1979) indicated that shallow groundwater tables replaces about 60% crop ET. Prathapar and Qureshi (1999) suggested that irrigation could be reduced by 80% under shallow groundwater conditions. For sugarcane crop, the GW contribution increases as function of increment in GWTD (Kahlown et al., 2005). In the case study area, about 90% of the plantation areas have GWTD less than 1.5 m (Figure 3). Consequently, significant GW contribution to crop ET is expected, in some cases exceeding the crop water requirement; hence, completely eliminate irrigation requirements without compromising on crop yield. Thus, effective drainage is required instead of irrigation for some periods of time depending upon the crop growth stage and GWTD condition. This strategy is very important to maximize productivity and control the GWTD at desired level. This requires quantification of groundwater flux from shallow water table using appropriate modelling techniques.

4.3 Implications of Shallow Groundwater to the Region

This study result (Figures 3-4 and Table 1) clearly showed that the GWTD of WSSE is very shallow, experiencing great spatio-seasonal fluctuations and showed a rising trend. Such characteristics of GWTD are expected to negatively impact the socio-economics and environment of the region; thus, a concern for the sustainability of the sugar estate. The most important negative effects are on crop production and productivity (discussed earlier), machinery performances, agronomic practices, yield-increasing interventions, soil behaviour and performance, etc. The potential impacts of shallow GWTD have been extensively reviewed (e.g., Grable, 1966; Feddes, 1981; Bouwer et al., 1990; Datta & de Jong, 2002; Kahlown & Azam, 2002; Barrett-Lennard, 2003; Asmuth & Knotters, 2004; Kahlown et al., 2005; Tsubo et al., 2006; Aslan & Gundogdu, 2007; Boling et al., 2007; Gundogdu & Guney, 2007; Dinka, 2010a).

The status of waterlogging in the study area is indicator for the deterioration of soil quality and hence, environmental degradation because of the significant salt and water contribution, thereby affecting the soil behavior and performance (Kahlown et al., 2005). Waterlogging causes a condition of hypoxia (low O_2 concentrations) in soils because of the low solubility of oxygen in water (0.28 mol m^{-3} at 20 ºC), the low diffusivity of oxygen in water-filled pores and the rapid use of dissolved O_2 by bacteria and roots (Barrett-Lennard, 2003). Hperoxia in soils imposes challenges for plants, as roots normally require O_2 for optimal production of adenosine triphosphate (ATP) from sugars. Thus, the transfer of roots from drained (aerobic) to waterlogged (anaerobic) conditions can decrease ATP production by about 95%, which has an important consequence for the metabolism activity of plants growing under waterlogged soils as ATP is the fuel for nearly all cellular processes. In addition to imposing oxygen shortage, waterlogging impedes the diffusive escape and/or oxidative breakdown of gases, causes the accumulation of ethylene and other products produced by plant roots and anaerobic bacteria (CO_2, ethanol, lactate, etc) (Barrett-Lennard, 2003; Bennett et al., 2009). The adverse impacts of waterlogging on the soil quality (physical, chemical and biological) have been extensively reviewed by different research reports (e.g., Grable, 1966; Vartapetian & Jackson, 1997; Barrett-Lennard, 2003; Bennett et al., 2009; Dinka, 2010a).

WSSE had already experienced most of the impacts of waterlogging. The most direct and currently visible economic impacts are on machinery operations (land preparation, cultivation, harvesting, etc), agronomic practices (weeding, fertilizing, cultivation, etc), yield-increasing interventions (eg., crop varietal selection, optimum planting date, optimum dry-off period, ratoon reshaping, varietal selection, cane cycling) and ultimately on crop yield (quantity and quality). Also, there are preliminary indicators for the degradation of soil quality (especially fertility) of the study area. Some of the negative consequences of shallow GWTD to WSSE, in particular, and to the region, in general, are presented as bellows. The discussions are mostly limited to the impact of waterlogging on, machinery operations, yield increasing interventions and groundwater pollution. The consequences on sugarcane crop production and productivity is briefly presented earlier under section 4.2.

4.3.1 Difficulty in Machinery Operations

Waterlogging conditions are creating serious problems on machinery performances during land preparation, harvesting and ratoon-reshaping operations. These problems are becoming a bottleneck to the production and productivity of the sugar estate since majority (≈80%) of production costs are related to these operations. As the result, the sugar estate is incurring excess production cost in recent years (database of WSSE). The problems in seed bed preparation and delayed harvesting operations are resulting in late seed plantation and low burning to cane weighing (BTW), respectively. The first problem (late seed plantation), in turn, since sugarcane has optimum planting period, affects the normal growth of sugarcane (*germination, stock population, tillering, stock height*), which are indicators for final yield (*quality and quantity*). Delayed harvesting operation, beyond the normal growing period, has economic implications because of its effects on the final yield as well as land preparation (in case uprooted). The later effect, in turn, will result in the problem of delayed seed plantation. The first harvesting effects are reduction of crop yield per hectare per month as well as the deterioration of sugar quality (sucrose accumulation) due to sucrose inversion (Dinka, 2004).

4.3.2 Interference With Yield Increasing Interventions

Waterlogging interferes with yield-increasing interventions (Boling et al., 2007; Dinka, 2010a). In the study area, waterlogging is affecting the different agronomic practices such as crop varietal selection, optimum sowing date, optimum dry-off period, ratoon reshaping, cane cycling, weeding, assimilation of agro-chemicals, etc. According to the report made by the agricultural management of the sugar estate in 2007, during the annual agricultural conference, waterlogging is seriously affecting crop varietal selection, cane composition, crop cycling and dry-off period.

In waterlogged fields, the Plantation Department of WSSE is obliged to plant only resistant cane varieties (*CO-421 and/or M165/38*), though the performance of these cane varieties are less compared with other commercial cane varieties available in the area (eg. *B52-298 or N-14*). These cane verities also have high fiber content, are susceptible to disease (e.g., smut) and probably flowering. That means waterloging problem has become one of the governing factors in determining the composition of cane and varietal selection. The cane varietal selection is creating differences among managers of agriculture and factory. The sugar factory management prefers cane varieties which are easily millable, with good juice quality, etc.

Waterlogging is also affecting the performance of cane cycling. Some fields were demoted (ploughed-out or uprooted) before completing one crop cycle (usually 6-9 years at WSSE). The productivity of certain sugarcane cultivated lands is valued based on the number of successive cuttings (ratooning). Prolonged ratooning will reduce the production cost compared to plant canes. The production result (2000-2010) of the area (database of WSSE) reveals the deterioration of yield in those parts of the plantation affected by serious waterlogging. Consequently, fields affected by very critical waterlogging were uprooted after 2^{nd} and 3^{rd} ratoon (i.e., 3^{rd} and 4^{th} cutting) stages because of their poor performance far below expected amount. This is not economical as far as ratooning and cane production policy is concerned owing to the large cost (~70%) of cane production associated with land preparation discussed earlier. Usually, uprooting below third-ratoon (4^{th} Cutting) is considered to be not economical.

Waterlogging also affecting the practice of optimum dry-off period (achieved through withholding moisture and nutrient supply for a matured cane) of the study area, which results in late harvesting and inversion of sucrose content discussed earlier. The later effect (i.e., sucrose inversion), in turn, impacts the sugar quality and quantity significantly. Though sugarcane, to obtain maximum potential yield, require adequate moisture supply throughout the growing periods (*i.e. establishment, tillering, stem elongation and maturity*), cane harvesting should be done at the most suitable moment when an economic optimum of recoverable sugar per area is reached. In the case study area, however, the GWTD is shallow throughout the growing season and, hence, as mentioned earlier (section 4.1), contribute water to sugarcane even if irrigation water is withheld. Studies (e.g., FAO, 2001; Dinka, 2004) have indicated that water surplus during the late growing periods (*stem elongation and maturity*) has adverse effects on the yield than the water surplus during the first periods (*establishment and tillering*). Excess moisture during the maturity (yield formation) period has an accelerating effect on flowering, which is not desirable as far as sugar production is concerned due to the fact that it reduces sugar yield (both quality and quantity) significantly.

4.3.3 Contamination of Groundwater and Environment

WSSE is using different agrochemicals (herbicides, pesticides, inorganic fertilizers and organic compounds like filtercake) for the last 60 years. As per Bouwer (1990), the rising of water table are expected to decrease residence time for infiltration causing fast downward mobility of agro-chemicals into the shallow GWTD and contaminating them quickly. The residence time of deep percolation water in the vadose zone determines the arrival of possible pollutants at the groundwater. Groundwater of the area is used for drinking, domestic and other purposes. The leaching of agro-chemicals to GW of the Wonji area will bring a long-term threat to the sustainability of WSSE, in particular, and health and environmental protection, in general. Hence, a detailed investigation on groundwater quality of the study area is highly recommended.

5. Conclusions and/or Recommendations

The study result clearly revealed that GWTD at WSSE was extremely shallow and showed great spatio-seasonal variability. Approximately, 90% (≈5500 ha) of the plantation fields are critically waterlogged (GWTD <1.5 m), with 15% affected by GW inundation (<0.5 m). The GWTD of Wonji plain remained high, probably due to the recharge from rainfall, and the poor performances of irrigation and drainage systems in relation to topography of the area. The waterlogging condition had caused considerable economic and environmental consequences to the study area; mostly on crop production and land productivity. WSSE is producing sugar for the last 60 years, at the expense of unsustainable use of the available resources and currently facing different problems. For instance, the sugar estate is experiencing greater yield reduction (≈45%) in recent time, mostly because of waterlogging and its allied problems. Waterlogging problems have been reported every year since 2000 by different divisions (*Plantation, Agronomy, Harvesting, Land Preparation and Clearance*, etc) during their annual agricultural conferences and no solution has been obtained. Despite different management efforts, GWTD continued rising.

Past trends indicate that the GWTD has the potential to inundate Wonji plain and is anticipated to devastate production during the next 10-15 years. As the area is situated in the uppermost part of MER, other factors are expected to exacerbate its rise even in the future. The GWTD will continue rising in the future following the topographic features of the area, resulting in obvious repercussions and grave consequences on the environment and socio-economics of the region. Hence, GWTD will continue to be a threat in Wonji Plain. The waterlogging and other allied problems have potential to devastate production at WSSE, inundate the villages, bring other environmental problems, etc; thereby challenging the socio-economics of the society (>50,000) who depend on the sugar estate directly or indirectly.

It is most likely that waterlogging will affect the sustainability of WSSE greatly in the future. Unless effective and feasible strategies for mitigating GW rise are developed and the existing problems are tackled soon, severe crises in the region are inevitable. New and concrete solutions are required in order to maintain the resource base, improve agriculture productivity and sustain irrigated agriculture in the region. Therefore, a comprehensive study that includes all the possible sources of GW recharge should be studied in depth. Above all, the authors view is that the sustainability of irrigation scheme in the area largely depends on the appropriate water management measures, mostly irrigation and drainage system. Managing irrigation and drainage system not only helps to control the rise of GWTD, but also to maximize the water productivity of sugarcane. Thus, radical redesign, rehabilitation and optimization of irrigation and drainage systems plays a leading role for the control of GWTD in the sugar estate and hence, should be prioritized by the managers of WSSE with due attention as water table management strategy. This demands a comprehensive water management and planning strategy requiring a number of functions that are closely related. It is helpful if irrigation scheduling in the area depends on groundwater contribution. This requires quantification of groundwater flux using appropriate modelling techniques. Moreover, a detailed water budget modeling in such shallow water table area is extremely important to understand the interaction of groundwater with rainfall, irrigation and drainage practices.

Finally, the spatial mapping of GWTD with identified waterlogging classes, indicated in the current study, is very crucial and provides vital information for reclamation measures to be taken for sustainable production and productivity of the sugar estate. It provide a tool for water management; hence, helpful in decision making and actions taking process. It urges the concerned bodies (planners, managers, researchers) to design and implement appropriate corrective measures to optimally utilize the available water and land resources.

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