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The Impact of Climate Change on Water Resources, Agriculture and Food Security in the Ethiopian Rift Valley: Risk Assessment and Adaptation Strategies for Sustainable Ecosystem Services

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Table of Contents

The Impact of Climate Change on Water Resources, Agriculture and Food Security in the Ethiopian Rift Valley: Risk Assessment and Adaptation Strategies for Sustainable Ecosystem Services

Executive Summary

A multidisciplinary team of researchers including water quality experts, climate scientist and hydrologists were drawn from Duke University (USA), Addis Ababa and Jimma Universities (Ethiopia) and investigated **the linkages between climate change, water resource quality and availability, agricultural productivity, food security and livelihood in the Main Ethiopian Rift (MER) and to inform decision-makers how adaptation to climate change impacts on water resources and agriculture might be enhanced**. We have addressed the following specific aims to achieve the objective of the project:

Aim 1: Evaluate water quality in MER for their suitability to agricultural use and how climate change impacts influence the shifting in reliance of different sources of water (shifting from scarce surface to groundwater resources).
Aim 2: Evaluate farmers' perception, coping mechanisms (adaptation strategies) for dealing with changes in agricultural productivity, and their constraints to adaptation in changing climate.
Aim 3: Establish hydrological model for the Rift Valley for simulations and predictions of surface water availability given evolving patterns of climate change and water demands.

The study area is situated in the Main Ethiopian Rift (MER) Valley that encompasses the Ziway-Shala basin, Awasa basin, and Abaya-Chamo basin (**Fig. 1**). Water quality assessment were conducted in all basins, whereas the agricultural household survey were conducted across different agro-climatic zones in the Ziway-Shala basin for farmers' perception, barriers and adaptation options of climate change (**Fig. 2**). The study collected water samples and primary information from farmers in a participatory fashion. Moreover, discussions were made with water bureaus, local agricultural institutes and development agents (DAs) to explore additional information on the farming systems, socio-economics, natural resources, crop production of the study areas.

A total of 162 water samples from 135 groundwater wells, 8 cold springs, 8 rivers and 11 lake samples were collected in the basins for water quality assessement. Based on the Food and Agricultural Organization (FAO) irrigation water classification, most of the samples were found not suitable (categorized as severe) for agricultural use as they affect soil permability and reduce water infilteration. This includes 76 (56%) of the groundwater samples and all of the rift lakes except Lake Ziway. Likewise, significant proportion of the studied waters are in excess of bicarbonate, boron and residual sodium carbonate (RSC) that are deterimental for irrigation use. High Salinity and SAR (Sodium Adsorption Ration) values were found mostly in the Ziway-Shala basin which is currently under high pressure of surface and groundwater demand for farmings.

Our preliminary modeling using a single IPCC AR5 model – HadGEM2 ES –indicates that precipitation in the studied region may decrease even as temperature increases. These dual effects could reduce water availability and compromise water supplies for surface water dependent communities, and may increase dependence on groundwater which is already likely be detrimental to agricultural use.

Most farmers reported that lack of rain is one of the main constraints in agricultural productivity and many also indicated that rainfall is becoming more erratic. In the last 5 years, 66.7% of the farmers have experienced crop failure on average of 1.6 and 0.5 times in the rift floor (<1750 m.a.s.l) and highlands (>2100m.a.s.l) respectively. 80% of the farmers in the rift floor and 22% in the highlands had at least one crop failure in the last 5 years. It appeared that agriculture in the rift is about 76 % higher in crop failure than the highland areas. The crop failure causes some of these households not to meet their food needs and rely partly on food assistance, thus food security is a concern in

the region. The adaptation methods identified include use of different crop varieties of high yield, early maturing seeds are key climate change adaptation mechanism. Large proportion of farmers applies fertilizer and practice crop rotation to improve their farming. Some use terracing, afforestation, and conservation of natural resource and irrigation to protect environmental degradation. The main barriers include lack of: access to water, credit or saving, lack of appropriate seed, knowledge and information on weather and climate.

Overall, large fraction of the MER groundwater have a significant water quality problem that could jeopardize the agricultural sector, particularly of the horticulture and floriculture sector that are the most vulnerable as they mainly depend on groundwater for irrigation. This study also explored and identified the perception, adaptation and constraints of farmers' to adaptation across the highland to the rift floor. The results were showed that the rain-fed agriculture is considerably threatened by changing climate and crop-failure is prevalent in the rift floor within the Ziway-Shala basin, where most farmers have limited access to alternative water for irrigation. The outcomes of this study help decision-makers to design feasible strategies for adaptation measures and food security policies that help farmers better adapt with changing climate and to improve their livelihood.

1. Introduction

Recent climate change impact assessment studies have indicated that changes in rainfall (amount and variability) and increase in temperature are causing stresses on agriculture, water as well as human health, and likely to continue to progress negatively in the future (IPCC, 2001; 2007). Although the precise extent of these changes and their consequences is subject to considerable scientific uncertainty, there is high confidence that these factors significantly impact the agricultural sector, and the socio-economic and ecosystem functioning of most climate-vulnerable regions of developing countries. This is particularly the case for African countries that are characterized by semi-arid and arid climatic condition where the domestic economy heavily relies on rain-fed based agricultural sector which is significantly impacted by changing climate. One of the East African countries of this concern is Ethiopia with the current population about 82.4 million (CSA, 2012) and agriculture contributes livelihood of over 80% of the population and 40% of the GDP (Alemayehu, 2006). In Ethiopia, the close link between climate and Ethiopia's economy is demonstrated by close pattern of rainfall variability and GDP growth (World Bank, 2006).

The agricultural sector in Ethiopia including other African countries use low capital intensive agricultural technologies that results in low productivity and income that constrain farmers' capacity and options to adaptation under climate change (Dinar et al., 2008). The low adaptive capacity coupled with other environmental factors including precipitation variability, population pressure, natural resource degradation and water quality and supply will continue to harm the agricultural sector. With regard to water resources, any changes in hydrological balance such as change in runoff due to climate change may limit surface water supply for irrigation which is already in high demand and may force shifting to poor quality groundwater resources. Water quality studies in the Main Ethiopian Rift (MER) Valley, which is the focus area of the current study, revealed that the groundwater and surface water resources of the region are characterized by high salinity (e.g., Na, Cl, and B) that determine their use for irrigation (Rango et al., 2010; 2012). In such case, irrigation water quality should be evaluated as one of the factors that may affect the agricultural sector. The quality of irrigation water may affect the soil physical conditions such as permeability and crop quality and yields especially in the saline and alkaline soil areas. Salinity and sodium hazard indicators can be used as a criterion to find the suitability of irrigation waters (Gratten, 2002; Nishanthiny et al., 2010). Sodium adsorption ratio (SAR) is an effective evaluation index for most irrigation water (Richards, 1954; Ayers and Westcot, 1985).

Consequences of climate change and other environmental factors on the agricultural sector have to be dealt with proper adaptation mechanisms to building resilience and reducing vulnerability. In the agricultural sector, the frequently implemented adaptation methods are the use of new crop varieties and livestock species that are better suited to drier conditions, irrigation, crop diversification, adoption of mixed crop and livestock farming systems, and changing planting dates (Dinar et al., 2008; Kurukulasuriya and Mendelsohn, 2008).

This study therefore addreses the outcome from agriculturall survey conducted to understand farmers' sensitivity to changing climate and the way they percieve the notable changes in rainfall and temperature condition and its impacts on crop production. The role of the current adptation mechanisms and constraints were evaluated across different agro-climatic zones in Ziway-Shala basins of the MER. Furthermore, the surface and groundwater quality were assessed for their suitability for agricultural irrigation use in the basins which may further constrain the sector in the changing climate. Understanding these components would enhance policy measures directed toward tackling the challenges and thus will likely be of great importance for sustaiable development of the agricultual sector under future climate and environmental changes.

2. Study area and regional setting

The study area comprises two large basins; the Ziway-Shala and Abaya-Chamo basins, and a small catchment (Awasa) located in the central sector of the Main Ethiopian Rift (MER) valley (**Fig. 1**). The MER is characterized by a chain of lakes (Ziway-Langano-Abijata-Shala-Awasa-Abaya-Chamo) that lie at an average altitude of 1600 m above sea level (m.a.s.l). These lakes receive surface inflow from rivers and springs that drain western and eastern highlands (elevation above 2500 m.a.s.l. on average) bordering the MER.

The climatic conditions characterizing the highlands, the escarpment, and the Rift valley differ greatly. Mean annual rainfall in the highlands ranges from about 800 mm to over 2400 mm, while the Rift valley is semi-arid to arid, with rainfall varying from 300 mm to 800 mm (Ethiopian Mapping Authority, 1988). The mean annual temperature in the highlands is less than 15 °C and evaporation less than 1000 m; on the Rift floor, mean temperature is greater than 20 °C and evaporation exceeds 2500 mm (Le Turdu et al., 1999). Rainfall in the Rift is concentrated during the summer months from June to September, with additional modest rains coming from March to May. During the long, dry period between October and February, water availability is low. As evapotranspiration significantly exceeds rainfall, water quality in the Rift valley, particularly in its lakes, is negatively affected by evaporative enrichment, which increases its salinity. Currently, surface and groundwater resources are used by the region's small-scale agro-industries, commercial irrigation, and fluriculture farms.

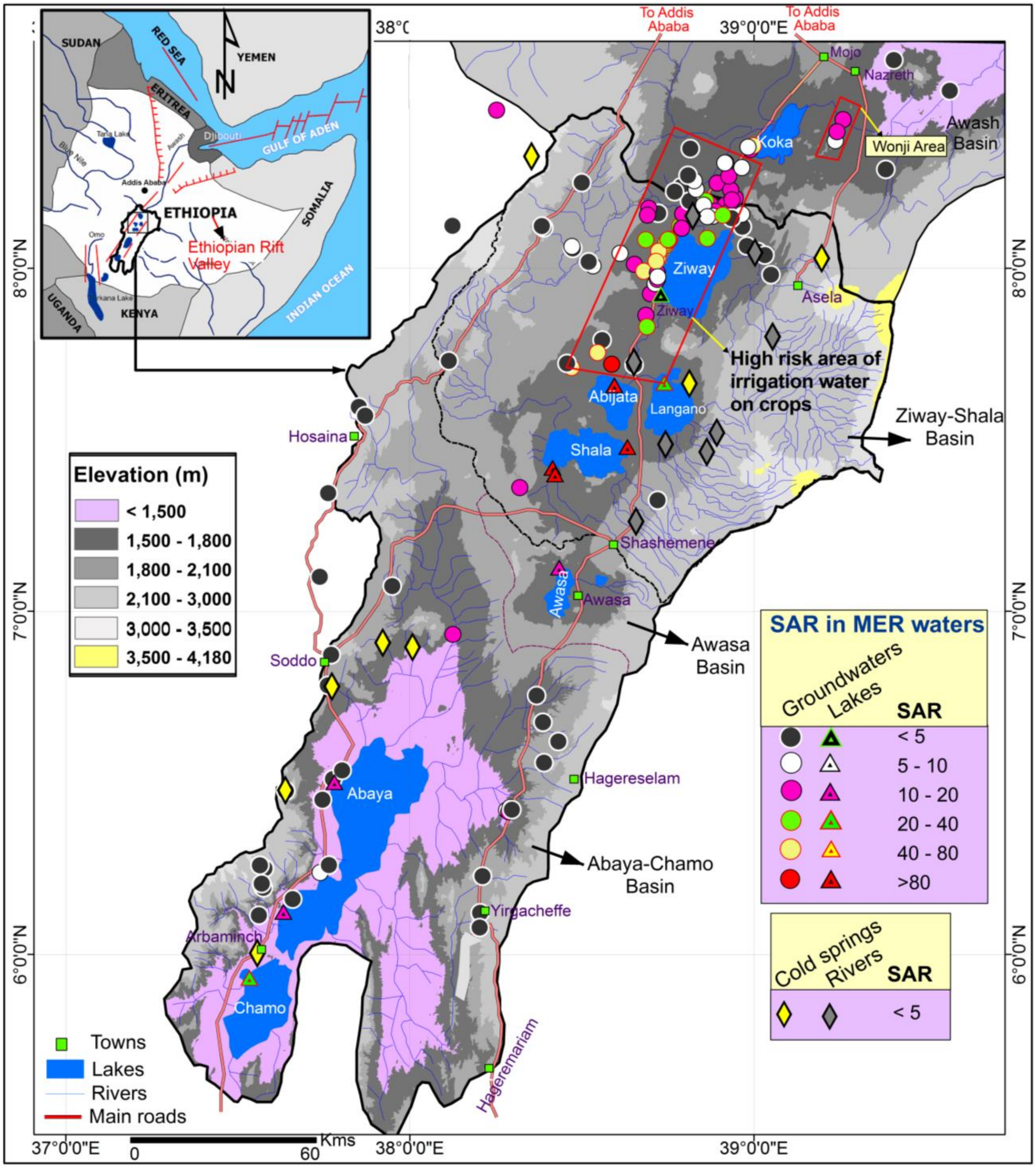

Fig. 1. Distribution of water sampling sites in the MER basins according to type (groundwater, lakes, cold springs and rivers). The values of SAR are color-coded. Note that the squared block represents the site with high risk of irrigation water in crops.

3. Materials and Methods

3.1. Water sampling and analysis

Surface and groundwater samples that are currently being used for irrigation or potential for irrigation water use were collected in two large basins of Ziway-Shala, Awasa and Abaya-Chamo basins in April–May 2010, March 2011 and November 2012. The sampling constitutes a total of 162 waters from 135 groundwater wells, 8 cold springs, 8 rivers and 11 lake samples (**Fig. 1**). The groundwater samples were collected typically from active pumping wells, allowing the water to flow for a few minutes from the sources prior to sampling. Water from springs and lakes was collected at the mouth of the source and 50–100m away from the shore, respectively. The samples were collected after insitu measurements of pH, temperature and electrical conductivity (EC). Major and trace element samples were filtered in the field using 0.45 μm filters. Major cation/trace metal samples were filtered directly into 60ml polyethylene bottles that had been cleaned with trace metal grade ~1N HCl and ~1N HNO_3, then rinsed with deionized water having resistivity >18 MΩ/cm. Major cation/trace metal samples were immediately acidified with high-purity HNO_3 (Fisher Optima). Unfiltered and unacidified samples were also collected into 60 ml and 30 ml polyethylene bottle for alkalinity and hydrogen/oxygen isotopes measurement.
Concentrations of major cations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and silica (SiO_2) were measured using a direct-current plasma spectrometer (DCP) calibrated using solutions prepared from plasma-grade single-element standards. Major anions of chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-) were analyzed using an ion chromatograph (IC). Fluoride content was determined by ion-selective electrode (ISE). Samples were mixed at a 1:1 volume ratio with a total ionic strength adjustment buffer (TISAB) of pH 5 – 5.5, which allows optimum analyses of fluoride in the aqueous solution. Total alkalinity (as HCO_3^-) was measured using titration techniques to pH 4.5. Trace elements including of boron (B) others were analyzed via a Perkin-Elmer Elan 5000 inductively coupled plasma–mass spectrometer (ICP-MS) calibrated to the National Institute of Standards and Technology (NIST) 1643e standard.

3.2. Survey questionnaire – farmer's perception on climate change, agriculture and adaptation

A total of 147 farmers were randomly selected across different agro-climatic zones from the highland to the rift floor in the Ziway-Shala basin and interviewed in December-January 2012 (**Fig. 2**). During these interviews, data were collected on houshold characterstics, land ownership, the type of crop grown, factors determining high/low crop yield, source of water for agriculture (rainfed or irrigation), crop failure, distance to their nearest market for the purchase of their inputs or the sale of their outputs, use of improved seed variety and fertilizer, crop pattern change, crop marketing, soil and water conservation, access to extension service. Farmers were also requested a set of question on their perception on past and present observed trend of rainfall and temperature, and measures they take to adapt to the changes. Finally they were asked the constraints to undertake the possible adaptation options.

The survey data were then subsequently coded in Microsoft Excel 2010 and IBM SPSS statistics 19 spreadsheet-based statistical packages. Responses of farmers to rainfall change comparing in the last three years with ten years ago were catagorized under 'changes in timing of rain', 'predictability on rainfall pattern', 'no change', 'drier' and 'wetter'. For temperatre the answers categorized into 'no change', 'hotter' and 'colder'. Questions were also asked for the general farming condition including any change they have made in the past 10 years under climate change. Each farm surveyed was assigned a unique identifying code enabling it to be matched spatially referenced data on climate. The selected participants at the household level were selected randomly and were contacted with a formal letter written from Addis Ababa University and asked for interview permission. The farmers were also asked for verbal consent (ethical consideration) and the interview data were collected after their full consent and the anonimity of all investigated subjects have been kept in any communications.

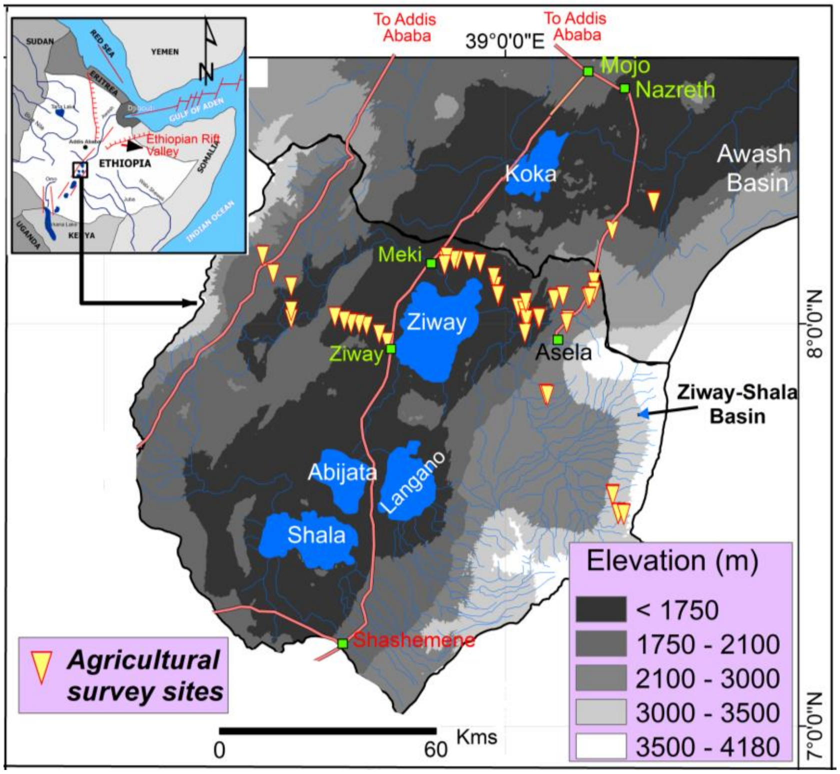

Figure. 2. Location of agricultural survey sites of 147 farmers.

4. Results

4.1. Water quality and suitability for agriculture

Hydrochemical constituents of irrigation waters can have a significant negative effect on crop productions and soil fertility. With increased evaporation due to warming combined with reduction in rainfall may lead to stress in water availability and quality. As a result the MER groundwater can potentially substitute for unreliable surface water supplies for irrigation, especially under climate change, and thus evaluation of the surface and groundwater suitability for agricultural uses in the MER is necessary for current and future use of the resource. Major ions of Na^+, Cl^-, HCO_3^-, Ca^{2+} and Mg^{2+} including some trace elements such as boron determine suitability of irrigation water to agriculture. Most of the water samples lie within EC value of below 3000µS/cm and SAR below 80. Rivers and cold springs have EC below 500 µS/cm and SAR below below 3. Rift floor lakes are fresh (e.g., Lake Ziway) to highly alkaline (e.g., Lake Chitu). The EC of highly alkaline lakes of Shala, Abijata, Chitu were 22,500, 40,800 and 45,800 µS/cm respectively. EC and SAR values of Lake Ziway, Langano, Awasa, Abaya and Chamo samples are plotted on **Fig. 1**. The most critical parameters that potentially constrain soil permeability and crop yields are salinity (as electrical conductivity; EC), sodium adsorption ratio (SAR) or sodium (Na%) and residual sodium carbonate (RSC). The parameters are expressed by the following formulas and concentrations are in equivalent unit.

SAR= $Na+ / \sqrt{(Ca^{2+} + Mg^{2+})/2}$

Percent Na = $Na^+/(Na^+ + K^+ + Ca^{2+} + Mg^{+2})*100$

RSC= $(CO_3^{2-} + HCO_3^-)-(Ca^{2+}+Mg^{+2})$

4.2. Effect of EC and SAR on irrigation water infiltration in soil

Excessive Na^+ and salinity concentrations in irrigation water result in sodium hazard and salinity hazard respectively. The high Na^+ content in irrigation water can enhance cation-exchange replacement of Na^+ in water to Ca^{2+} and Mg^{2+} ions in the soil, and reduce soil permeability and water infiltration (Shaki and Adeloye, 2006). Suitability of waters were evaluated based on the Food and Agriculture Organization (FAO) and the United States Department of Agriculture (USDA) classifications. **Fig. 3** demonstrates the FAO guidelines on the relationship between salinity and sodicity and infiltration rates using Ayers and Westcot (1985) classification diagram. Most of the samples lie in severe and slight-moderate to reducing infiltration. The result suggests that even at low EC, the high SAR can likely cause potential water infilteration problem in the soil. Although infiltration may be acceptable when SAR and EC values are both high, the high salinity alone may inhibit crop yields by restricting the availability of soil water to the crop. If salinity increased beyond the safe threshold of a crop, the crop yield will decline linearly with increase in salinity (Mass and Hoffman, 1977).

Irrigation water quality	Groundwater wells	Rivers	Lakes	Cold springs
Severe	76 samples	6 samples	5 samples	6 samples
Slight to moderate	54 samples	2 samples	1 samples	2 samples
No problem	5 samples	none	none	none

Table 1. Water types and their irrigation water classification shown in **Figure 3.**

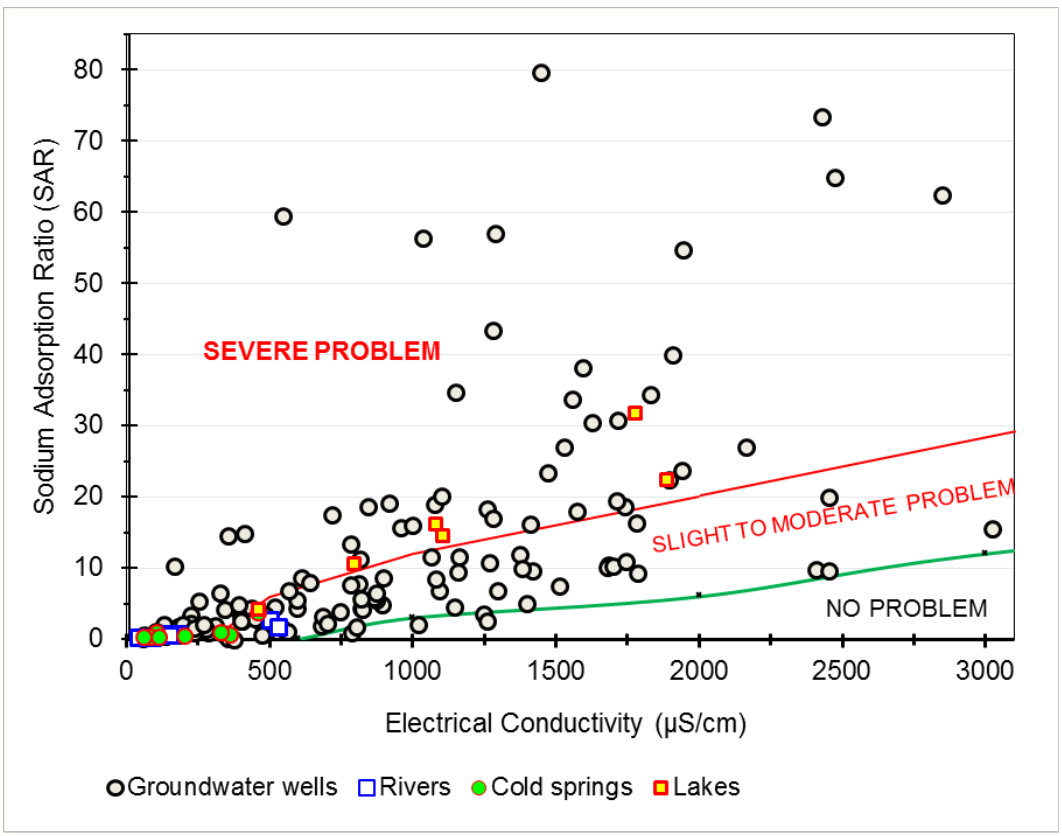

Fig 3. Guidelines for saline-sodic water quality suitability for irrigation, presented in terms of reduced infiltration (After Ayers and Westcots, 1985).

The irrigation water quality was also evaluated based on USDA classification diagram (Richards, 1954) (**Fig. 4**). 18 of the groundwater samples and most of the cold springs and rivers lie in the category C1-S1 with low salinity and low sodium which are suitable for irrigation water in almost all soil types. 60 groundwater samples including Lake Ziway (the only available freshwater lake in the rift that intensively being used for irrigation) fall in the category C2-S1 and C3-S1 (medium to high salinity and low sodium). These waters can be used as irrigation in almost all soil types with little danger of exchangeable sodium. Groundwater samples that fall in medium salinity hazard class (C2) can be used if a moderate amount of leaching occurs. Most of the samples (71 groundwater samples and all lakes except Lake Ziway) were categorized in high to very high salinity water (C3 and C4) and medium to very high sodium (S2, S3 and S4) cannot be used in soils with restricted drainage. Even with adequate drainage, special management for salinity control is required and crops with good salt tolerance should be selected. Therefore, groundwater wells and rivers from the highlands of the basins and Lake Ziway were suitable for irrigation with little danger to the soil and crops. However, the sodium concentrated lake and groundwater samples were required treatment before irrigation.

Sodium hazard		**Salinity hazard**			
		Low	Medium	High	Very high
		C1	**C2**	**C3**	**C4**
Low	**S1**	18gw, 6r, 6cs	42gw,2ri,1la,2cs	18gw	-
Medium	**S2**	-	2gw	16gw, 1la	1la
High	**S3**	-	1gw	11gw, 2la	2gw
Very high	**S4**	-	1gw	19gw,2ri	5gw

Table 2. MER water types (gw: groundwater well, ri: river, la: lake, cs: cold spring) and their irrigation water classification according to the USDA method shown in **Fig. 4**

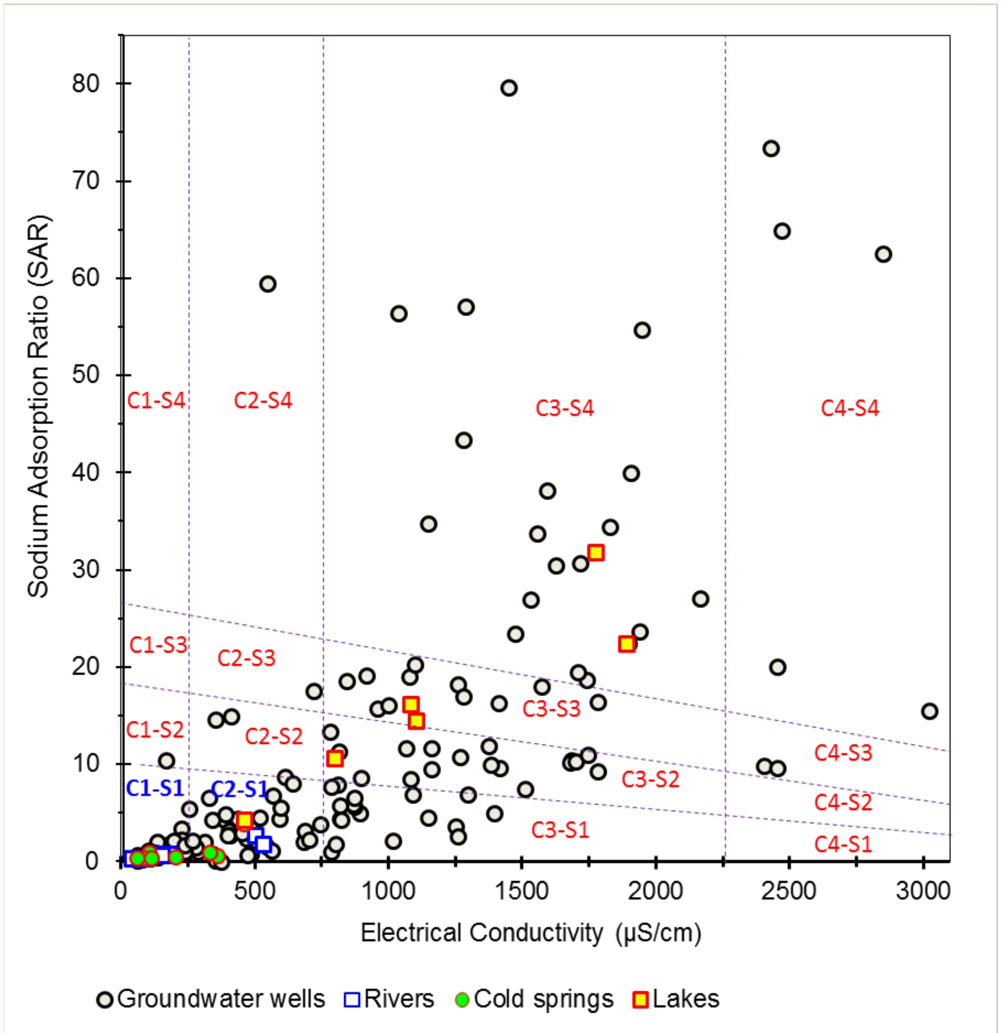

Fig. 4. USDA diagram for irrigation waters classification based on SAR and EC (after Richards, 1954).

4.3. Bicarbonate, RSC and boron

An additional limiting factor for irrigation water is the content of HCO_3^- anion, which can trigger carbonate precipitation and cause scaling in irrigation pipes and pumps. Saturation of carbonate minerals may reduce the Ca^{2+} and Mg^{+2} content of the soil water, and consequently increase SAR values.
RSC is an alternative measure of the Na^+ content in relation with Ca^{2+} and Mg^{+2}. If the RSC < 1.25, the water is considered safe and RSC >2.5 is not appropriate for irrigation. The MER groundwater RSC varied from –1.3 to 33.4 with more than 20 and 60 % of the samples were found to be safe and unsuitable for irrigation, irrespectively. An excess quantity of Na^+ together with HCO_3^- is considered to be detrimental to the physical properties of soils, as it causes dissolution of organic matter in the soil, which in turn leaves a black stain on the soil surface on drying. This condition were observed in some irrigation sites in the studied site and also complained by the farmers as it changes the color of crops leaf which also tends to get burnt.
Different plants have varying tolerance to salinity, but adverse effects on crop yields are typically apparent at EC exceeding 1000 µS/cm (Grattan 2002). Similarly, concentrations of boron above 0.5 mg/L significantly reduce crop yields, particularly for boron-sensitive crops like strawberries, beans, onion, and garlic (Grattan 2002). **Fig. 5** shows that the salinity and boron in a large proportion of the groundwater wells exceed threshold values for long-term sustainable irrigation

water. These results indicate that future agriculture applications using MER groundwater would likely be limited due to problems with groundwater quality. This would greatly limit the ability of irrigators to supplement irregular or insufficient surface water supplies with more dependable groundwater sources. Other factors such as climate, soil type, crop and plant species and management practices also need to be accounted for when determining acceptable levels of salinity and sodicity of irrigation water. If the soil never used for farming, the crop productivity is good even with high water salinity, however, when the soil used for farming for long years, the water salinity is more detrimental and in such case the high productivity is expected only with the use of rain water (local communication).

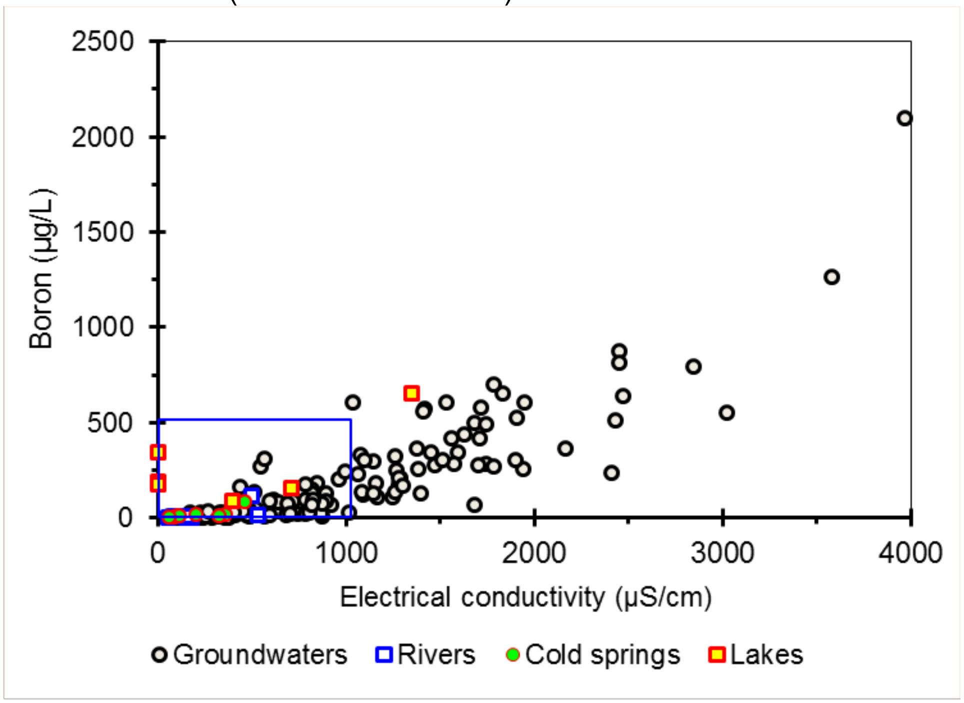

Fig. 5. Variation of boron versus electric conductivity (EC) in MER groundwater. Square areas represent acceptable values for irrigation water, while values outside these areas indicate limitation for sustainable agricultural utilization of the groundwater.

5. Analysis of climate change, farmers' constraints and adaptation to changing climate

5.1. Preliminary climate change analysis

Across many regions, and also in Ethiopia, it is not possible to state with confidence the direction (increase, no trend, or decrease) of precipitation change, even though climate models have been consistent in predicting rising temperature (Meehl et al. 2005; Conway et al. 2007; IPCC 2007; Diro et al. 2011). Our preliminary modeling using a single IPCC AR5 model – HadGEM2 ES – suggests a significant decrease in rainfall over the Rift Valley in the main part of the rainy season since 1979 (**Fig. 6**), and a corresponding continued decrease in average annual precipitation in the 21st century, due to changes in local circulation and low-level moisture transport from the Indian Ocean and the Atlantic.

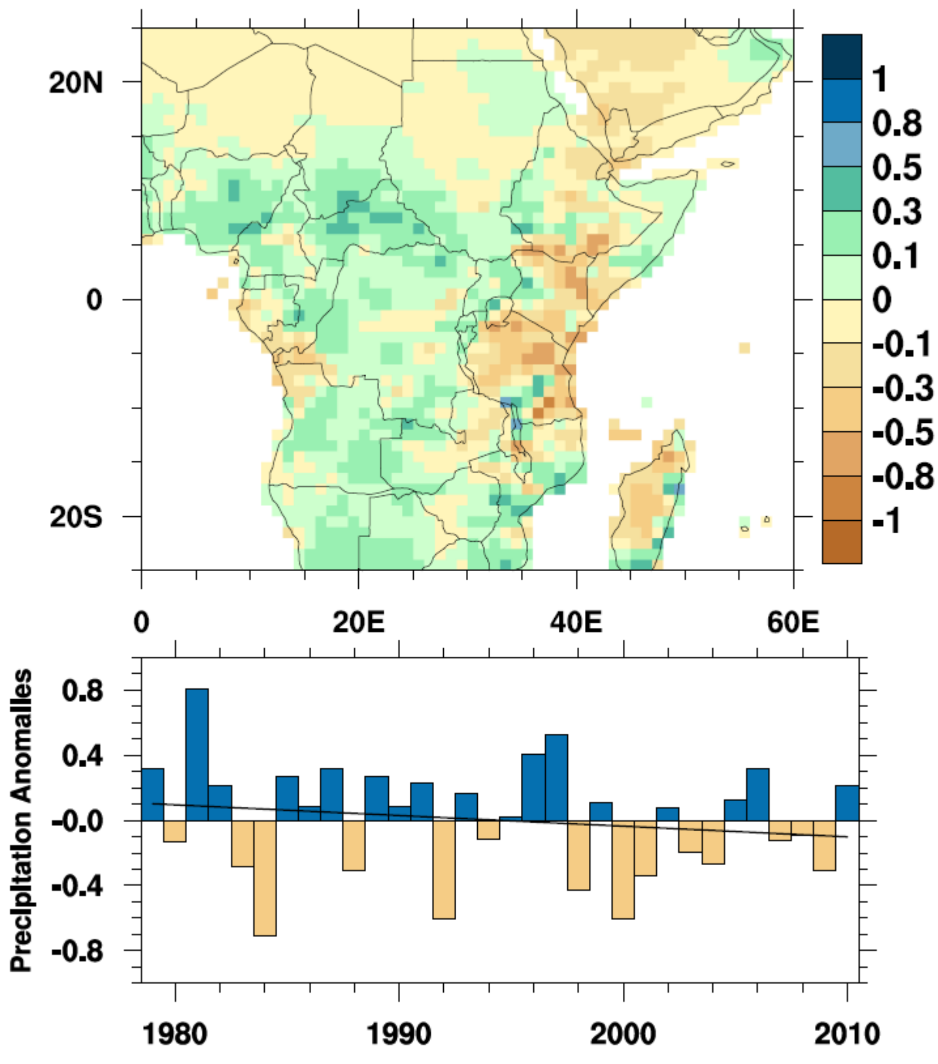

Fig. 6. Precipitation changes over East Africa obtained from the HadGEM2_ES model *(produced by Dr Wenhong Li at Duke University*)

5.2. Framers' demographic information

From 147 interviewed farmers, 94.6% (n=139) and 98.4% were male household heads. More than 87% of the households are predominantly Oromo ethnicity. About 75% of the head of the household can read and write. About 28% of the farmers had no education and the rest had education from primary to high school level.

5.3. Crop choice

The farming system of the study areas is characterized by crop and livestock mixed farming that represents 90% of the farmers and the rest are restricted to crop farming. Farm households depend mainly on crops both for food and cash income. Across the different agro-climatic zones, farmers grow crops suitable to the rainfall and temperature conditions. In the Rift floor areas (<1750m.a.s.l), maize and teff are predominantly grown. The rift is also suitable for other cereals including wheat, haricot bean and sorghum. Farmers located at higher altitude (1750-2100 m.a.s.l) also grow mostly maize, wheat and teff. The highland (>2100m.a.s.l) predominantly produce wheat, and barley. Faba bean, field pea and maize are grown in the highland. With this regard, the farmers have already adapted to the historic climatic condition suitable for current crop choice. However, the farmers particularly situated in the lowland have currently reported changes in the amount and timing of rainfall and increasing temperature that endanger their farming (**see section 5.5**).

5.4. Farmers' irrigation use

Most farmers have no access to irrigation and they rely on rain water to cultivate crops. In a few of irrigated areas visited in the Rift Valley such as at Arata and around Lake Ziway, the farmers produce horticultural crops that include tomato, onion, pepper and cabbage. The farmers that use irrigation have usually a better productivity and profit, although there are cases that they lost their crops due to too much rain, or become unprofitable due to price drop during a period of such high productivity.

5.5. Farmers' perceptions to climate change

Most farmers reported that lack of rain is one of the main constraints in agricultural productivity and many also indicated that rainfall is becoming more erratic. **Fig. 7** shows farmer's perception on changes in the pattern of rainfall and temperature. Comparisons of these changes between the last three and ten years indicated more than 70% of the farmers stated that rain comes and stops later from the expected rainfall season. Moreover, they already perceived that the current climate is drier, hotter, less predictable and generally worst for farming. A few farmers (6%) have reported no change in temperature and rain. Despite the climate is becoming unsuitable, some farmers reported their farming is becoming better due to the use of improved seeds and fertilizers.

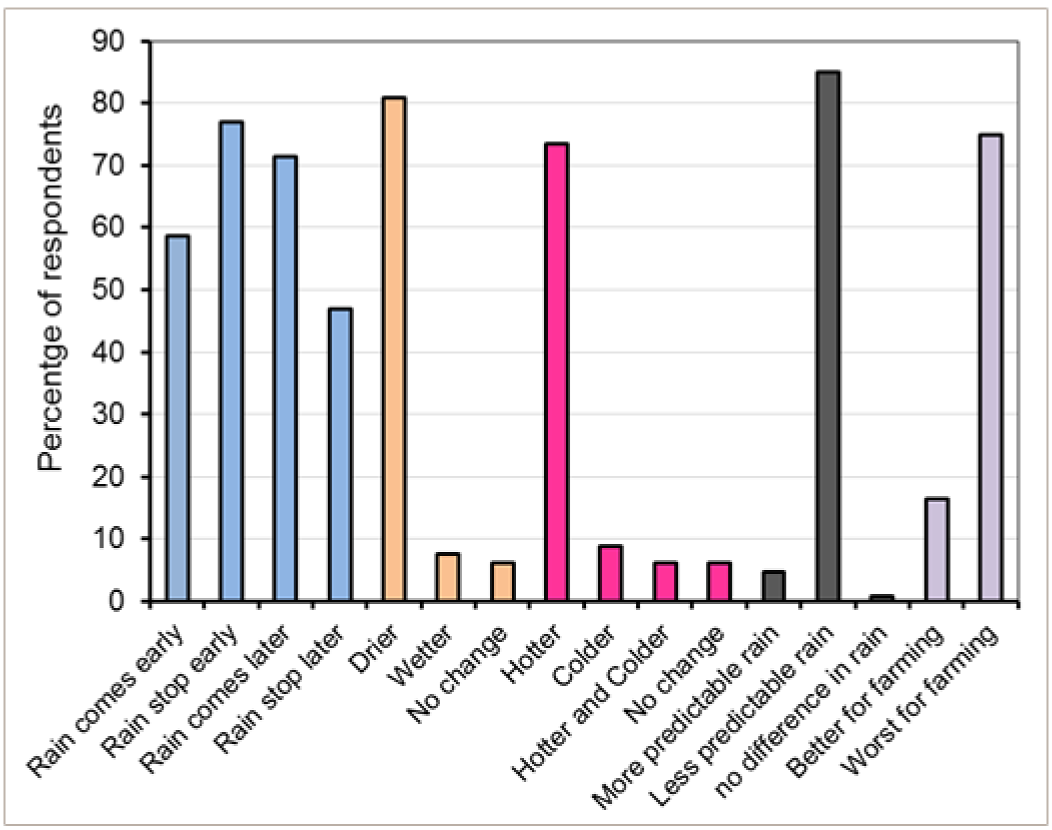

Fig 7. Perceptions of farmers on climate change across Ziway-Shala basin

5.6. Factors determining good and bad crop yield

Farmers pointed out that uninterrupted and enough amount of rain, the availability of farming inputs (fertilizers and seeds) and personal efforts are some of the most important factors that determine good crop season and productivity (**Fig. 8**), whereas lack or excessive rain or unexpected rain, low crop price, lack of available/affordable farming inputs, and inefficient personal effort have contributed negatively in the overall agricultural productivity in terms of lowering crop productivity and farming profit (**Fig. 9**).
The study revealed that insect pests and diseases were, and still are, the major production constraints in the study areas.

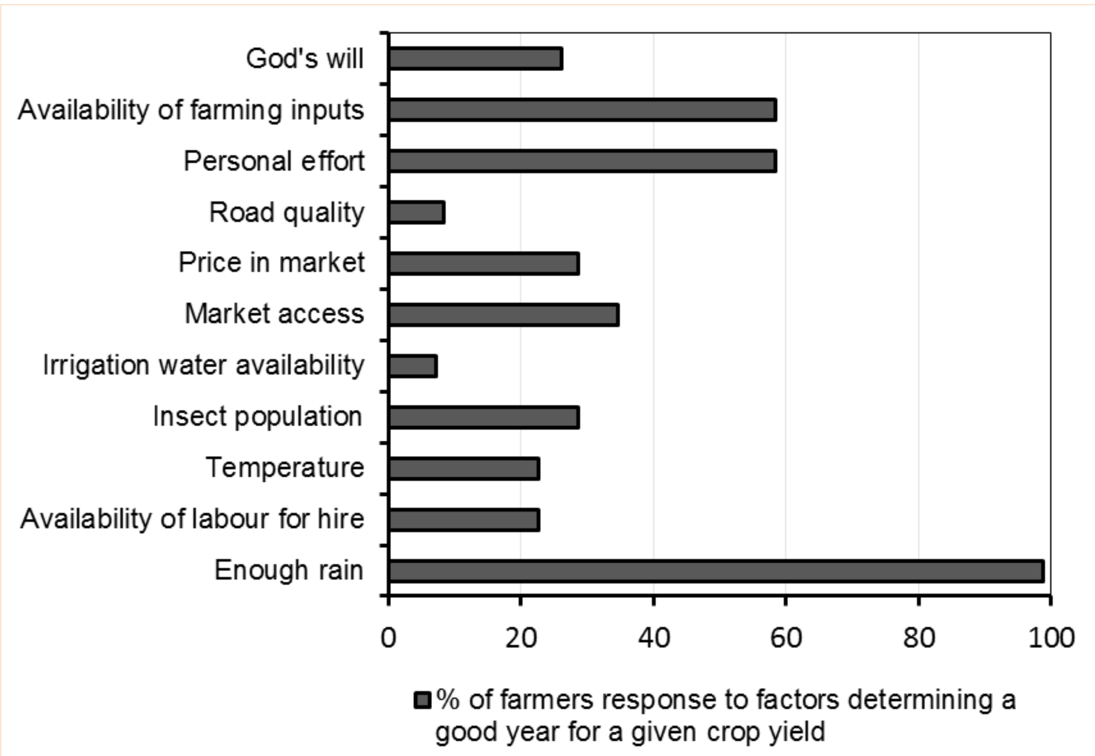

Fig. 8. Relative importance of factors determining a good crop year

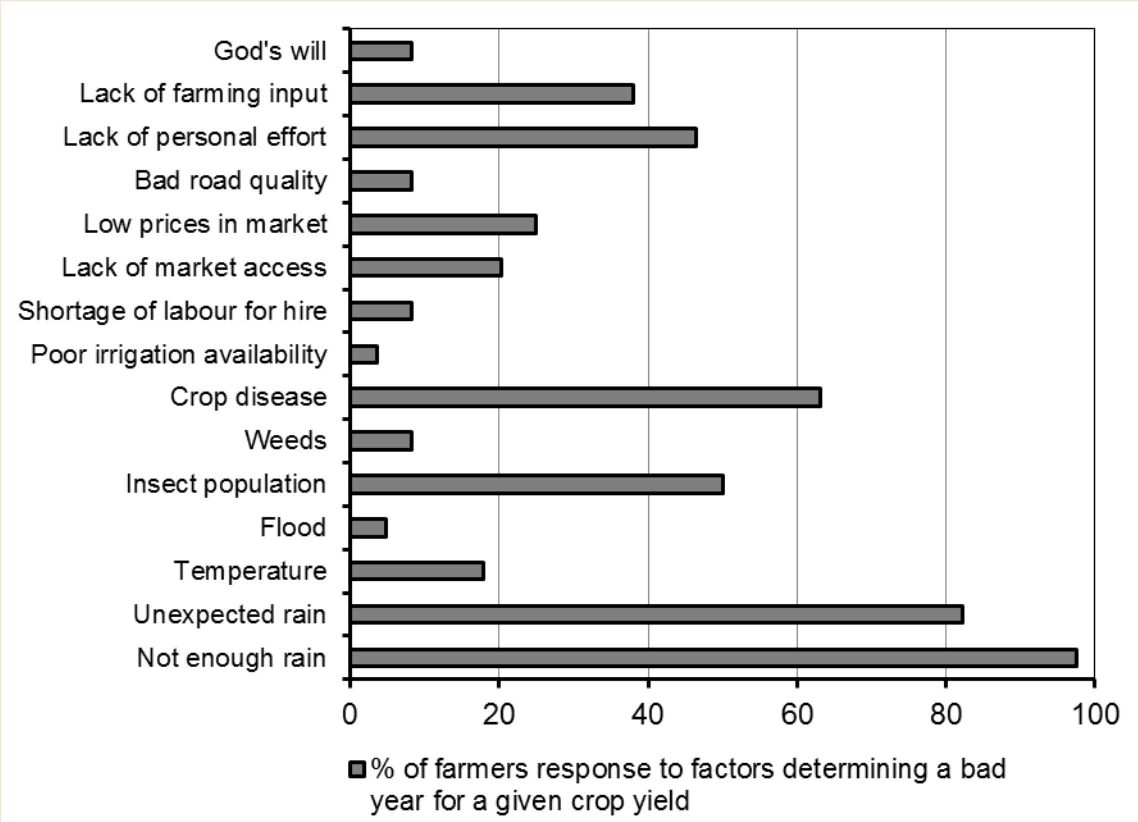

Fig. 9. Relative importance of factors that determine a bad crop year

5.7. Climate change impact on agriculture, adaptation practices and constraints

5.7.1. Climate change impact on agriculture

In the last 5 years, 66.7% of the farmers have experienced crop failure on average 1.6 and 0.5 times in the rift floor (<1750m.a.s.l) and highlands (>2100m.a.s.l) respectively. 80% of the farmers in the rift floor and 22 % in the highlands had at least one crop failure in the last 5 years. **Table 3** shows the number of crop failure at different altitudes. Lack and unexpected rain are the most important constraints for crop failure that account more than 61% and 27 % of farmers' response, respectively. It appeared that agriculture in the rift is about 76 % higher in crop failure than the highland areas. During time of high crop failure, farmers tend not to farm next crop season due to high uncertainty on the rainfall and high price of improved seed. The crop failure causes some of these households not to meet their food needs and rely partly on food assistance.

Number of crop failures in the past 5 years	***1640-3100m*** (n=147)	***<1750m*** (n=76)	***1750-2100m*** (n=35)	***>2100m*** (n=36)
	Percentage of respondents			
0	33.3	19.7	17.1	77.8
1	24.5	23.7	**48.6**	2.8
2	**25.2**	**34.2**	20.0	11.1
3	16.3	22.4	11.4	8.3
4	0.68	0.0	2.9	0.0

Average crop failure	1.14	1.6	1.3	0.5

Table 3: Response of farmers to crop failure in the past 5-year at different elevation from the floor of the rift to the highland.

5.7.2. Climate change adaptation practices

The different practices that farmers are currently implementing to improve their farming are shown in **Fig. 10.** About 70% of the interviewed farmers use crop varieties of high yield, early maturing seeds as key climate change adaptation mechanism. A large proportion of farmers uses fertilizer and practice crop rotation to improve their farming. They also use terracing, afforestation, conserving seeds, conservation of natural resources and irrigation as key practices to protect environmental degradation. About 50% of the farmers in the study areas practice crop rotation as a means to restore the fertility status of the soil as well as to minimize the buildup of weeds, insect pests and plant diseases. The most common crop rotations are cereal-cereal. In areas with irrigated farming, farmers also alternate different vegetables with cereals. A few wealth farmers on the highlands use technology based options (e.g. renting tractors) to quickly collect crops during unexpected rainfall in harvesting season.

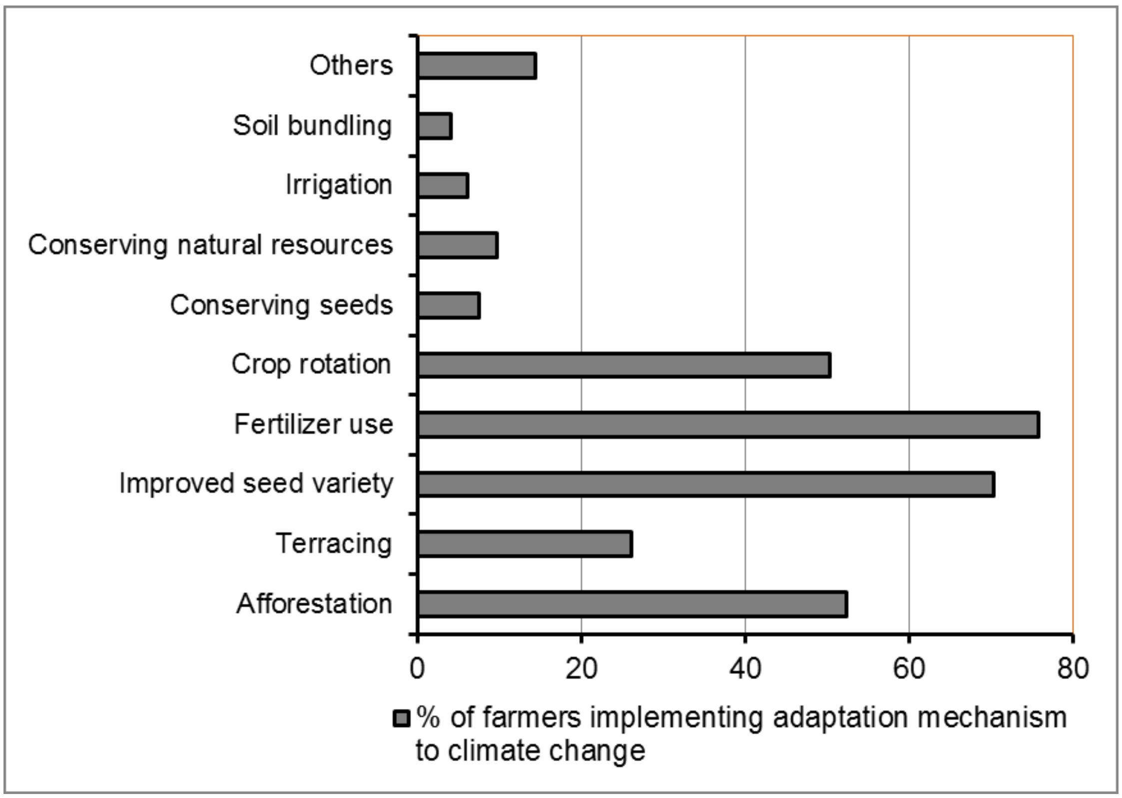

Fig. 10. Different adaptation measures that farmers implement to deal with climate change and/or restore soil fertility

5.7.3. Constraints to climate change adaptation

Lack of: access to water, credit or saving, knowledge, information on weather and climate change were identified as major barrier to adaption to climate change. Even if lack of credit were mentioned as an important constraint, some farmers in the Rift Valley area are reluctant to take the available loans because of the high uncertainty on rainfall variability which likely to cause crop failure. Because of the some farmers unable to pay back the loan, they were forced to selling e.g. their livestock or resulted in bad debt.

Market access or transportation was not found to be a major barrier to adaptation, however, many farmers pointed out that the market is not functioning in a way that allows the farmers to maximize their profit. As farmers' life is hand-to-mouth, more than 50% of the farmers sell their crops within 3 months of harvesting which is the period the price is too low and later the price rise up following shortage of the crops in the market. The farmers have limited influence on the market prices which is normally fixed by the local traders, suggesting that the market is not efficient to enhance farmers' adaptability to changing climate. We, however, have noticed encouraging activities by farmers association who purchase the crops from the local farmers while the price is low and sell to the market during high price and give the net money difference back to the farmers.

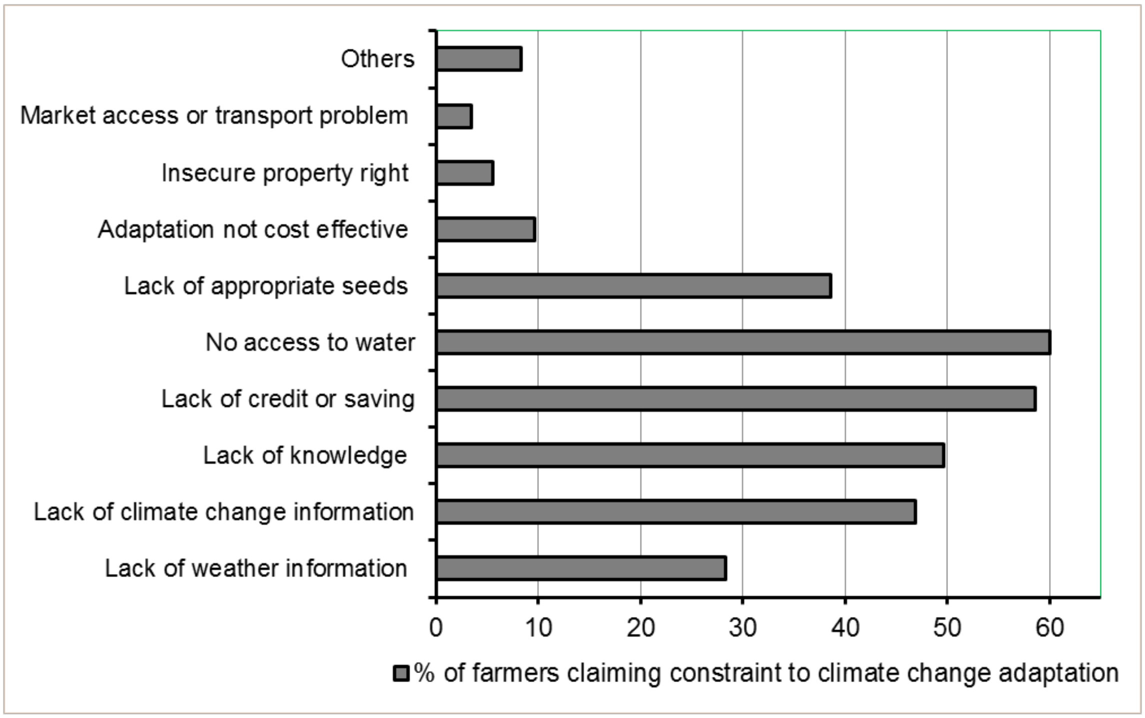

Fig. 11. Farmers' perception on barriers to adaptation

6. Conclusion

Climate change is mainly threatening the rain-fed agricultural sector by affecting the livelihood of the rural communities, particularly in highly vulnerable and poorest countries in Africa and Ethiopia is one of typical example (World Bank, 2006; Boko et al., 2007; Thornton et al., 2011). This study is based on primary data produced from water quality assessment of major and trace elements in order to evaluate their suitability for irrigation use as well as evaluation of the effect of climate change impacts on the agricultural sector from data derived from household survey on farmers' perception, their adaptation and barriers to the changing climate in the MER areas.

The irrigation water quality assessment based on EC and SAR values showed that most of the investigated samples categorized in severe and slight-moderate group for irrigation use as they are detrimental for soil physical properties which affect soil permeability and reduce water infiltration. High bicarbonate and boron concentration are additional water quality problem for irrigation use in MER.

The most commonly observed climate related shocks are linked with lack of rainfall and variability in time. As a result, crop failure is the most common consequence of changing climate in MER. The study also identified the major adaptation mechanism undertaken by households in response to climate related shocks. The main mechanisms include the use of different crop varieties of high yield, early maturing seeds as key climate change adaptation. Large proportion of farmers applies fertilizer and practice crop rotation to improve their farming. They use also terracing, afforestation, conserving seed, conservation of natural resources and irrigation as a means to control environmental degradation. The main barriers to implement adaptation options include the lack of: access to water, credit or saving, lack of appropriate seed, knowledge and information on weather and climate.

Improving access to credit, increased control on market price of local agricultural products, access and distribution of sufficient seed (in variety and amounts), early warning on weather during planting and harvesting seasons, knowledge on farming practices (e.g. the use of fertilizers that are suitable and proper amount for a given soil type) are some of the necessary measures that has to be taken to improve farmers' adaptive capacity to climate change. We have noticed that the role of Development Agents (DAs) is vital to enhance the knowledge of farmers on the agriculture. This service is currently available in the studied basin and has to continue to sustainably increase farmers' adaptability in the face of continuing climatic variability.

Overall, large fraction of the MER groundwater has a significant water quality problem that could jeopardize the agricultural sector, particularly of the horticulture and floriculture sector that are the most vulnerable as they mainly depend on groundwater for irrigation. This study also explored and identified the perception, adaptation and constraints of farmers' to adaptation across the highland to the rift floor. The results were showed that the rain-fed agriculture is considerably threatened by changing climate and crop-failure is prevalent in the rift floor within the Ziway-Shala basin, where most farmers have limited access to irrigation. The outcomes of the study help decision-makers to design feasible strategies for adaptation measures and food security policies that help farmers better adapt with changing climate and to improve their livelihood.

7. Future direction

Our work is one of important studies that investigated the response, constraints and adaptation mechanisms of farmers to climate change impact on agriculture in the Ethiopian Rift Valley area. The region is understudied, rural, already exposed to climate variability, and highly dependent on rainfall for subsistence agriculture and will continue to be an ideal site to related impact studies under different scenarios of climate changes. In future studies we look funds to conduct:

1) Climate and hydrologic modeling

In order to understand the potential effects of climate change on surface and ground water systems and the extent to which the local populations affected by the availability of the water resources for different purposes including for drinking and agricultural purposes, we foresee to use PRMS (Precipitation-Runoff Modeling System) water balance model calibrated for the Rift. The model helps us to study the effects of climate change on surface water runoff and groundwater recharge (Leavesley et al. 1995; Legesse et al. 2003). In addition, downscaled precipitation and temperature outputs from the climate change projections analysis will be utilized as inputs for the model to study the potential changes in surface and ground water availability. Then, explore the effects of evolving demands for groundwater (due to economic development, demographic change, and/or supply shocks to the substitute surface water supply). To achieve this, we will develop and conduct scenario analyses – specified using planning studies and the outputs of the PRMS model under climate change – with a water utilization model. Depending on the complexity of the allocation problem, the scenario assessment may be conducted using existing tools such as the Water Evaluation and Planning System (Yates et al. 2005), or new Excel-based tools.

2) In the current study, we have conducted focus group discussions of farmers and community leaders in representative rural villages in the Ziway-Shala basin (see detail in Appendix 1). We will seek to extend additional interviews with policy makers at the local, regional and national levels aimed at understanding the institutional context of water management and farming. This research will provide new insight into household and community resiliency to climate change.

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Appendix-1: Summary from focus group discussion

The field work was conducted in six communities (5 in Ziway-Shala basin and 1 in Awash basin) (**Fig.1a and b**). These are:

1. District - Adami Tullu, peasant association - Anano shasho, 3 female and 7 male participants
2. District - Adami Tullu, peasant association - Kamo Garbi, 4 female and 11 male participants
3. District - Adami Tullu, peasant association - Ilka Chalamo, 15-20 male participants
4. District - Dodota Alem, peasant association - Amigna Dugda, 4 male and 1 female participants
5. District - Ziway Dugda, peasant association - Arata Tuffa , 4 female and 11 male participants
6. District -Tiyo , peasant association – Dosha, 2 female and 3 male participants

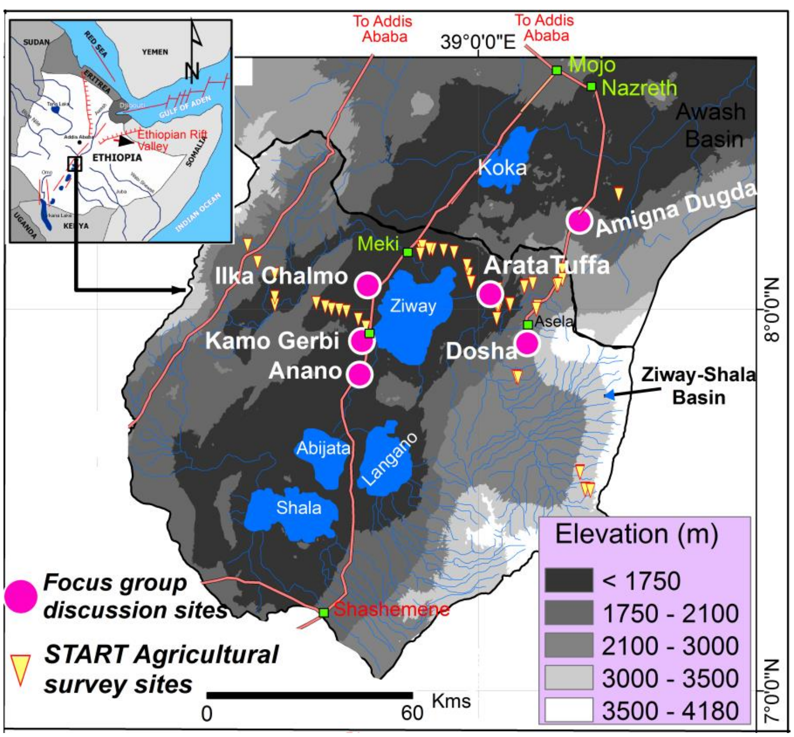

Fig 1a. Location map of focus group discussion sites


Fig 1b. A focus group discussion at Ilka Chalamo

1. *<u>What do households expect about climate change? Do people know what this is? Do people agree about what it means or will mean for them?</u>*

- Farmers are well aware of the climate is becoming a serious problem. The climate change is perceived as rainfall pattern variability (rain comes and stops early or later from the expected season and is uneven in amount - too high or too low). The farmers in the Rift have experienced a significant reduction in rainfall with rarely unexpected heavy rainfall. In the highland there was no complaint about the reduction, but more on variability.

- Due to rainfall shortage, farmers start planting drought tolerant early maturing maize varieties though there is limited supply. There are cases that they skip planting maize when rain is absent in months of April and May.
- In all sites, they argue that deforestation of indigenous trees such as 'Tid', 'Zigba', and 'Kosoo' for fire wood and charcoal is the main cause for changing in climate. One participant pointed that expansion of farming area along with tree cutting causes reduction for instance in bee population since 1980s. He also mentioned that production of honey is becoming very low as he thinks the bees are dying by chemical pesticides that are used by floriculture farming in the area. Currently, farmers are actively involving in the protection and planting of new trees (area closure plan) that organized by the government.

- In the past, people in the region have been engaged in livestock production, but now they are more dependent on crops. This is because of decreased grazing land that cause decrease in total livestock and dairy output.

- Maize productivity is also decreasing from time to time; however, they are getting better yields by changing their farming to wheat, barley and teff crops.

2. *What information have household received about climate change. From where? What (if anything) have they done with this information?*

   - In the last 2-3 years, under the Growth and Transformation Plan (GTP) that targeted the food security and poverty reduction in the country, the farmer's at each household have received training for 5 to 15 days. As a resource person, agricultural experts at district level (from ministry of agriculture) and development agents (DAs) (mostly trained in plant, animal and natural science) were participated in the training program and transfer knowledge to the farmers. The farmers were trained about the importance of using early maturing, disease and pest resistant crop varieties, improved crop varieties, and farming methods such as row planting and BBM. The use of manure, compost, and chemical fertilizer are also advised to farmers. Some also mentioned increased crop productivity because of better farming methods, DA participation and hard work.

   - Community village elders (Oromiya cultural leaders called Aba-Gedaa) have a responsibility to inform farmers to protect the existing indigenous trees. A punishment is also put for those that not comply with the rule. Rehabilitation of trees (Area Closure) that include protecting tree cutting, planting new trees as well as land terracing, soil bunding and overall watershed management are among the information directed from government bodies to farmers. The farmers are currently practicing these activities.

- Most of farmers have also learnt by themselves about rainfall and temperature variability. Farmers also get information from Radio, TV and meetings with government bodies.

3. *How do households expect their health to be affected by climate change (through channels such as water availability, agriculture/nutrition, temperature, exposure to disasters or extreme events, etc.)?*
   - Typhoid, typhus, malaria, eye diseases, influenza and diarrhea (they believe) are due to changes between hot and cold weather.

   - Some years ago water was easily available from year to year from river, stream, pond and lake, and now farmers travel long distance to fetch drinking water mainly during dry season. Some also get tap water in short distance.

   - Change in physical appearance due to inadequate intake of milk and milk products

4. *What are the adaption activities households engage in to respond to climate variability? (with respect to water availability for drinking and other purpose, effects on crops, reducing exposure to extreme events, as well as various health effects listed above)*
   - Farmers use improved seed as a primarily response to climate change. The major limitation is access to improved seeds (such as maize, wheat, barley and haricot bean). Fertilizer is also becoming too expensive and a few farmers could afford to use farming inputs or do not use at recommended amount and rate.

   - Tree planting, protecting tree cutting, pond preparation, water conservation, flood protection, forest rehabilitation, manure/compost and chemical fertilizer use, crop rotation and crop diversity are some of the activities that farmers engaged in to respond to changes in climate.

5. *What resources have households in this community received from the local government, NGOs, etc. in general (i.e. social assistance)? What about for climate change adaption?*
   - Farmers get information on crop, livestock, and soil and water management from DAs, Ministry of Agriculture and Rural Development (MoARD), research centers and NGOs. DAs are the most important sources of information at each village.

   - MoARD plays as an extension agent through its structure at zonal, district, and kebele levels. Improved seeds of wheat, maize and haricot bean from Kulumsa and Melkasa research centers are available through different seed dissemination system. Seed distribution is run through MoARD or directly by research centers. A technology package of poultry was also added to the extension program.

   - For food insecure area e.g., at Dodota district, food aid (wheat flour, biscuits and edible oil) is provided for the households.

   - Different credit providers are available both from the government side and NGOs. Low income farmers and unemployed youths often receive the loan. Farmers buy oxen, sheep/goat to feed and resell for a profit and then pay the full money back with its interest rate. In the case of some NGOs there is a way in which the farmers pay a portion of the livestock price in one year and the money will circulate to other poor farmers in the Kebele.

6. *How often do households have to switch water sources and way do they do so?*

- Different water sources are used for human and livestock. In most areas surface water sources (river, stream, and pond/lake) are used for human and livestock drinks. A few farmers that are located close to nearby town can access piped clean water.

7. *How do people feel about the water board and water management schemes?*

- The water committee provides a service at community water points that include maintenance report, financial report and control. It consists of 7 people (a chairman, a reporter, an accountant, a casher, a store man and 2 additional members).

8. *Do households participate in any associations/committees/groups? What types?*

- According to the number of households at each Kebele, a number of groups or 'Garees' form and each consists of 25 to 30 farmers. These farmers also subdivided into 5 to 6 cells. Each cell has 1 leading farmer with other 4 farmers. With this structure many development activities including community policing, peace and security, health extension, education, and good governance are carrying out at grass root level.

- Available association are farmer association, women association, youth association, saving and credit association, and seed multiplying farmers association.

- Social activities such as 'Ider', and religious associations are as common in this area as elsewhere in the country.

9. *What community goods /projects do households contribute to? (This should cover shared water projects for drinking or other purpose, agricultural cooperatives or risk sharing measures, village sanitation/clearing activities, planting trees, education, etc.)*

- At each Kebele (or a couple of them) has one service cooperative in common. The cooperatives provide improved seed, fertilizer and pesticides including herbicide, insecticide and fungicide. Farmers who are the member of the service cooperative get some amount of dividend share at yearly basis. A few service cooperatives form a union.

- Common grazing land and water sources, irrigation projects for instance at Arata Tuffa (see Fig 1), 324 organized farmers use 100 ha of land for farming

10. *For each of these community projects, when do households share resources with other households, the community at large, or other organizations? Do they share resources in other ways?*

- Farmers share knowledge from farmer-to-farmer with a structure already established by the government: Cell, Gares (Group), Kebele etc.

11. *Do households in this community have access to loans? From what sources? (e.g. neighbors, micro-finance, agricultural banks, money lenders)*

- They can get loan frequently from private bodies and catholic church

- Personal credit is also available within communities for reliable persons (social capital) with no interest rate

12. *Do households in this community have places where they can save money? In what ways? (e.g. savings clubs, micro-finance, banks)*
    - Farmers save money in commercial banks, 'Ider' (a group of households save money monthly that often be used when a person is ill or died) and by means of buying crop or livestock.

13. *Who makes decisions in the households about planting? About health? About education for children? About purchases?*

    - Crop planting, health, and education decisions in the households are often decided both by the husband and wife with a partial participation of their children. Children care is mostly handled by the housewife. Livestock sell/buy is commonly handled by the husband.

Appendix-2: meetings

1. *Dr. Tewodros R. Godebo attended a workshop on "Climate Impacts Modelling for Developing Countries: Water, Agriculture and Health" from 5 - 16 September 2011, Trieste, Italy. The topics include:*

- CORDEX Climate products for impacts research
- Comparison of high resolution satellite rainfall products over Africa
- Satellite retrieval of rainfall and the new TAMSAT time series and climatology for Africa
- Climate change, agriculture and food security
- Quantifying and managing uncertainty in crop and climate models
- Climate indices in sectoral applications
- Wheat yield modelling in China in a dynamic crop model with a new treatment of waterlogging
- Hydrological modelling requirements for Water Resources Applications I
- The Parameterization of hydrological processes in earth system models
- Calibration and parameter estimation requirements of hydrologic models
- Modeling of the response of rivers to global change
- The use of climate models for disease risk: The QWeCI project
- Statistical modelling of vector borne disease: a case study of dengue fever in Brazil
- VECTRI: a new community dynamical disease model for malaria that accounts for population
- Records of long-term climate variations in eastern Africa
- State of the art of seasonal to decadal prediction
- IRI sectoral activities and associated climate research in Africa
- Operational seasonal forecast system development in South Africa
- Decadal climate forecasting: an introduction and an illustration for West Africa
- Climate change and health in the developing world
- Systematic rainfall biases in ECMWF system 3 seasonal forecasting system over West Africa
- The NEW ECMWF system 4 seasonal forecasting system
- RegCM downscaled seasonal forecasts: A case study from Eastern Africa and preliminary results for QWeCI target regions

2. *Dr. Tewodros R. Godebo participated to the START Learning Forum in Accra from 14 - 16 November 2012. The topics include:*

   - Environmental Services & Food Security
   - Environmental Services & Food Security
   - Climate Information & Knowledge Systems
   - Rural Livelihoods & Adaptation
   - Climate Information & Knowledge Systems

3. *Two MSc students were involved in the project and received field training and mentoring by the project investigators.*

   a. Debele Abera, Department of Earth Sciences, Addis Ababa

      Estimation of actual evapotranspiration using geospatial tools in main Ethiopian Rift

   b. Wondimu Paulos, Ethiopian Institute of Water Resources, Addis Ababa, Ethiopia

      Impact of climate change on water resources of tropical lakes watershed, the case of Ziway-Shala Lakes Basin, Main Ethiopian Rift Valley

Appendix-3: water quality parameters

Type	N	E	Elev	pH	EC	TDS	F	Cl	NO3	SO4	HCO3	Ca	Mg	Na	Si	B	V	Cr	As	Mo
W	8.2	38.9	1751	7.6	354	312	9.8	2.4	0.1	4.7	201	2.5	0.3	91	37.0	16	3.7	0.7	4.1	2.3
W	8.1	38.9	1669	7.6	386	273	3.5	2.3	0.1	4.3	180	13.9	2.9	66	40.6	19	2.8	0.4	0.6	9.9
W	8.1	39.0	1678	7.7	342	314	2.5	2.7	0.1	2.8	221	12.8	3.6	68	39.3	24	4.8	0.2	1.6	4.9
W	8.0	39.0	1682	7.4	248	223	1.5	2.3	0.1	1.1	162	15.4	5.5	35	33.9	15	9.4	0.1	1.7	3.4
W	8.7	39.3	1565	7.5	511	426	1.7	6.1	1.2	8.0	301	47.2	7.9	52	43.8	133	22.5	8.3	5.0	11.8
W	8.3	38.8	1724	8.0	401	324	3.2	4.1	0.2	1.3	238	20.5	1.6	56	42.8	53	21.7	1.6	4.5	6.7
W	8.2	38.7	1733	7.9	518	455	3.6	3.4	0.1	4.8	322	24.5	4.2	92	43.6	46	19.6	0.2	11.8	17.7
W	8.2	38.8	1678	8.0	470	423	1.1	5.7	0.1	9.0	305	31.4	10.3	61	26.6	32	0.7	0.2	2.6	1.5
W	8.6	39.4	1547	7.6	891	631	1.8	9.7	21.2	14.2	418	29.3	11.7	125	45.9	127	22.1	8.1	4.9	11.5
W	8.2	38.9	1690	8.1	959	808	8.3	47.0	0.2	5.4	517	10.9	2.2	217	39.2	202	9.1	1.1	5.6	10.0
W	8.2	38.9	1709	8.9	844	757	14.3	22.5	0.2	5.9	493	7.8	1.3	212	43.4	184	1.2	0.5	3.8	10.8
W	8.3	38.9	1637	7.8	612	545	5.1	6.3	1.8	2.5	368	15.9	2.7	142	41.0	94	28.4	1.0	6.3	6.1
W	8.2	38.9	1705	8.4	719	652	8.6	8.5	0.2	4.3	435	5.5	1.9	187	35.2	89	31.6	0.9	20.3	2.6
W	8.2	38.9	1718	7.9	816	715	9.9	18.4	0.2	0.9	477	14.9	3.8	190	38.4	151	0.5	0.4	1.5	6.9
W	7.9	38.7	1597	8.2	998	843	5.2	18.0	0.3	0.1	596	6.1	4.3	212	41.2	244	51.8	0.5	21.0	6.4
W	8.0	38.6	1774	8.2	642	579	4.0	14.5	0.2	24.1	368	20.0	2.8	146	49.1	82	44.7	0.5	10.2	27.1
W	7.7	38.7	1609	7.5	818	761	4.1	22.2	0.4	11.6	514	53.5	15.0	140	41.4	127	9.2	0.6	9.9	3.1
W	7.4	38.3	1804	8.1	918	741	12.2	39.2	15.1	34.1	421	7.5	1.0	210	45.2	67	149.6	1.2	16.2	42.6
W	8.2	38.9	1658	8.3	1940	1687	10.7	13.8	4.3	7.2	1174	15.6	7.4	454	34.5	253	2.7	1.2	15.1	10.6
W	8.1	38.8	1664	8.5	1557	1359	9.5	22.0	0.6	0.2	941	6.0	2.1	378	41.1	416	23.5	0.6	17.0	7.1
W	8.4	39.2	1543	7.3	1417	1130	12.4	77.6	0.5	76.4	644	41.3	10.1	267	39.4	573	0.7	1.9	12.3	49.3
W	7.9	38.7	1651	6.9	1077	971	5.7	21.0	0.6	1.8	678	7.7	3.4	253	43.8	331	29.9	0.8	48.7	10.6

W	8.0	38.7	1674	6.9	1945	1785	10.8	54.6	0.4	22.3	1217	3.9	1.1	474	38.4	606	71.3	2.6	73.4	19.5
W	7.8	38.7	1662	8.4	1148	940	8.8	16.3	0.4	5.3	639	3.4	0.6	266	39.7	294	38.9	0.4	22.8	12.5
W	8.2	38.9	1683	8.1	1740	1528	8.8	120.1	0.3	6.3	959	19.6	9.6	403	33.7	283	1.4	3.3	0.9	4.4
W	8.2	38.9	1675	8.1	1896	1765	10.2	65.3	0.3	25.5	1192	16.6	8.1	447	35.1	300	2.6	1.9	15.0	11.3
W	8.2	38.9	1690	8.6	1473	1303	8.2	84.1	0.6	2.6	830	12.2	3.4	360	39.0	274	1.1	1.8	5.1	7.7
W	7.7	38.5	1652	8.5	1288	1112	7.1	25.7	5.4	23.9	748	2.0	0.1	299	36.9	211	37.1	2.6	22.9	27.6
W	8.0	38.7	1647	7.6	1397	1181	3.7	139.8	0.5	26.4	656	89.9	38.2	225	41.7	127	2.7	4.2	7.4	1.7
W	8.1	38.7	1674	8.5	1906	1674	11.3	25.8	0.6	3.1	1178	5.0	2.7	447	39.9	524	63.9	0.8	44.7	8.4
W	8.0	38.7	1655	8.1	1710	1532	4.6	83.2	0.4	22.9	1019	12.8	9.5	378	39.7	415	31.7	2.2	19.0	9.5
W	8.4	39.3	1551	7.7	1410	1071	9.5	49.1	0.5	37.5	673	15.0	4.6	281	42.2	557	0.4	1.2	3.2	27.8
W	8.1	38.8	1678	8.3	1829	1691	17.2	30.7	0.5	7.6	1173	6.2	4.2	451	43.9	650	46.0	8.5	55.1	17.9
W	8.0	38.7	1717	6.9	1260	910	11.9	52.7	0.4	67.8	511	11.0	2.2	253	40.7	321	12.4	1.3	35.7	102.8
W	8.3	39.0	1632	7.7	1266	867	10.8	61.8	1.3	14.7	518	30.3	2.2	227	46.6	250	4.2	1.8	1.6	21.1
W	7.7	38.5	1656	8.5	1280	1161	7.1	25.6	2.3	23.8	767	3.8	0.4	331	44.5	178	33.2	1.9	21.6	26.6
W	8.8	39.5	1184	8.1	1593	1029	5.8	46.8	3.1	47.6	661	1.4	1.3	262	34.5	345	41.5	0.7	19.3	57.7
W	8.4	39.2	1537	7.3	1682	1145	12.9	77.9	0.9	82.7	634	41.4	9.4	284	39.3	497	0.8	1.1	10.3	46.5
W	8.1	38.7	1721	8.1	1100	805	10.4	43.8	1.0	26.8	486	8.2	0.9	228	49.8	302	30.4	0.7	18.3	66.0
W	8.3	38.9	1695	8.0	1280	1036	9.5	60.6	0.7	2.5	681	14.0	2.7	264	36.8	212	2.3	2.7	3.0	10.4
W	7.3	38.7	1931	6.3	182	139	1.0	2.3	1.3	2.4	101	10.5	2.7	25	41.7	11	10.1	4.2	1.2	1.8
W	8.5	38.0	2046	8.5	327	278	1.9	7.3	0.5	3.8	186	5.8	1.9	71	8.7	26	13.7	0.4	0.6	5.6
W	8.5	38.3	2467	9.3	167	158	0.7	4.1	0.5	3.5	103	1.2	0.1	44	17.4	7	0.8	0.2	1.1	1.5
W	8.1	38.4	2070	6.8	341	324	0.5	3.4	0.9	1.9	243	41.7	10.8	21	38.1	7	7.1	0.4	0.5	0.6
W	8.3	39.4	1662	9.5	224	204	1.3	7.6	0.0	6.0	135	8.3	2.8	44	2.2	25	1.3	0.4	0.4	3.6
W	8.6	38.0	2057	7.8	543	280	1.0	4.2	0.0	2.5	208	25.6	9.5	36	22.7	15	9.2	1.4	0.6	3.5
W	8.1	38.4	2062	6.9	487	396	0.4	17.4	1.0	9.2	268	58.3	15.6	26	39.5	7	7.2	2.5	0.6	0.7
W	8.2	38.5	1898	6.9	473	301	0.5	8.9	2.8	67.7	205	63.8	10.9	20	40.1	16	6.8	1.6	0.8	1.2
W	8.0	38.5	1871	7.6	810	648	3.0	9.8	1.4	6.6	450	21.5	4.1	152	48.8	84	4.1	1.2	4.2	6.9
W	8.1	38.5	1843	7.4	682	555	1.4	19.0	1.4	13.7	366	65.1	17.5	71	40.2	14	16.6	1.5	1.3	2.1
W	8.1	38.5	1845	7.3	873	792	3.2	21.3	0.5	20.1	564	47.1	11.8	166	41.1	6	26.6	2.0	2.0	2.6
W	8.0	38.5	1882	7.6	896	668	3.0	10.0	1.4	6.2	461	20.2	4.0	162	51.9	86	3.0	0.5	3.7	7.5
W	8.0	38.5	1818	7.3	687	636	2.1	9.9	0.3	10.8	447	52.0	13.3	100	38.5	76	2.3	0.5	4.4	2.8
W	8.2	38.7	1763	8.2	782	660	3.0	21.0	1.5	0.0	430	9.8	3.4	191	28.8	94	120.6	0.8	18.6	38.9
W	8.2	38.8	1809	8.2	1574	1122	7.6	103.9	2.7	36.0	628	15.8	5.2	323	46.8	284	18.3	2.8	7.5	14.5
W	8.1	38.7	1664	8.2	1717	1460	12.3	16.2	nd	1.2	1035	4.9	4.3	387	41.4	576	76.8	1.0	58.8	9.0
W	8.5	39.6	1249	7.3	1249	919	1.1	77.0	3.3	40.1	535	89.5	23.7	148	30.3	105	17.5	8.0	1.3	1.8
W	8.0	38.7	1697	8.5	2847	2629	8.7	182.7	nd	474.6	1432	4.1	0.8	524	35.4	797	26.7	5.5	42.0	58.1
W	8.0	38.7	1683	8.8	2429	1746	13.0	164.9	2.0	100.6	992	3.0	0.1	470	40.3	512	81.2	6.3	67.0	94.0
W	7.8	38.5	1614	8.4	3575	2165	39.0	211.1	0.7	133.0	878	1.2	0.1	901	30.3	1267	148.8	14.2	121	113
W	7.7	38.6	1586	8.6	3969	3555	61.6	251.9	nd	83.2	2045	0.9	0.4	1111	33.1	2100	7.3	7.3	190	128
W	7.7	38.1	1980	7.1	746	643	3.1	2.3	0.0	3.8	393	59.4	9.0	121	51.7	18	15.5	2.1	3.6	6.7
W	7.6	37.9	2306	6.5	256	251	0.8	3.7	0.0	2.5	148	24.4	5.0	23	43.8	5	1.4	0.8	0.2	1.0
W	7.6	37.9	2262	7.6	224	236	1.3	1.3	0.0	1.9	137	10.7	4.4	34	45.0	11	5.7	2.3	3.0	4.3
W	7.3	37.8	2300	7.2	312	286	1.3	1.5	0.0	0.8	176	16.6	6.0	38	46.0	9	0.2	0.4	0.0	0.8
W	7.1	37.7	1734	6.5	198	212	1.0	0.3	0.0	0.1	123	10.1	2.9	29	45.6	7	0.5	0.6	0.3	2.1
W	6.8	37.8	1817	5.7	133	92	0.1	6.1	5.3	0.3	39	3.9	1.0	18	18.6	4	0.2	0.3	0.0	0.0

W	6.8	37.3	1825	5.9	131	129	0.2	2.9	3.3	0.1	57	8.0	2.0	10	45.5	4	0.2	0.3	0.0	0.1
W	6.9	37.8	2148	5.5	62	46	0.1	2.5	4.0	0.4	14	2.8	0.4	5	16.1	3	0.2	0.4	0.1	0.0
W	6.9	38.1	1502	7.3	1162	889	13.7	18.7	0.2	24.1	538	19.9	3.7	216	53.6	106	8.0	1.9	4.3	33.1
W	6.2	37.6	2434	5.5	66	60	0.1	1.7	2.6	0.4	24	3.9	1.2	5	20.9	2	0.1	0.2	0.0	0.0
W	6.3	37.6	2691	5.2	287	101	0.1	34.2	0.0	1.9	11	19.1	6.0	20	8.6	3	0.4	1.4	0.1	0.0
W	6.3	37.6	2754	6.8	102	105	0.2	0.3	0.0	0.9	59	4.7	1.7	11	27.4	3	0.0	0.0	0.0	0.1
W	6.2	37.6	2537	6.1	55	38	0.1	1.1	1.8	0.4	18	2.4	0.7	3	11.3	2	0.1	0.0	0.0	0.1
W	6.2	37.7	1185	7.0	785	502	0.4	5.7	2.2	14.0	299	101.4	10.8	40	27.9	18	10.7	0.6	0.2	1.2
W	6.1	37.6	1243	7.7	134	122	0.1	1.8	0.0	0.9	84	13.3	5.2	8	9.3	4	1.2	0.1	0.1	0.3
W	6.2	37.7	1219	7.2	866	733	0.7	14.8	0.0	4.7	477	35.3	10.8	154	35.0	21	9.7	0.9	0.3	3.8
W	6.3	37.8	1221	7.1	565	501	0.4	5.6	4.1	9.0	338	58.8	17.6	39	28.3	9	10.7	0.7	0.2	1.4
W	6.5	37.7	1227	7.0	1018	867	0.6	29.1	0.0	13.6	592	60.4	45.4	90	35.4	24	35.9	10.0	0.3	2.4
W	6.5	37.8	1204	7.0	802	599	0.6	12.5	0.0	2.7	378	71.7	23.8	69	40.6	24	19.1	1.3	0.3	4.0
W	6.5	37.6	2263	5.7	134	100	0.1	4.9	2.0	1.0	57	12.4	2.5	6	14.6	3	0.4	0.4	0.0	0.1
W	6.5	37.8	1205	7.1	702	669	0.9	11.6	0.0	2.4	441	45.2	26.2	78	63.9	22	4.3	1.1	0.5	3.0
W	7.1	37.9	1883	7.2	594	579	2.2	5.2	0.0	5.3	368	31.6	10.3	110	46.0	11	3.5	0.5	0.9	13.1
W	6.8	38.4	1726	6.3	277	226	0.4	23.2	6.1	8.6	92	18.9	4.5	26	46.1	6	2.1	1.3	0.3	0.4
W	6.7	38.4	1824	6.0	112	122	0.1	1.3	0.2	0.0	58	4.9	1.1	10	46.5	3	0.3	0.2	0.1	0.3
W	6.6	38.4	1917	6.2	186	157	0.3	1.6	0.1	2.8	88	9.8	2.9	9	43.4	4	0.1	0.1	1.6	0.7
W	6.6	38.4	1944	5.8	77	63	0.1	1.6	1.6	0.6	34	8.5	0.7	3	13.3	2	0.3	0.2	0.0	0.0
W	6.4	38.3	1423	7.1	1159	859	1.4	27.1	0.0	45.8	498	22.5	6.6	199	58.4	183	0.6	1.3	1.1	8.9
W	6.4	38.3	1452	7.1	1510	1168	2.9	45.2	0.0	82.0	649	68.2	11.3	253	55.8	304	0.9	2.4	2.3	8.6
W	6.4	38.3	1453	6.9	1066	886	3.2	32.2	0.0	61.1	490	19.5	5.1	224	52.0	226	1.6	1.6	1.6	6.9
W	6.1	38.2	1891	7.7	354	313	0.1	1.2	1.1	1.3	237	37.0	18.2	4	13.0	2	0.3	0.1	0.1	0.1
W	6.1	38.2	2229	7.0	375	327	0.3	7.6	0.0	0.0	237	43.1	17.9	1	20.4	2	0.6	0.7	0.1	0.4
W	6.2	38.2	1855	6.9	238	224	0.2	1.3	0.1	0.8	150	20.2	5.7	19	26.6	2	2.1	0.1	0.1	0.4
W	6.4	38.3	1508	6.2	236	184	0.3	12.2	10.1	1.5	71	11.7	3.3	24	48.9	2	1.4	1.4	0.2	0.5
W	8.4	39.0	1598	8.7	1448	1273	13.7	62.0	0.2	16.4	766	1.4	0.2	373	39.7	347	67.3	2.1	7.3	16.9
W	8.2	38.8	1711	7.9	486	454	4.0	3.3	0.4	4.4	280	33.3	4.3	79	44.3	41	14.7	1.7	2.1	7.0
W	7.6	36.8	1799	nm	59	51	0.1	0.7	0.2	0.0	31	5.1	1.1	1	12.2	5	0.7	0.4	0.0	0.0
W	8.2	38.9	1646	7.8	1091	909	5.5	8.4	1.9	31.0	685	15.4	4.3	118	39.4	124	17.7	0.4	13.0	3.6
W	8.2	38.8	1706	8.2	461	446	1.7	4.6	0.0	6.6	289	21.3	6.8	75	40.9	53	2.5	0.0	1.9	2.5
W	nm	nm	nm	nm	2472	2126	17.3	144.7	0.0	0.0	1391	3.2	1.1	526	42.7	640	100.3	4.8	55.1	76.3
W	8.2	38.8	1709	8.3	1082	842	6.2	56.7	0.0	13.2	564	15.2	3.1	138	45.2	138	5.9	0.8	6.4	6.5
W	8.1	38.8	1670	8.4	1530	1375	12.0	15.1	0.0	3.9	921	7.2	4.0	364	48.5	605	44.6	1.9	32.8	7.2
W	8.2	38.9	nm	nm	1680	935	2.7	33.2	0.3	0.0	465	70.4	6.4	334	22.7	68	8.2	1.1	0.1	21.3
W	8.1	38.9	nm	nm	2452	2416	3.8	68.0	0.0	0.0	1772	22.7	14.5	496	37.7	873	0.9	2.2	16.7	2.8
W	8.2	38.9	nm	nm	1700	1475	8.9	62.5	0.0	19.2	1098	24.5	8.1	231	22.6	279	1.0	2.1	2.2	10.2
W	8.1	39.0	nm	nm	406	400	2.1	3.8	1.2	4.4	257	25.3	8.3	60	37.3	30	7.8	0.3	1.5	3.1
W	8.2	38.9	nm	nm	1784	1392	10.3	129.1	0.0	2.8	957	24.8	10.9	221	36.1	270	1.3	2.7	0.1	2.2
W	8.2	39.0	nm	nm	255	453	3.1	4.3	1.1	3.3	326	6.6	1.6	60	46.8	8	1.6	0.3	0.5	1.2
W	7.8	38.6	nm	nm	435	484	2.8	18.4	0.2	21.7	283	19.9	9.3	94	35.4	162	12.0	0.5	1.6	17.8
W	8.2	38.9	nm	nm	412	354	10.0	3.1	0.3	5.0	204	2.5	0.2	93	36.7	16	4.2	0.7	3.8	2.2
W	8.1	38.9	nm	nm	390	375	6.6	7.6	1.1	18.1	198	14.1	3.1	77	48.6	43	3.0	1.2	0.3	6.4
W	7.8	38.5	nm	nm	548	1223	7.8	26.7	1.3	25.9	781	2.2	0.1	330	48.5	272	40.8	2.8	23.3	26.5

W	7.7	38.5	nm	nm	1147	482	2.9	18.3	0.2	21.8	278	18.2	8.9	94	39.5	127	12.5	0.8	1.4	17.7
W	8.0	38.7	nm	nm	1781	1666	5.5	90.7	0.0	20.6	1040	21.5	17.5	422	47.1	697	49.8	25.6	22.0	9.7
W	8.0	39.0	nm	nm	268	304	2.6	4.6	0.0	3.1	181	22.9	7.1	45	37.6	31	11.1	2.6	1.7	3.2
W	8.1	38.8	nm	nm	1626	1398	11.9	15.0	0.0	3.8	921	6.4	3.6	389	47.0	437	40.6	1.0	30.0	6.6
W	nm	nm	nm	nm	872	641	4.6	14.6	0.1	22.1	404	20.8	3.0	120	51.4	71	41.9	0.0	9.4	24.6
W	8.2	38.7	1743	8.2	3022	1279	8.4	91.1	0.7	148.7	850	3.8	0.5	122	52.4	550	1.1	2.3	32.3	120.0
W	8.1	38.8	1652	7.9	1374	1182	6.9	29.4	0.0	3.1	844	13.8	9.3	234	42.2	366	131.5	12.3	39.7	8.5
W	8.2	38.9	1645	7.6	2406	1681	6.6	100.1	0.0	19.2	1243	16.3	16.7	235	42.6	236	70.9	1.5	20.0	34.7
W	8.3	38.9	1691	7.8	596	543	5.6	4.6	0.5	4.9	369	17.9	2.7	96	41.6	88	28.3	1.0	5.9	5.6
W	8.0	38.7	1646	7.4	1744	1502	8.1	141.9	3.0	32.4	814	43.5	26.5	374	57.6	493	12.7	4.1	4.2	0.4
W	8.0	38.7	1702	8.6	1036	1423	9.1	27.6	0.0	11.2	955	2.3	0.6	374	43.5	603	76.7	2.0	70.9	8.8
W	8.1	38.1	1651	7.1	1261	1033	2.2	32.4	0.0	6.5	718	80.6	39.8	112	41.8	133	2.6	0.9	3.9	6.2
W	8.0	39.0	1679	7.7	823	794	3.9	5.7	0.2	27.5	532	37.4	13.2	119	54.1	95	53.5	0.7	35.0	13.8
W	8.3	38.8	1706	7.9	569	546	5.9	3.4	0.8	3.7	347	22.3	0.6	119	42.9	310	18.1	9.9	1.5	13.4
W	8.2	38.8	1729	8.2	451	430	3.5	3.4	0.0	3.5	270	31.4	6.9	70	41.0	37	9.3	1.4	0.8	6.2
W	8.0	38.7	1646	7.6	2453	2156	4.9	251.3	0.0	51.9	1120	74.8	84.7	509	56.6	815	39.6	66.1	11.9	1.1
W	8.0	39.0	1737	8.0	171	174	0.5	1.5	0.2	2.3	111	16.3	5.2	16	21.1	28	6.8	0.2	0.2	0.9
W	8.4	39.0	1617	7.7	1381	946	11.7	49.7	0.0	10.6	613	25.6	0.8	188	46.0	256	5.1	1.8	1.9	19.4
W	8.3	39.0	1647	8.2	784	676	8.7	27.8	0.1	3.8	455	16.9	2.3	127	33.9	177	3.2	1.0	2.0	9.8
W	8.3	38.8	1709	nm	400	377	2.5	1.9	0.3	2.6	237	30.4	2.8	57	42.5	27	15.6	2.0	4.6	1.6
W	8.2	38.9	1643	nm	1298	1117	7.6	7.3	2.3	47.3	873	15.4	4.5	120	38.6	165	71.2	1.2	32.0	7.4
W	8.0	38.6	1773	7.9	819	617	4.8	14.9	0.0	22.5	399	20.4	2.7	105	48.1	70	41.7	0.4	9.4	24.7
W	8.2	38.9	1663	nm	2165	1862	14.7	74.9	2.5	33.5	1180	12.2	7.9	495	40.8	361	10.1	4.8	13.0	19.4
CS	7.7	38.8	1596	7.7	462	337	2.2	10.0	0.2	10.4	228	13.4	6.1	66	35.6	83	11.3	0.2	1.5	13.9
CS	8.3	38.4	2858	6.8	106	99	0.5	1.4	0.3	1.1	72	8.9	2.2	12	26.8	5	11.4	0.7	0.3	0.7
CS	8.0	39.2	2292	7.0	88	77	0.2	2.8	0.3	2.6	54	10.1	3.3	4	21.8	4	6.6	2.1	0.2	0.3
CS	6.8	37.8	1771	5.7	116	74	0.3	2.5	2.4	0.6	57	4.8	1.3	3	1.2	5	0.5	0.6	0.1	0.3
CS	6.9	37.9	1692	6.6	205	138	1.6	1.7	0.7	1.2	118	6.5	1.7	5	1.7	11	1.4	0.8	0.7	4.4
CS	6.9	38.0	1465	6.2	363	240	1.6	6.0	1.6	4.9	202	11.2	2.1	8	2.1	15	0.3	0.3	0.1	0.7
CS	6.0	37.6	1157	7.1	331	300	0.2	3.5	0.7	2.0	205	37.0	14.3	25	11.8	5	9.7	1.0	0.2	0.4
CS	6.5	37.6	2236	5.0	62	32	0.3	3.3	3.5	0.7	17	3.2	0.8	2	0.8	3	0.4	0.6	0.0	0.0
L	7.9	38.7	1691	9.1	461	400	1.8	15.9	0.8	8.6	267	14.4	8.6	82	17.5	87	9.7	2.4	2.4	4.3
L	7.1	38.4	1683	8.7	797	708	8.4	29.2	1.4	4.2	469	10.8	6.4	179	25.7	157	2.1	1.4	2.6	9.1
L	7.7	38.7	1582	6.9	1775	1349	13.9	166.6	2.7	16.7	755	7.1	2.4	384	37.6	653	12.3	9.1	5.2	19.2
L	8.9	39.9	nm	9.4	6770	5533	30	506	nm	475	2886	2.8	0.4	1630	42.8	4139	84.3	11.2	71	286
L	7.4	38.4	1556	9.5	25980	22470	200	3291	1.3	201	13613	5.7	0.6	5143	49.7	17688	95.0	65.0	154	1050
L	7.5	38.6	1557	9.7	25160	21250	184	3063	2.9	138	12833	6.5	1.1	5009	45.7	16185	42.8	45.3	91	842
L	7.7	38.6	1577	6.9	49480	40859	316	5727	11.3	701	25350	3.6	0.4	8720	80.2	30972	62.4	83.0	428	1498
L	7.4	38.4	1569	10.1	48500	45764	171	5839	6.6	315	30376	7.0	1.4	9034	106.2	21334	110.0	78.1	566	7713
L	6.1	37.6	1182	8.8	1104	0.72	8.4	65.1	nm	50.3	559	16.7	3.1	246	23.8	189	30.1	3.8	6.0	38.0
L	5.9	37.5	1115	9.0	1888	1.22	9.1	128.8	nm	50.6	968	10.1	10.1	421	2.2	344	41.6	9.3	4.1	41.2
L	6.5	37.8	1181	8.7	1082	0.70	7.5	65.1	nm	110	545	16.8	3.0	274	28.2	176	30.1	6.6	5.5	34.8
RI	7.7	38.7	nm	8.4	500	425	2.2	15.0	3.8	7.0	287	25.9	9.4	64	nm	114	10.1	17.4	3.4	5.3
RI	8.2	38.8	nm	8.7	530	583	1.5	16.0	2.0	25.0	409	42.1	20.9	56	nm	11	13.3	1.9	3.4	8.9
RI	8.0	39.0	nm	7.8	180	174	1.6	4.0	2.6	1.0	125	16.8	5.2	15	nm	0.0	3.3	4.6	0.1	1.3

RI	7.8	39.1	nm	8.3	90	98	0.2	1.4	2.0	0.8	67	18.5	2.7	5	nm	5.6	1.7	1.2	0.1	0.4
RI	7.5	38.9	nm	7.9	60	73	0.1	2.2	6.2	1.5	49	10.7	1.4	5	nm	1.0	0.6	1.2	0.1	0.3
RI	7.5	38.9	nm	7.8	40	53	0.1	1.0	1.8	0.2	37	8.4	1.2	3	nm	0.0	0.3	1.1	0.0	0.2
RI	7.5	38.7	nm	7.9	150	118	0.5	3.4	11.9	2.3	73	17.9	2.3	13	nm	2.4	1.3	1.7	0.1	0.5
RI	7.3	38.7	nm	7.9	150	156	0.3	6.8	10.2	4.1	79	40.7	2.2	16	nm	3.9	0.6	2.1	0.1	0.6

Table a: *Summary of EC, Eh, DO and major and selected trace elements of 162 water samples from groundwater wells, hot springs, cold springs, and lakes in the studied basis. Note: w=groundwater wells; CS=cold springs; L=lakes; RI=rivers and nm=not measured.*