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Full Length Research Paper

Application of density-dependant finite element model for studying seawater intrusion in coastal aquifer of Ras El-Hekma, Northwestern Coast, Egypt

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A numerical model of variable-density groundwater flow and miscible salt transport is applied to investigate the extent of seawater intrusion in coastal aquifer of Ras El-Hekma, northwestern coast, Egypt. The SEAWAT 2000 code is used to solve the density-dependent groundwater flow and solute transport governing equations. Seventeen groundwater samples were collected in 2015 for routine chemical analysis and water level monitoring were carried out and interpreted. The model was calibrated using data measured for heads (m) and TDS (mg/L) in 2009 compared with data collected in 2015. Three scenarios of pumping and fourth scenarios of sea level rise by 0.5 m were applied. The results of three scenarios of pumping revealed that there was a general trend of drawdown in water table (~5 m) of observed wells located at about 1 to 1.5 km from the coast at the end of 20 years of simulation. At the same time there was replenishment from rainfall and surface runoff caused a water table rise in some observed wells that were located inland. For the proposed fourth scenario of sea level rise, the seawater/freshwater interface will migrate more inland (0.5 to 2 km) than its current position. The result of the numerical model shows a transgression of seawater inland and along the coast. The model and chemical results recommend a decrease in pumping to the drilled wells should not exceed 40 m^3/day in order to avoid further seawater intrusion along the coast and upwelling of deep saline groundwater with continuous monitoring of the groundwater level and salinity measurements in north coast of Mediterranean Sea.

Key words: Seawater intrusion, groundwater modeling, SEAWAT code, Ras El-Hekma, Egypt.

INTRODUCTION

Coastal areas are important for human settlement and development. It is estimated that more than half the world's population lives within 60 km of the shoreline, and this number could increase up to three quarters over a decade (UNCED, 1992). Over exploitation of groundwater in coastal aquifers may result in intrusion of saltwater. Contamination of coastal aquifers may lead to serious consequences on environment, ecology and economy of that region. The saltwater intrusion in a coastal aquifer is a highly complex and nonlinear

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process. Management of coastal aquifers requires careful planning of withdrawal strategies for control and remediation of saltwater intrusion (Datta et al., 2009). Egypt has a relatively long coast line of about 950 km along the Mediterranean Sea, with Ras El-Hekma representing one of the main headlands along the southern Mediterranean coast subjected to several problems such as scarcity of rainfall and high pumping rates that degraded groundwater quality in the main water supply wells. Northwestern coast of Egypt was subjected to several studies that focused on water resources. Youssief and Bubenzer (2013) studied groundwater at Ras El-Hekma area and clarified the relationship between depth to water, sea level and salinity of water. Morad et al. (2014) assessed the hydrologic factors controlling groundwater salinity in the coastal area between El-Dabaa and Sidi Barani, Egypt, and demonstrated that the aquifers in the area are recharged by seasonal rainfall of the order of 150 mm/year and the ability to be recharged is a measure of the vertical permeability due to lithological and structural factors that control groundwater salinity in the investigated aquifers. Soliman et al. (2013) mapping of seawater/freshwater interface at Ras El-Hekma city by 2-D resistivity imaging and transient electromagnetic soundings, concluded that the upper aquifer represented by Oolitic limestone of Pleistocene age and the lower aquifer represented by Middle Miocene age were affected by seawater, but the lower one showed larger effect than the upper one. The freshwater/saltwater interface could be delineated at a depth of 20 to 30 m below the ground surface according to the ground surface elevation. To numerically simulate seawater intrusion, a density-dependent groundwater flow simulation model is required to track the movement and change the transition zone between fresh water and salt water. The last decade has seen the appearance of several density-dependent simulation codes that are based on the commonly used groundwater model, MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1998; Harbaugh et al., 2000). These codes include SEAWAT (Guo and Bennett, 1998a, b; Guo and Langevin, 2002; Langevin et al., 2003).

The objective of the study is to apply numerical model to investigate seawater intrusion in Ras El-Hekma coastal aquifer based on SEAWAT 2000 which is a quasi-three-dimensional variable-density numerical model, where after the model calibration by using the observation data in August 2009 (Youssief and Bubenzer, 2013), the calibrated model will be used to predict the extent of seawater intrusion for the next 20 years taking into consideration groundwater samples collected in 2015.

Study area description

Ras El Hekma, a prominent cape of the Egyptian northwestern Mediterranean coast, is situated about 200 km to the west of Alexandria and covers about 230 km^2 (Figure 1). Whereas the coast eastward and westward of Ras El Hekma is heavily overbuilt for touristic reasons, the cape is relatively sparsely built and shows a more traditional land use. The climate of the study area is characterized by southern Mediterranean conditions (Harding et al., 2009) with rainy mild winters and a warm, dry summer, while spring and autumn are comparably short. During spring, some storms occur and during autumn, occasional sudden heavy rainfalls are possible. Climatic data from 1945 to 1992 (Ali et al., 2007) for Matrouh station (70 km to the west) shows a mean monthly minimum temperature of 8°C in January and a maximum of 29.8°C in August. The average annual precipitation is 155 mm, but with a relatively high variation coefficient of 0.42. The annual evaporation rate is 1578 mm. However, due to the fact that rainfall normally occurs only between October and February, rainwater harvesting for agricultural and pastoral uses is possible with surface water considered as the main source for recharge of the groundwater.

Geomorphology, geology and hydrogeological settings

Geomorphological aspect illustrate that two main topographic features are predominant in the study area; the tableland in the south and the coastal plain in the north (Figure 2). In Ras El Hekma, the following landscape units are distinguishable from south to north (Yousif and Bubenzer, 2011): (a) the tableland; (b) The piedmont plain and; (c) The coastal plain.

Geological aspect based on geological map (CONOCO, 1986) and the Landsat images show that the following stratigraphic units can be distinguished from young to old (Yousif and Bubenzer, 2011): (a) Holocene deposits are known along the present beach. The sand near the beach is highly polished and contains small quantities of fine clayey and/or calcareous particles, while inland the sand contains a high amount of these fine materials. (b) Pleistocene sediments are also widely distributed in the study area and are mainly represented by Oolitic limestone, which constitutes the main bulk of the Pleistocene sediments covering the greater part of the coastal zone and are almost developed in the form of elongated ridges running parallel to the present coast. (c) Tertiary deposits are exposed in the southern parts of the study area (the tableland); these deposits are represented by Pliocene sediments which have limited exposures and Miocene sediments represented by the Marmarica limestone formation. The Marmarica formation is built up of fissured and cavernous limestone, dolomitic limestone, and sandy limestone intercalated with clay and marl interbeds.

Hydrogeologically, the area of study is characterized by an aquifer system belonging to the Quaternary (Holocene

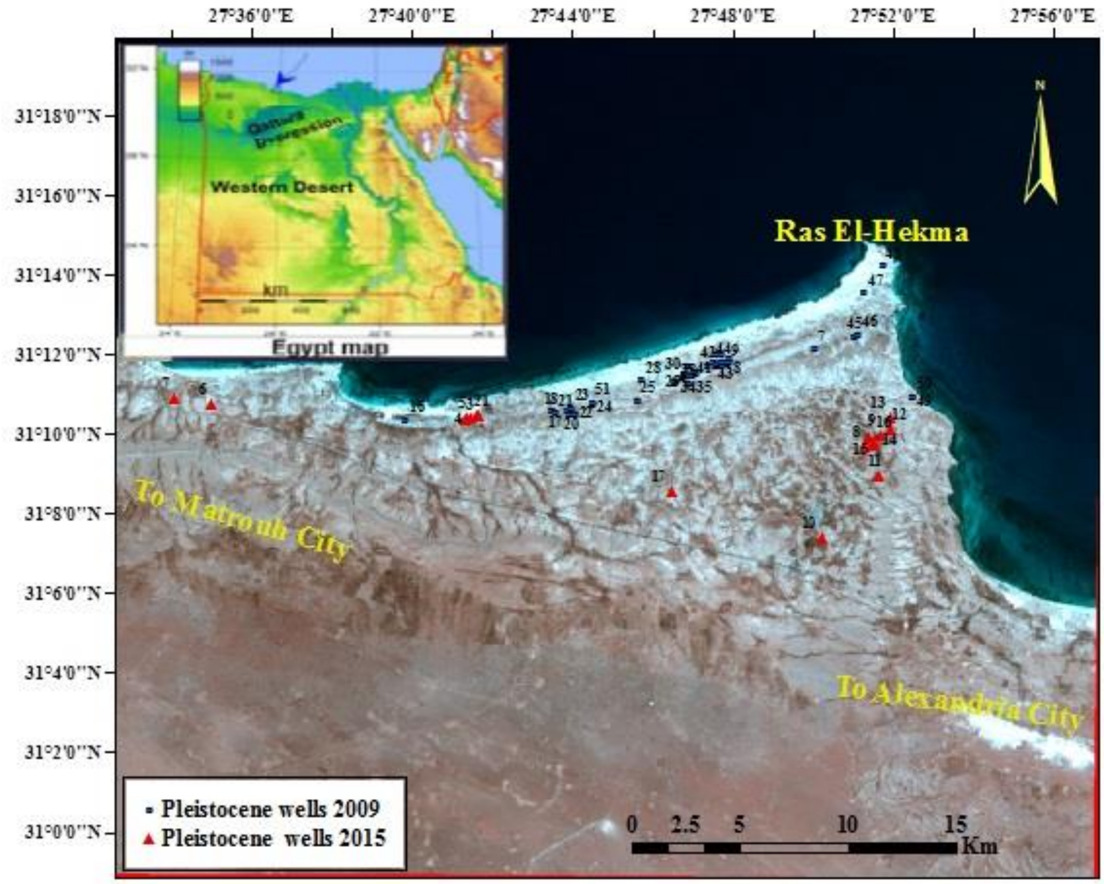

Figure 1. Location map of the study area and the collected groundwater samples in 2009 and 2015. Source: Yousif and Bubenzer (2013).

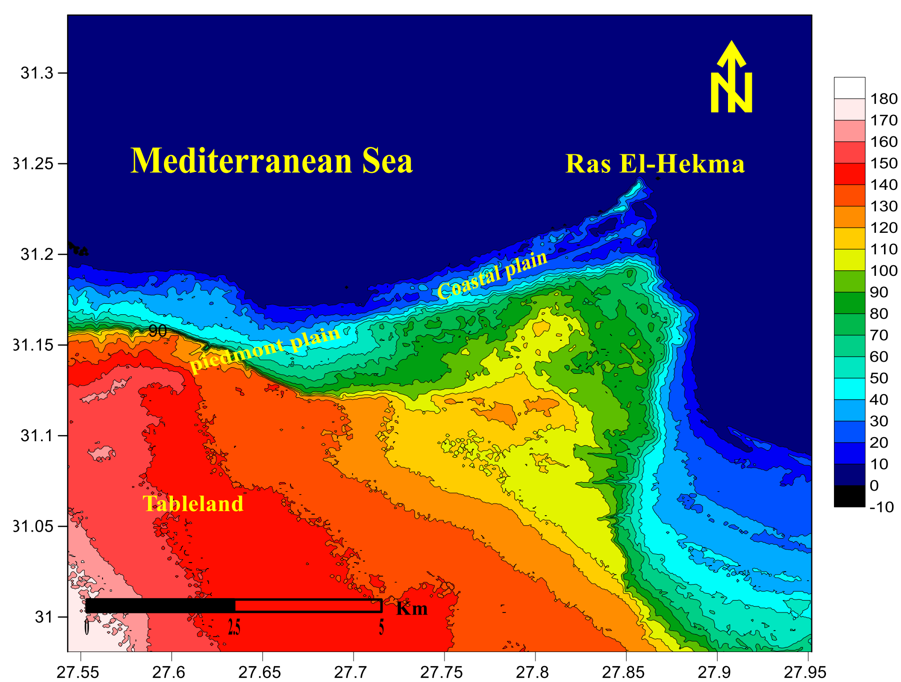

Figure 2. Digital elevation model (DEM) showing the main landforms in the study area.

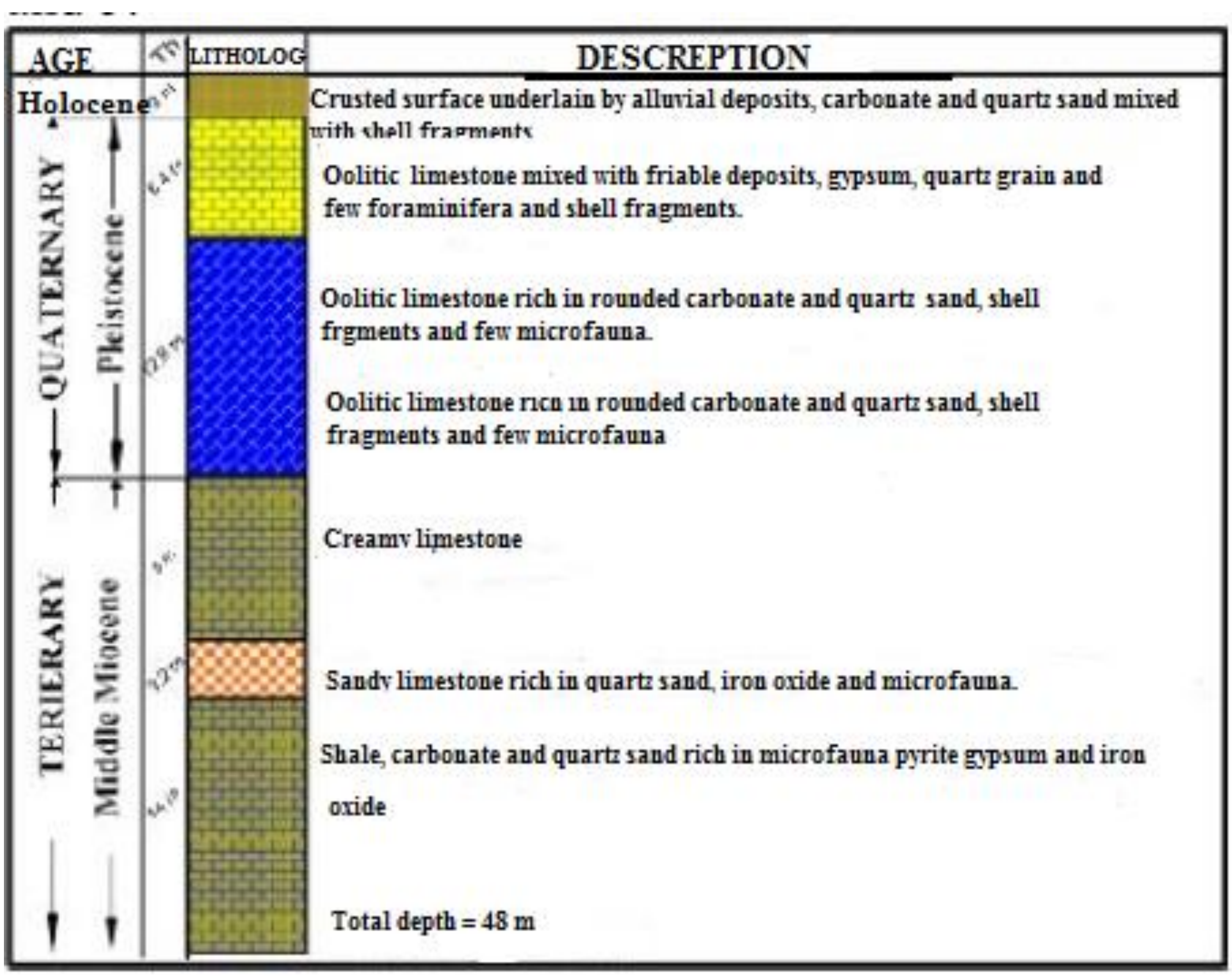

Figure 3. Lithological description of shallow dug well.
Source: Hammad (1972).

and Pleistocene) and the Tertiary (Miocene) as illustrated in Figure 3. Holocene aquifer (alluvium aquifer) forms a limited groundwater aquifer (Sewidan, 1978) and occupies the main trunk and deltas of some drainage basins. Here, precipitation forms the main sources of recharge. Pleistocene aquifer (Oolitic limestone aquifer) is composed of Oolitic limestone interbedded with sandstone and clay which is considered to be the most important aquifer dominating the whole coastal strip. The Oolitic limestone aquifer extends southward from the coastal line to about 4 km. Groundwater generally flows from south to north following the general slope. Groundwater salinity ranges from brackish to high saline water according to rainfall quantity, over pumping and sea/salt water intrusion. Tertiary aquifer (Fissured limestone aquifer) is composed of limestone with little clay intercalations. Groundwater occurs in two forms; shallow groundwater (Perched groundwater) and deep groundwater. Rain water forms the main recharging source of this aquifer. Deep groundwater is formed when rainwater is accumulated in the fractures, fissures solution plains of the limestone rock. This aquifer is a generally low potential aquifer with salinity ranging from fairly fresh to hyper saline water.

MATERIALS AND METHODS

For hydrochemical evaluation, about 17 groundwater samples were selected from shallow aquifer of the studied area. The samples were collected in 1 L narrow-mouth pre-washed polyethylene bottles. Electrical conductivity (EC), temperature and pH values were measured in the field using a portable conductivity and pH meters. In the laboratory, the water samples were filtered through 0.45 µm to separate suspended particles. Acidification (pH<2) with concentrated nitric acid was performed on the filtered samples for heavy metals analysis using ICP (inductively coupled plasma) at the central laboratory of Desert Research Centre. The acid titration method was used to determine the concentration of bicarbonate HCO_3^- (APHA, 1995). Major anions (Cl^-, SO_4^{2-}) and major cations (Ca, Mg, Na, K) were analyzed using ion chromatography (Dionex DX-600). All reported values have an ionic balance within 5%.

In addition to a three-dimensional variable-density, transient groundwater flow model was developed to assess salt water intrusion phenomena in shallow aquifer of Ras El-Hekma area. The flow model was constructed using SEAWAT-2000 (Langevin et al., 2003), a computer program that combines a modified version of MODFLOW-2000 (Harbaugh et al., 2000) with MT3DMS (Zheng and Wang, 1998). While there are a variety of codes available that are suitable for this purpose, SEAWAT-2000 affords the flexibility of supporting several different boundary conditions and provides a choice of numerical methods for solving the transport equation. SEAWAT-2000 has accurately reproduced the solutions to several benchmark problems commonly applied in literature (Guo and Langevin, 2002). The SEAWAT program solves the variable-density flow equation by formulating the matrix equations in terms of fluid mass and assuming that the fluid density is solely a linear function of solute concentration. The flow and transport equations were explicitly coupled using a one-time step lag and solved alternately until the maximum difference in fluid density was less than 10^{-6} kg/m^3, which provided a mass-balance error less than 0.01%. The effect of variable fluid viscosity on flow was not considered in these simulations because the temperature range in this shallow aquifer system is small (Langevin and Guo, 2006) and showed that accounting for variable viscosity in their SEAWAT simulation of fluids with sharply contrasting densities in the salt-pool problem had a negligible effect on model results. An implicit finite difference (FD) method was selected to solve the advection equation and central-in-space weighting was specified to minimize numerical dispersion.

Governing equations

Variable density groundwater flow is described by the following partial differential equation (Langevin et al., 2003) as presented in:

$$\nabla\rho K+\left(\nabla hf+\frac{(\rho-\rho f)}{\rho f}\nabla z\right)=\rho Sf\frac{(\partial hf)}{\partial t}+n\frac{\partial\rho}{\partial C}\frac{\partial C}{\partial t}-\overline{\rho q} \qquad (1)$$

Where z is a coordinate direction aligned with gravity (L); ρ is fluid density (ML^{-3}); K_f is the equivalent fresh water hydraulic conductivity (LT^{-1}); h_f is the equivalent fresh water head (L); ρ_f is the density of fresh water (ML^{-3}); S_f is equivalent fresh water storage coefficient (L^{-1}); t is time (T); n is porosity (L°); C is the concentration of the dissolved constituent that affects fluid density (ML^{-3}); ρ is the fluid density of a source or a sink (ML^{-3}); and q is the flow rate of the source or sink (T^{-1}). To solve the variable density ground water flow equation, the solute-transport equation must also be solved because fluid density is a function of solute concentration, and concentration may change in response to the groundwater flow field. For dissolved constituents that are conservative, such as those found in sea water, the solute transport equation is:

$$\frac{\partial C}{\partial t}=\nabla(D\nabla C)-\nabla(vC)-\frac{qs}{n}\,Cs \qquad (2)$$

Where D is the dispersion coefficient (L^{2}T^{-1}); v is the groundwater flow velocity (LT^{-1}); qs is the flux of a source or sink (T^{-1}); and C_s is the concentration of the source or sink (ML^{-3}).

Simulation code

To simulate variable density effects on groundwater flow, the coupled flow and transport code SEAWAT was used. Coupling flow and transport computations allow the effects of fluid density gradients associated with solute concentration gradients to be incorporated into groundwater flow simulations (that is, density dependent flow). It uses the finite difference method of numerical integration to solve 3-D confined and unconfined groundwater flow under many types of natural and artificial aquifer stresses. The original SEAWAT code was written by Guo and Bennett (1998a, b) to simulate groundwater flow and salt water intrusion in coastal environments. SEAWAT uses a modified version of MODFLOW (McDonald and Harbaugh, 1998) to solve the variable density, groundwater flow Equation 1 and MT3D (Zheng, 1990) to solve the solute-transport (Equation 2).

Spatial and temporal discretization

The model domain and finite difference grid used to simulate groundwater flow within Ras El-Hekma coastal aquifer is illustrated in Figure 4. The model encompasses an area of about 1516.5 km^2. The grid consists of 200 rows and 200 columns with 40000 regular cells in plain view. Each cell is 0.1521 × 0.1521 km^2 in the horizontal plane. Coastal unconfined Pleistocene aquifer was treated as a single layer with mean hydraulic conductivity that ranges between 20 to 60 m/day (Eissa et al., 2017). Longitudinal and lateral dispersivities were set equal to 10 and 1 m, respectively. The effective porosity was set equal to 35%. The northern boundary is saline seawater transport boundary (39.7 g/L) since the Pleistocene aquifer was in direct hydraulic contact with the Mediterranean Sea in which the water level is known (zero). At the western-southern boundary, the salinity is fixed (~5 g/L) and the groundwater level reached 6 m asl. The groundwater salinity during 2009 ranged between 1 to 8 g/L according to Yousif and Bubenzer (2013) and reached 10 g/L in this study above datum of the eastern and western sides, respectively. For the upper boundary, the water table was considered higher than the Mediterranean Sea water level. The concentration was constant and equal to the groundwater concentration. The bottom boundary was impermeable, that is, the normal flux through the bed for both fluid and salts was equal to zero. The input data required for the model include: well location and pumping rates, aquifer configuration, including top and bottom of the system, hydraulic conductivity of the system, amount of recharge and potentiometric head.

Calibration in steady state

Model calibration was achieved through trial and error by adjusting the values of recharge at the boundaries. The calibration in the steady state has been conducted versus potentiometric head data in August, 2009 and compared with data measured in 2015 to calibrate the spatially variable hydraulic conductivity and recharge, and hydraulic conductivity of the general head boundary. Calibration process produced an acceptable comparison between observed vs. calibrated heads (Figure 5) and concentration in (mg/L) (Figure 6).

Testing scenarios

Four proposed pumping scenarios were simulated based on the potentiality of the Oolitic limestone Pleistocene aquifer to examine the impact of seawater intrusion. The first scenario considered 40 m^3/day as pumping rate (base case scenario) where (El-Raey, 1998) mentioned that underground water can also be found in the limestone layers below the Fuka Basin. They can produce water with an average quality at a rate of 20 m^3/h. The second scenario considered the extra pumping rate of 80 m^3/day. The third scenario considered an increase of number of pumping wells (2009 and 2015 with pumping rate of 40 m^3/day). Also, El-Raey et al. (1999) stated that natural sea level rise along the northern Egyptian coast is about 0.4 and 5 mm/year; while IPCC (2007) predicted that the sea level rise will be between 0.15 and 0.9 m until the year 2100.

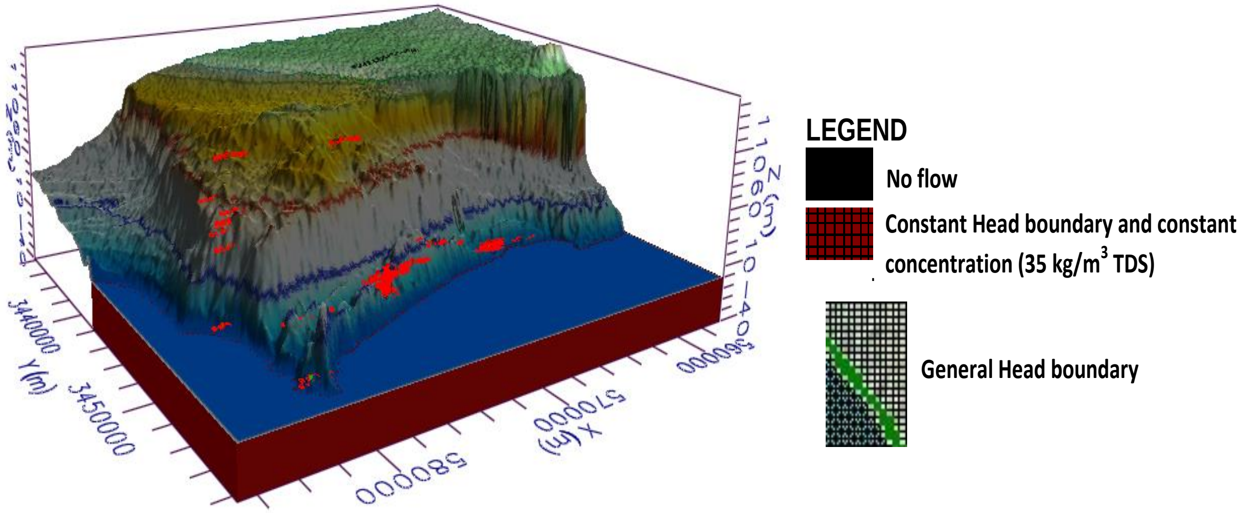

Figure 4. Finite-difference grid and boundary conditions for Ras El-Hekma shallow aquifer.

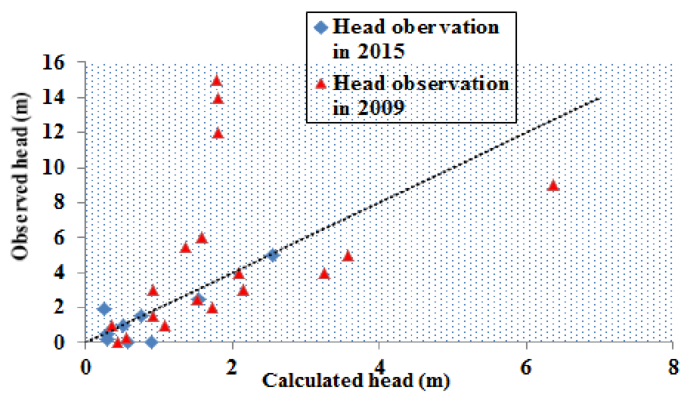

Figure 5. Steady state calibration of observed and calculated heads in August 2009 and compared with 2015.

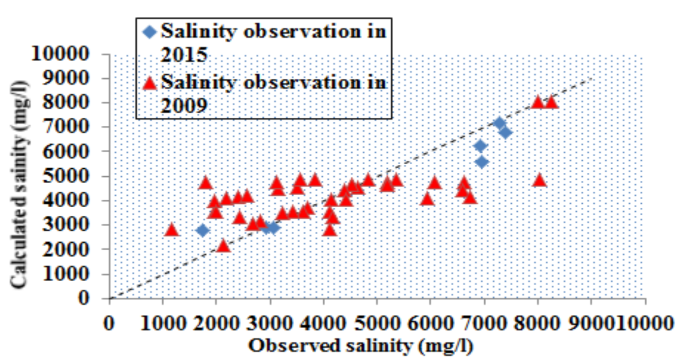

Figure 6. Calculated versus observed groundwater salinity in August 2009 and compared with 2015.

This change is expected to exacerbate the already existing environmental problems. In particular, coastal areas all over the world are expected to suffer from the impacts of sea level rise, that is, from coastal erosion, subsidence, pollution, and land use changes, hence the fourth scenario considered a rise of sea level of 0.5 m.

Table 1. Physical and chemical results of the collected groundwater samples.

Sample No.	TD (m)	DTW (m)	Eh (mv)	Temp. (°C)	pH	EC (μScm^{-1})	TDS (mg/L)	Cations (meq/L)				Anions (meq/L)			
								Na	K	Ca	Mg	CO_3	HCO_3	Cl	SO_4
1	5.5	4.5	86.3		8.50	5420	3068	36	1.0	3.94	12.41	0.00	4.05	37.92	10.42
2	12	4.8	102.3		8.20	5220	2917	31	1.3	4.74	14.06	0.00	4.97	37.47	8.33
3	4.5	4.05	42	24.6	8.70	3110	1733	18	0.6	3.26	9.57	0.21	3.98	20.52	5.12
4	8.5	7.8	138	24	8.60	2210	1201	11	0.4	2.91	9.12	0.57	4.69	14.08	1.98
5	7.5	4.65	126	22.7	8.70	2802	1535	14	0.6	3.14	10.98	0.36	4.40	18.73	3.75
6	6.8	6.33	137	23	8.10	17000	9852	117	1.7	17.23	40.89	0.00	3.76	150.70	16.39
7	30	26.2	60.2	26	8.50	16050	9315	122	2.0	7.52	22.71	0.21	4.19	118.78	34.26
8	41	25.4	90	26.5	8.70	8390	4993	67	1.3	6.99	11.16	0.57	3.98	67.40	12.13
9	30	190	83.2	28.5	8.60	13080	7408	96	1.6	10.97	17.29	0.50	4.33	109.58	13.84
10	88	84	49.3	25	8.30	12310	6946	95	1.4	7.51	15.77	0.50	5.61	94.65	16.70
11	95	90	3.2	27.2	8.60	12420	6931	89	1.3	10.54	17.69	0.43	3.41	99.79	0.27
12	11	10.5	95.5	27	8.50	12920	7271	100	1.8	7.13	13.42	0.28	2.98	103.67	17.06
13	10.8	10.3	56	24.5	8.40	17160	10048	130	2.0	13.44	26.64	0.28	1.99	145.55	23.76
14	11.5	11	58	24	9.20	4540	2697	38	0.8	2.02	5.15	0.57	1.21	38.95	5.09
15	10.5	10	69	24	9.00	1209	723	10	0.8	0.55	1.05	0.28	4.19	6.88	0.98
16	11.5	11	172.6	25.5	9	2132	1234	18	0.4	0.66	1.07	0.50	4.69	13.86	2.23
17	25	18	45.8	26.5	8.3	15210	8762	115	1.5	13.06	23.75	0.36	4.54	125.66	18.34
Min	**4.5**	**4.05**	**3.2**	**22.7**	**8.10**	**1209**	**723**	**10**	**0.4**	**0.55**	**1.05**	**0.00**	**1.21**	**6.88**	**0.27**
Max	**95**	**190**	**172.6**	**28.5**	**9.20**	**17160**	**10048**	**130**	**2.0**	**17.23**	**40.89**	**0.57**	**5.61**	**150.70**	**34.26**
Average	**26.8**	**37.5**	**83.69**	**25.31**	**8.59**	**8924**	**5127**	**66**	**1.2**	**7.02**	**15.51**	**0.33**	**3.88**	**71.67**	**11.85**

RESULTS AND DISCUSSION

Table 1 summarizes the results of hydrochemical parameters for the analyzed groundwater samples of Pleistocene aquifer with basic statistical parameters (N=17) from the study area. The comparison of the hydrochemical data with guidelines of standard water quality (WHO, 2011) shows that for Pleistocene aquifer, groundwater samples have pH values that vary from 8.10 to 9.20 with an average value of 8.59. In general, pH of water samples was slightly alkaline, compared with WHO (2011) standards; all samples fall within the recommended limit (6.5 to 8.5) for human consumption except 53% exceeding this limit. The EC values vary from 1209 to 17160 μScm^{-1}, with a mean of 8924 μScm^{-1}. EC values are above the permissible limits of WHO (2011) of 1500 μScm^{-1} in all groundwater samples except sample No. 15 (EC=1209 μScm^{-1}). Total dissolved solids (TDS) varies from 723 to 10048 mg/L (average 5126 mg/L), classified as 18 and 47% classed as moderately saline and slightly saline groundwater samples, respectively, according to Konikow and Reilly (1999) and Rhoades et al. (1992), and 35% as highly saline groundwater samples. The cation chemistry is dominated by sodium followed by magnesium, calcium and potassium in all of the samples, and anion chemistry are dominated by chloride followed by sulfate and bicarbonate in about 76% of the samples.

The hypothetical salts combination (Table 2) illustrate that for Pleistocene aquifer, increase in TDS in most of the groundwater samples is due to the increase in soluble salts (NaCl, Na_2SO_4 and $MgCl_2$). The dominant ions show that all samples have water type Na-Cl. The presence of bicarbonate salts (Group 4) reflects the dilution effect of rainwater on the groundwater. On the other hand, some groundwater samples (Group 1) have a mixed source of mineralization, indicated from hypothetical salt containing $MgCl_2$ (marine origin) and $Mg(HCO_3)_2$ salts.

For elucidation of the mineral saturation indices which reflect water-rock interactions using PHREEQC program, positive values of mineral indices indicate supersaturation with these minerals, while negative values indicate under-saturation conditions and 0 values indicate saturation in equilibrium state. The obtained data in Table 3 reveal that for Pleistocene aquifer all the samples are supersaturated with carbonate minerals, which is represented by calcite $CaCO_3$, dolomite $CaMg(CO_3)_2$ and other minerals such as Gibbsite $Al(OH)_3$ and Quartz SiO_2. However, all samples are undersaturated with gypsum $CaSO_4.2H_2O$, anhydrite $CaSO_4$ and halite NaCl minerals.

Seawater mixing index (SWMI)

Statistical methods for chemical data were used in the coastal area to understand how geochemical processes influence groundwater quality. For quantitative estimation of the relative degree of seawater mixing with

Table 2. Assemblages of the hypothetical salts in Ras El-Hekma area.

Well No.	Groups	Assemblages of the hypothetical salts				
1-2-3-4-5-6	1	$NaCl$	$MgCl_2$	$MgSO_4$	$Mg(HCO_3)_2$	$Ca(HCO_3)_2$
8-12-13-14	2	$NaCl$	$MgCl_2$	$MgSO_4$	$CaSO_4$	$Ca(HCO_3)_2$
11	3	$NaCl$	$MgCl_2$	$CaCl_2$	$CaSO_4$	$Ca(HCO_3)_2$
15-16	4	$NaCl$	Na_2SO_4	$NaHCO_3$	$Mg(HCO_3)_2$	$Ca(HCO_3)_2$
7-9-10-17	5	$NaCl$	Na_2SO_4	$MgSO_4$	$CaSO_4$	$Ca(HCO_3)_2$

Table 3. Saturation index values with ionic ratios and Br concentration (mg/l).

Well No.	Saturation Index (SI)							Br	Na/Cl	Br/Cl
	Calcite	Dolomite	Anhydrite	Gypsum	Halite	Gibbsite	Quartz	(mg/L)		
1	0.97	3.55	-1.65	-1.36	-4.66	2.12	0.44	33	0.95	0.025
2	0.88	3.35	-1.66	-1.37	-4.72		0.44	19	0.84	0.014
3	1.05	3.68	-1.89	-1.60	-5.19	3.65	0.43	27	0.89	0.037
4	1.16	3.95	-2.29	-2.00	-5.55	2.86	0.49	14	0.76	0.028
5	1.20	4.06	-2.04	-1.75	-5.33	2.49	0.59	9.4	0.73	0.014
6	1.00	3.52	-1.23	-0.95	-3.64	3.07	0.62	10	0.78	0.002
7	1.08	3.76	-1.22	-0.93	-3.72	2.58	0.43	74	1.03	0.018
8	1.29	3.90	-1.47	-1.18	-4.17	3.45	0.37	62	0.99	0.026
9	1.23	3.79	-1.35	-1.06	-3.84	3.95	0.51	22	0.87	0.006
10	1.13	3.70	-1.42	-1.13	-3.90		0.41	28	1.01	0.008
11	1.35	4.07	-3.03	-2.74	-3.89		0.41	44	0.89	0.012
12	0.98	3.37	-1.43	-1.14	-3.84	2.93	0.72	71	0.96	0.019
13	0.76	2.95	-1.15	-0.86	-3.61	3.90	0.72	83	0.89	0.016
14	0.64	2.78	-2.15	-1.86	-4.61	2.76	0.54	57	0.97	0.041
15	0.80	3.01	-3.11	-2.82	-5.86	2.82	0.51	24	1.48	0.098
16	0.88	3.09	-2.79	-2.50	-5.33	2.69	0.41	66	1.32	0.134
17	1.22	3.83	-1.23	-0.95	-3.72		0.42	76	0.92	0.017

groundwater, a parameter called seawater mixing index (SWMI) is proposed based on the concentrations of four major ions (Na^+, Cl^-, Mg^{2+} and SO_4^{2-}) as follows:

$$SWMI = a x\frac{C(Na)}{T(Na)} + b x\frac{C(Mg)}{T(Mg)} + c x\frac{C(SO4)}{T(SO4)} + d x\frac{C(Cl)}{T(Cl)} \quad (3)$$

Park et al. (2005) estimated the constant factors a, b, c and d according to the relative proportions of Na^+, Mg^{2+}, Cl^- and SO_4^{2-} in seawater, respectively; T_i represents the calculated regional threshold values of selected ions, which can be estimated from the cumulative probability curves for each ion in a specific site; C_i is the measured ion concentration in mg/L. It was found according to SWMI calculations that, groundwater samples collected in 2009 are classified into three groups (Figure 7a-e). Group I (SWMI<0.5) have a moderately saline groundwater (TDS values range from 1175 to 3663 mg/L). Group II (0.64<SWMI<1) has highly saline groundwater (TDS values range from 4111 to 6728 mg/L), while Group III (SWMI>1) was affected by mixing with seawater (TDS values range from 8001 to 8254 mg/L). Groundwater samples collected in 2015 based on SWMI calculations are classified into three groups (Figure 8a-e). Group I (SWMI<0.5) with TDS values range from 722.8 to 3068 mg/L at sites 1, 2, 3, 4, 5, 14 and 15 affected by rainfall and Group II with TDS ranges from 4993 to 7408 mg/L at sites 8, 9, 10 and 12 which may be affected by overpumping and mineral dissolution and finally, Group III with TDS values which ranges from 8761.8 to 10048 mg/L at sites 6, 7, 13 and 17 and may be affected by mixing with seawater. As ionic ratios are commonly used to evaluate the salinization sources and origin of groundwater in coastal aquifers (Barbecot et al., 2000), Na/Cl ratio can discriminate brackish and saline water, where the values of this ratio are higher than unity in fresh and meteoric water while it is less than unity in seawater or saline water (Starinky et al., 1983). In this study, most groundwater samples (Table 3) have Na/Cl ratio less than unity with an increase in Cl concentration values. Chloride Cl^- and Bromide Br^- ions are considered as conservative indicators of salinity origin. Seawater has

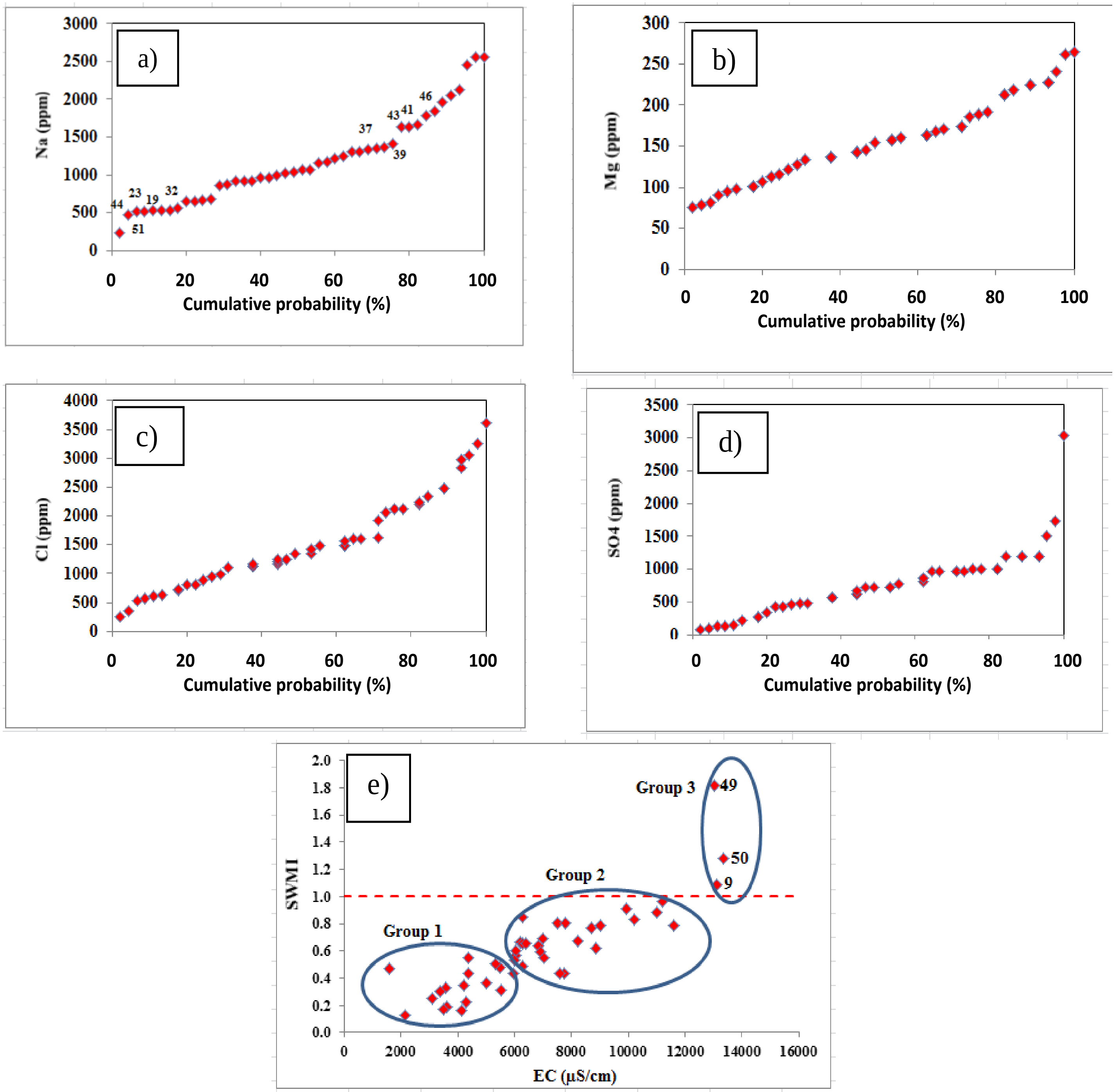

Figure 7. Cumulative probability curves for the distribution of a) Na^+, b) Mg^{2+}, c) Cl^- and d) SO_4^{2-} in groundwater of Pleistocene aquifer (2009). e) Cross-plot of SWMI vs. EC (μScm^{-1}) of the studied groundwater samples.

a Br/Cl ratio of 0.005 in Mediterranean countries (Jones et al., 1999; Vengosh et al., 1999). In this study area, the Br/Cl ratio ranges from 0.002 to 0.134 with an average of 0.03. This value is higher than 0.005 indicating that groundwater is affected by two sources of intruded seawater and rainfall through the recharge areas.

Seawater fraction

In fact, the fraction of seawater (f_{sea}) in a water sample can be approximated from the concentrations of Cl-(m_{Cl}) in meq/l as expressed in Equation 4 (Appelo and Psotma, 2005):

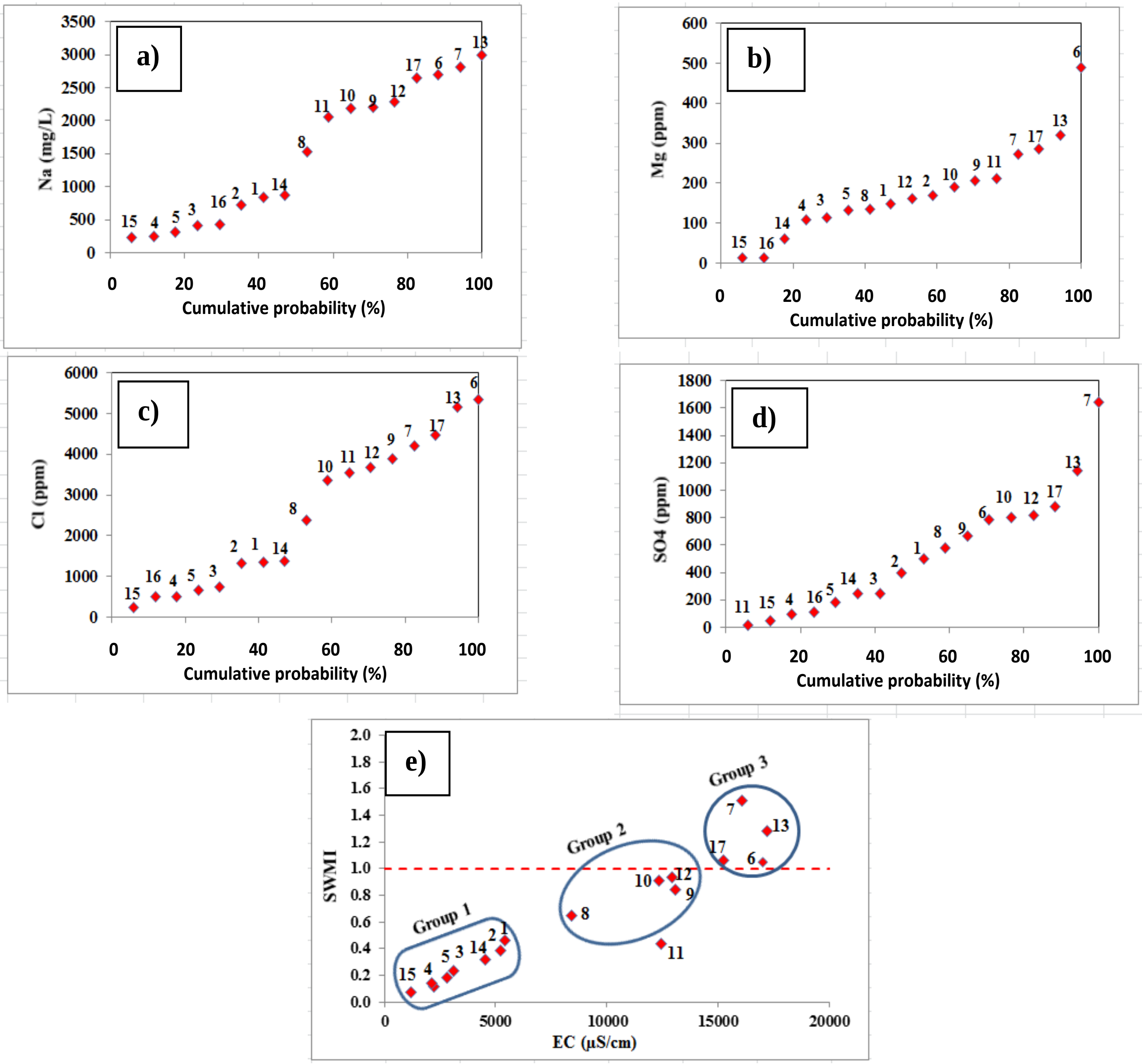

Figure 8. Cumulative probability curves for the distribution of a) Na^+, b) Mg^{2+}, c) Cl^- and d) SO_4^{2-} in groundwater of Pleistocene aquifer (2015). e) Cross-plot of SWMI vs. EC (μScm^{-1}) of the studied groundwater samples.

$$f_{sea} = mCl_{(sample)} - mCl_{(freshwater)} / mCl_{(seawater)} - mCl_{(freshwater)} \quad (4)$$

Similarly, the increase in total dissolved solids or electrical conductivity (EC) is a common simple indicator to identify an increase in salinity (Singhal and Gupta, 2010; Rhoades et al., 1992).

Calculation of seawater fraction for groundwater samples in 2009 (Table 4) reveals that about 38% of samples have *fsea* range values between 5 to 10 and about 11% have *fsea* >10. In groundwater samples collected in 2015, about 12% have 5 < *fsea>10* while, 47% of groundwater samples have *fsea>10* indicating more salinization in 2015 than 2009.

Model output

The model output gives the contours for equipotential,

Table 4. Seawater fraction calculations for samples in 2009 and 2015.

Final No.	Cl (ppm) (2009)	f_{sea} (%)	Final No.	Cl (ppm) (2009)	f_{sea} (%)	Final No.	Cl (ppm) (2015)	f_{sea} (%)
7	957.40	3.08	**30**	1347.5	4.81	**1**	1346.32	4.880
8	992.90	3.24	**31**	1134.8	3.87	**2**	1330.30	4.809
9	3617.00	14.87	**32**	815.6	2.45	**3**	728.55	2.145
10	1914.90	7.32	**33**	1418.4	5.12	**4**	500.00	1.133
11	2482.30	9.84	**34**	3262.4	13.29	**5**	664.90	1.863
12	1489.40	5.44	**35**	1205.7	4.18	**6**	5349.93	22.609
13	2482.30	9.84	**36**	1347.5	4.81	**7**	4216.84	17.592
14	2234.00	8.74	**37**	2198.6	8.58	**8**	2392.63	9.514
15	1241.10	4.34	**38**	709.2	1.98	**9**	3890.01	16.144
16	638.30	1.66	**39**	2127.2	8.26	**10**	3360.00	13.797
17	719.90	2.03	**40**	1099.3	3.71	**11**	3542.71	14.606
18	1489.4	5.44	**41**	1560.3	5.75	**12**	3680.31	15.216
19	815.6	2.45	**42**	2836.9	11.41	**13**	5167.1	21.800
20	1170.2	4.02	**43**	2127.7	8.27	**14**	1382.78	5.042
21	1489.4	5.44	**44**	602.8	1.51	**15**	244.2	0.000
22	1631.2	6.07	**45**	354.6	0.41	**16**	491.94	1.097
23	567.4	1.35	**46**	2340.4	9.21	**17**	4461	18.673
24	1595.7	5.91	**47**	886.5	2.76			
25	1170.2	4.02	**48**	531.9	1.19			
26	2978.7	12.04	**49**	2056.7	7.95			
27	1595.7	5.91	**50**	3049.6	12.35			
28	1134.8	3.87	**51**	262.4	0.00			
29	1241.1	4.34						

head difference, head flux, drawdown, water table and TDS concentration. The velocity vectors visualize the speed and direction of water particles as it moves through flow field. The output screen also gives the concentration versus time (in days). The visual MODFLOW output screen gives residual histograms as well as normalized RMS vs. time graph. The simulated results for four scenarios are plotted for TDS versus Year for 45 monitoring wells located on Ras El-Hekma area.

The simulated results of the four proposed scenarios are tabulated in Tables 5 and 6 for the observed and calculated heads (m) and TDS (mg/L), respectively. From all these scenarios, several observations are noticed as follows:

1) Increment in heads (m) with simultaneous decrease in TDS values in (mg/L) may be due to refreshment from the high tableland areas.
2) Decrease in heads (m) with increase in salinization of some wells may be due to overpumping that led to dissolution of some marine deposits and thus increment in TDS (mg/L) values.
3) The third observation is increment in both heads (m) and TDS (mg/L) simultaneously and this situation encountered seawater intrusion at some locations.
4) The distance between the wells and the coast and the recorded observed heads (m) greatly affected the previous observation noticed.
5) The more affected wells by intruded seawater are those that have a distance <1.5 km from the coast, and wells at a distance >1.5 km are affected by dissolution due to overpumping or refreshment from the higher table lands areas.

Scenario 1: The base case scenario of pumping 40 m^3/day shows a fluctuation in heads (m) as in Tables 5 and 6. Where the drawdown in heads range between 0.1 to 13.36 m and 0.05 to 13.32 m, with simultaneous decrease in TDS (mg/L), with values ranging between 84.9 and 3306 mg/L and 117 to 3466 mg/L at the end of 10 and 20 years of simulation, respectively. This may be due to refreshment from the higher tableland areas.

Scenario 2: With increasing stresses on the system by increasing the pumping rate to 80 m^3/day, the response of the system is illustrated in Tables 5, 6 and Figure 9. Increase in overpumping affected the wells more badly, where more drawdown occurred reaching 13.6 m in some wells with simultaneous increase in TDS values that reached 1083 mg/L and may be affected by dissolution of some marine deposits.

Scenario 3: Taking into consideration the presence of both wells (2009 and 2015) at the same time with

Table 5. Observed and calculated heads in (m) for the proposed four scenarios.

Well No.	Observed Head (m)	Scenario1		Scenario2		Scenario3		Scenario4	
		10 years	20 years	10 years	20 years	10 years	20 years	10 years	20 years
7	0.3	1.76	1.79	1.7	1.7	1.76	1.78	2.51	2.55
8	3	1.72	1.76	1.47	1.47	1.72	1.75	2.62	2.66
9	4	1.74	1.78	1.48	1.48	1.74	1.77	2.65	2.69
10	6	1.72	1.76	1.47	1.47	1.73	1.75	2.64	2.69
11	5.5	1.74	1.78	1.48	1.49	1.75	1.77	2.66	2.71
12	-0.8	1.36	1.39	1.2	1.2	1.37	1.39	1.76	2.27
13	-4	1.39	1.42	1.23	1.23	1.4	1.42	2.27	2.31
14	-6.7	1.57	1.6	1.37	1.37	1.57	1.59	2.46	2.51
15	-3.7	1.64	1.68	1.4	1.4	1.65	1.67	2.1	2.61
16	0	0.87	0.88	0.96	0.99	1.2	1.21	1.37	1.38
17	1.87	1.92	1.96	1.68	1.69	1.93	1.95	2.23	2.27
18	0.87	1.98	2.02	1.72	1.72	1.99	2.01	2.29	2.79
19	-1.23	2.07	2.11	1.77	1.77	2.07	2.1	2.39	2.43
20	0	1.97	2.01	1.87	1.87	2.2	2.23	2.51	2.56
21	0	2.01	2.06	1.89	1.9	2.25	2.27	2.57	2.62
22	0	2.24	2.29	1.9	1.91	2.26	2.28	3.02	3.08
23	1	1.95	1.99	1.68	1.69	1.96	1.98	2.28	2.32
24	-1	2.05	2.86	1.79	1.8	2.06	2.08	2.37	2.42
25	9	2.34	2.39	2.1	2.11	2.35	2.38	3.12	3.19
26	0	1.81	1.85	1.81	1.81	2.02	2.05	2.88	2.94
27	-1	1.76	2.01	1.76	1.77	1.98	2	2.84	2.89
28	4	1.7	1.52	1.6	1.61	1.71	1.73	2.51	2.55
29	1	1.61	1.87	1.61	1.61	1.84	1.86	2.27	2.31
30	1	1.81	1.85	1.58	1.59	1.82	1.84	2.71	2.76
31	2	1.74	1.78	1.53	1.53	1.75	1.77	2.19	2.23
32	-4	1.69	1.73	1.48	1.49	1.69	1.72	2.61	2.66
33	12	1.52	1.55	1.37	1.37	1.52	1.54	2.41	2.45
34	0	1.65	1.69	1.62	1.62	1.88	1.91	2.32	2.36
35	2	1.9	1.95	1.64	1.65	1.91	1.94	2.34	2.39
36	2.5	1.85	1.89	1.6	1.61	1.86	1.88	2.29	2.33
37	-5	1.78	1.82	1.54	1.55	1.78	1.81	2.69	2.73
38	1.5	2.13	2.18	1.87	1.88	2.14	2.17	3	3.06
39	-1	1.67	1.71	1.47	1.47	1.68	1.7	2.58	2.63
40	0	1.56	1.6	1.36	1.36	1.57	1.59	2.01	2.05
41	-3	1.69	1.73	1.46	1.46	1.7	1.72	2.62	2.66
42	2	1.67	1.71	1.42	1.42	1.67	1.7	2.61	2.65
43	15	1.64	1.68	1.4	1.41	1.65	1.67	2.58	2.62
44	14	1.63	1.67	1.39	1.39	1.64	1.66	2.56	2.61
45	0	1.24	1.27	1.26	1.26	1.25		2	2.02
46	-1	0.92	1.21	1.22	1.22	1.18	1.2	1.95	1.97
47	0	0.66	0.67	0.7	0.69	0.66		1.36	1.36
48	5	0.42	0.43	0.5	0.5	0.42	0.42	1.13	1.13
49	3	0.66	0.68	0.99	0.99	0.96	0.97	1.66	1.68
50	-1	0.7	1.01	1.01	1.01	0.99	1	1.7	1.72
51	0	2.02	2.06	1.78	1.79	2.03		2.8	2.38

pumping rate of 40 m^3/day, the results of this scenario are illustrated in Tables 5 and 6 and they show more decrease in heads due to densely crowded wells and low managed system.

Table 6. Observed and calculated TDS in (mg/L) for the proposed four scenarios.

Well No.	Observed TDS (mg/L)	Scenario1		Scenario2		Scenario3		Scenario4	
		10 years	20 years	10 years	20 years	10 years	20 years	10 years	20 years
7	3697	3586.7	3449.8	3730.2	3687.4	3586.7	3449.5	3755.4	3754.2
8	3842	4818	4557.4	4837.4	4730.6	4717.4	4557.5	4910.5	4844.6
9	8024	4717.5	4557.4	4837.4	4730.6	4717.4	4557.5	4910.5	4844.6
10	4828	4743.1	4514.9	4937.7	4833.9	4743	4515.4	4946.6	4843.8
11	6070	4572	4878.9	4986.6	4877.8	4792.5	4572.5	4961.6	4862.4
12	4537	4347.9	4420	4488.1	4405.5	4347.4	4228.8	4524.4	4489.5
13	5182	4575.6	4456.1	4726.9	4679.7	4575.2	4455	4752.5	4742.4
14	5352	4688.2	4552.6	4834.1	4765.2	4688	4552.3	4886.9	4864.4
15	3572	4818	4557.4	4837.4	4730.6	4717.4	4557.5	4910.5	4844.6
16	2117	2010.9	2056.1	2.084	2044.2	2010.7	2052.3	2091.3	2034.5
17	2427	2902.2	2821.4	3003.7	2982.3	2902.1	2821.1	3023	3026.5
18	4162	3063.5	3036.1	3051.6	3036.7	2949.4	2864.4	3058.8	3076
19	2000	3009.1	2967	3098	3125.8	3008.6	2967	3115.1	3143.8
20	3613	3150.7	3151.1	3244.9	3184.8	3150.5	3024.4	3232.2	3243.7
21	3429	3246.7	3100.1	3333	3254.5	3246.5	3101	3297.7	3302.4
22	4111	3330.3	3190	3333	3254.5	3246.5	3101	3297.7	3302.4
23	1961	2987.9	3031.3	3058	3140.3	2986.9	3030.3	3091	3174.6
24	4119	3010.8	2909.7	3009.5	2938	2932.7	2795.5	3020.6	2979.9
25	2830	2932.4	2879.1	3014.3	3008.5	2932.4	2878.5	3041.2	3062.8
26	6589	4489.3	4210.5	4638.4	4490.3	4490	4212.1	4630.7	4421.3
27	4630	4545.1	4213.1	4709.6	4485.3	4546	4215	4678	4477.6
28	3233	3258.3	3220.3	3353.6	3372.8	3257.8	3219.4	3383.6	3401.5
29	3516	4018.5	3898.7	4067.7	4023	3881.9	3701.3	4001.8	3943.7
30	3520	4018.5	3898.7	4067.7	4023.1	3881.9	3701.3	4001.8	3943.7
31	2413	3586.1	3593.8	3721.4	3661.7	3586.6	3420.6	3732.1	3717.4
32	1967	3586.1	3419.6	3721.4	3661.7	3586.6	3420.6	3732.1	3717.4
33	3663	3556.2	3413.2	3682.6	3633.2	3556.2	3413.3	3710.7	3704
34	6728	3553.1	3337.6	3559.5	3533.1	3425.9	3336.9	3624.7	3651.9
35	3821	3706.7	3685.7	3703	3681.6	3576.1	3453.8	3718.9	3704.5
36	4143	3752.6	3575.3	3896.8	3813.4	3752.7	3575.5	3892.5	3834.5
37	4420	3628.6	3641.3	3744.4	3660	3628.4	3497	3766.8	3730.8
38	2555	3498.2	3656.3	3645.5	3677.3	3497.9	3455	3660	3700.5
39	4380	4376	4200	4514.7	4470	4375.5	4199.8	4541.1	4502.5
40	3154	4491.9	4378.4	4614.6	4588.1	4491.2	4377.5	4666	4667.7
41	3119	4682.9	4509.8	4824	4740	4682.4	4509.7	4851.9	4795.7
42	6632	4682.9	4509.8	4824	4740	4682.4	4509.7	4851.9	4795.7
43	5199	4764.8	4642.9	4906.5	4846	4764.3	4642.6	4932.2	4898
44	1805	4731.9	4579.8	4887.2	4789.3	4731.6	4579.9	4927.2	4928.4
45	2194	4037.2	3694.5	4214.3	3991.8	4038.7	3696.6	4278.8	4123.3
46	5946	4561.4	4189.3	4731.3	4496.9	4562.8	4192.9	4774.2	4504.6
47	3877	3603.6	3419.1	3769.1	3615.1	3603.6	3418.9	3852.7	3719.2
48	2692	2602.1	2484.1	2716.4	3094.1	2602.1	2484.1	2763.7	2749.3
49	8254	7710.9	8858.8	7974.4	9070.6	7683	8860.5	7857.4	7496.9
50	8001	7710.9	8858.8	7974.4	9070.6	7683	8860.5	7857.4	7496.9
51	1175	2932.6	2909.7	3009.5	2938	2932.7	2795.5	3020.6	2979.9

Scenario 4: Based on the expected sea level rise of 0.5 m, the result of this scenario is illustrated in Tables 5, 6 and Figure 10. As expected there was an increase in heads that range between 0.19 to 9.16 m and 0.23 to

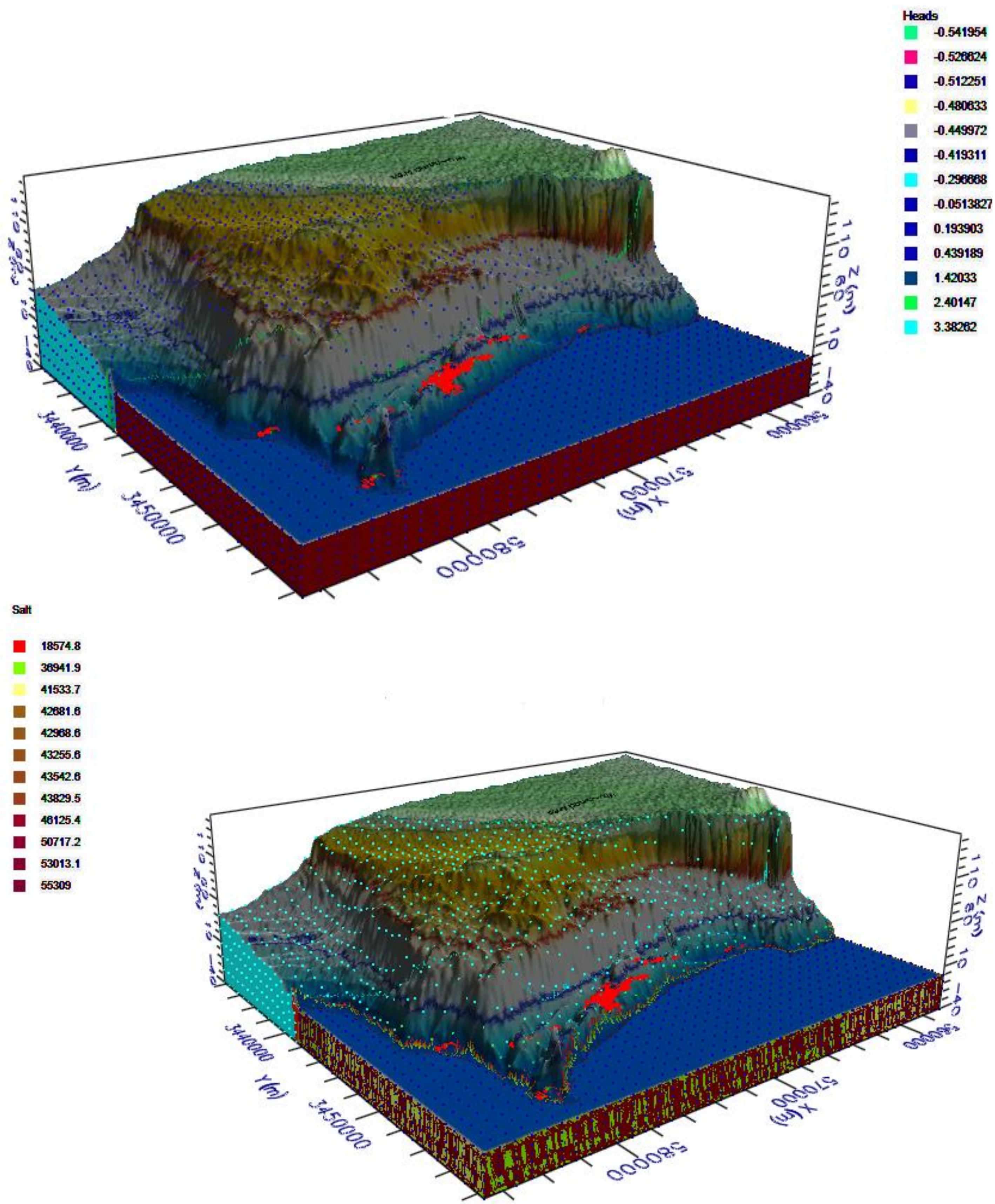

Figure 9. Estimated 3D –distribution of a) water table (m) and b) TDS (mg/L) of scenario2 at the end of 20 years.

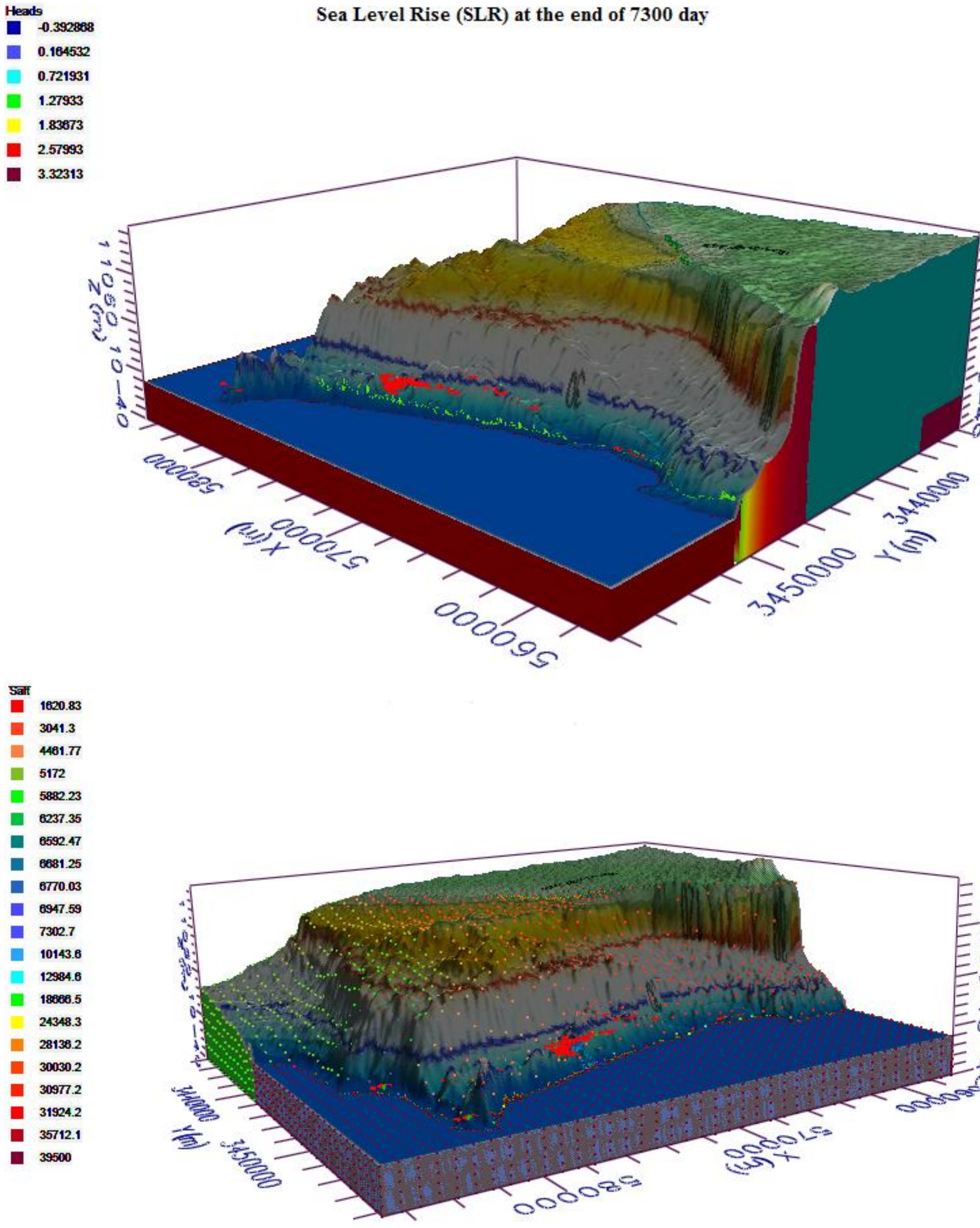

Figure 10. Estimated 3D –distribution of a) water table (m) and b) TDS (mg/L) of scenario4 at the end of 20 years.

9.21 m at the end of 10 and 20 years of simulation with simultaneous increase in salinity rate of some wells that reached to 2000 mg/L as in Well No. 51 which may be due to intruded seawater at this location. Seawater interface layer shifted more inland about 0.5 to 2 km and ensured that intrusion of seawater, especially at northeastern location occurred.

Conclusion

The effect of seawater intrusion on fresh groundwater in coastal areas requires more investigations, especially when the withdrawal for water supply in the coastal areas increases. An attempt has been made in the present study to demarcate the salinization influences by hydrochemistry and modeling approach. The groundwater flow is directed toward Mediterranean Sea with a steep groundwater gradient. Water chemistry data signifies high EC and TDS values along the coastal regions suggesting saline water traces. Sodium and chloride were found to be dominating along the coastal regions of Ras El-Hekma area. The SEAWAT model calibrated and validated for the present study with applying different scenarios suggests that drawdown in groundwater level of some observed wells range from 0.56 to 10.07 m especially in observed wells located at about 1 to 1.4 km with replenishment from rainfall and surface runoff causing a water table rise of about 11.5 to 14.8 m in some observed wells that were located inland. For sea level rise, the seawater/freshwater interface will migrate more inland (0.5 to 2 km) than its current position. The hydrochemistry and model results recommend a decrease in pumping to the drilled wells in order to avoid further seawater intrusion along the coast and upwelling of deep saline groundwater.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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Evaluating water quality of Awash River using water quality index

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Awash river has been impaired by various types of pollution owing to waste released from different socio-economic activities in its basin. This research was aimed at evaluating its quality status with respect to drinking and irrigation water uses. Based on accessibility and land use severity, 17 sample sites were chosen along the river and sampling was done twice in each of the dry and wet seasons. Thereafter, both onsite and offsite water quality analyses were undertaken following standard procedures. Canadian Council of Ministers of Environment Water Quality Index (CCME WQI) was applied to compute the water quality indices. Accordingly, the drinking and irrigation water quality indices of the upper basin were found to be 34.79 and 46.39 respectively, which were in the poor and marginal categories of the Canadian water quality ranking. Meanwhile, the respective indices for the middle/lower basin, which were 32.25 and 62.78, lie in the poor and fair ranges of the ranking. Although the difference in the dataset used for the two cases and natural purification in the course of the river might contribute to the difference in WQI, it is generally conceivable that the water quality of the river is below the good rank. Establishment of wastewater treatment plants and storm water quality management at hotspot areas are recommended to improve the quality.

Key words: Awash river basin, Canadian Council of Ministers of Environment Water Quality Index (CCME WQI), drinking and irrigation water uses, Ethiopia, water pollution.

INTRODUCTION

Water quality problems are caused by natural and anthropogenic factors. The most important of the natural influences are geological, hydrological and climatic since these affect both the quantity and the quality of water available (Bartram and Ballance, 1996; Pejman et al., 2009; Bu et al., 2010). Their impact is magnified especially when water scarcity is observed and maximum use is expected to be made of the limited resource, which is exemplified by a frequently high salinity problem in arid and coastal areas (Bartram and Ballance, 1996), like that of Awash River Basin. The impact of human activities on water quality is versatile in the degree to which it disrupts

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the ecosystem and restricts its use. These activities have usually affected water quality through either point sources such as wastewater treatment facilities or non-point sources such as runoff from urban areas and farm lands (Bartram and Ballance, 1996).

The impact of water pollution is seen on human-being who have been directly or indirectly consuming the contaminated water like Awash River. Irrigation water quality depends mainly on permeability (Hussain et al., 2010; Bauder et al., 2011). Permeability affects infiltration rate of water into the soil and is determined by the relative concentrations of salinity (Electrical conductivity (EC)) and sodicity. Sodicity is a measure of the relative amount of Na to Ca and Mg which gives an indication of the level at which the exchangeable Na percentage of the soil will stabilize after prolonged irrigation (Holmes, 1996). Alkalinity, on the other hand, is a measure of water's capacity of neutralizing acid and is expressed by Residual Sodium Carbonate (RSC). Alkaline water causes iron deficiency by increasing the pH of soil to unacceptable level. Drinking water quality determinants are broadly classified into physical (such as taste, odor and color), microbial (viruses, protozoa, helminths, total coliform (TC) bacteria, *Escherichia coli* (ECo)) and chemical (BOD, COD, F^-, NO_3^-, Fe, Cu, Ca, PO_4^{2-}, Cr, and others) (Sorlini et al., 2013; WHO, 2011; Amenu, 2014).

Most people living in the rural parts of Ethiopia rely on water from unprotected sources such as rivers which are unsafe to drink and Awash river is no exception. As a result, more than half a million people die each year from water-related diseases, mostly infants and children (Halcrow, 2008). Natural water constituents such as fluorides and inputs of socio-economic activities such as pesticides, herbicides, heavy metals and pollution from industrial effluents and domestic wastes are also threats to the water resources (Halcrow, 2009).

Although water quality problem is apparent to most Ethiopian Rivers, Awash leads in the extent of impairment due to its service as a sink for the basin-wide urban, industrial and rural wastes (Belay, 2009; Alemayehu, 2001). In assessing the pollution level of the river, it is concluded that attention needs to be paid in irrigating with the river for fear of public health effect. This is confirmed by examining the bacteriological contaminant level of leafy vegetables grown around Adama town with Awash River along with identifying heavy pollution loads on the vegetables (Benti et al., 2014).

Additionally, heavy helminths, bacteriological pollution load, toxicity level and the slight to moderate salinity effects of the Little Akaki River, which is a tributary of Awash river, made it unfit for any intended use (Taddese et al., 2004). According to this study, nitrate level of the river water is above 10 mg/L and mean concentration of heavy metals including Mn, Cr, Ni, Pb, As and Zn are reported to be more in soils and vegetables irrigated by Awash River than their allowable limits. The incidences of dental and skeletal fluorosis from the high concentration of fluoride are found to exist in its valleys (Reimann et al., 2003).

Evaluation and communication of quality status of the River to water quality professionals and the policy makers is needed to safeguard the public health and the environment. Having such a study, which is non-existent for Awash River, ultimately contributes towards quantification and understanding of the status of the River water and ultimately enables decision makers to have ample information so as to suggest if the water is suitable for intended uses. This study aims at evaluating the overall status of Awash River water quality in the upper and downstream sub-basins based on Water Quality Index (WQI) calculated for selected parameters relative to the irrigation and drinking water uses.

There are various ways of determining WQI although most indices measure the same attributes of deviation from the objectives (Wills and Irvine, 1996). Some of them being used worldwide are: National Sanitation Foundation (NSF) WQI (Kaurish and Younos, 2007), Canadian Council of Ministers of the Environment (CCME) WQI (Worako, 2015), Overall Water Quality Index (OWQI) and Oregon WQI (Tyagi et al., 2013; CCME, 2001b; Poonam et al., 2015). Though NSF WQI (Wills and Irvine, 1996; Tyagi et al., 2013; Poonam et al., 2015), CCME WQI and OWQI (Singh et al., 2015) are indices frequently used for water quality assessment, CCME WQI is the most efficient and flexible with respect to the type and number of water quality variables to be tested, the period of application, and the type of water body. OWQI is efficient but parameters should be carefully selected depending on the source and time. The main drawback of NSF WQI is the eclipsing effect, due to which one or more parameters that have values above permissible limit are masked if the rest of the parameters are within the limits (Poonam et al., 2015). Oregon WQI aids in the assessment only of water quality for general recreational uses and is designed only for Oregon streams (Cude, 2001; Tyagi et al., 2013).

MATERIALS AND METHODS

Description of the study area

Awash River Basin, with a total catchment area of 113,304 km^2, is located between latitudes 7°53′N and 12°N and longitudes 37°57′E and 43°25′E in Ethiopia (Figure 1). The Awash River originates from the high plateau Ginchi of 3000 m.a.s.l, 80 km west of Addis Ababa and terminates, after travelling about 1200 km, at Lake Abe of 250 m.a.s.l., at the border of Ethiopia and Djibouti (Tessema, 2011; Berhe et al., 2013; Degefu et al., 2013). With extreme ranges of topography, vegetation, rainfall, temperature and soils, the basin extends from semi-desert lowlands to cold high mountain zones. Land use in the catchment is mainly agricultural and shrub

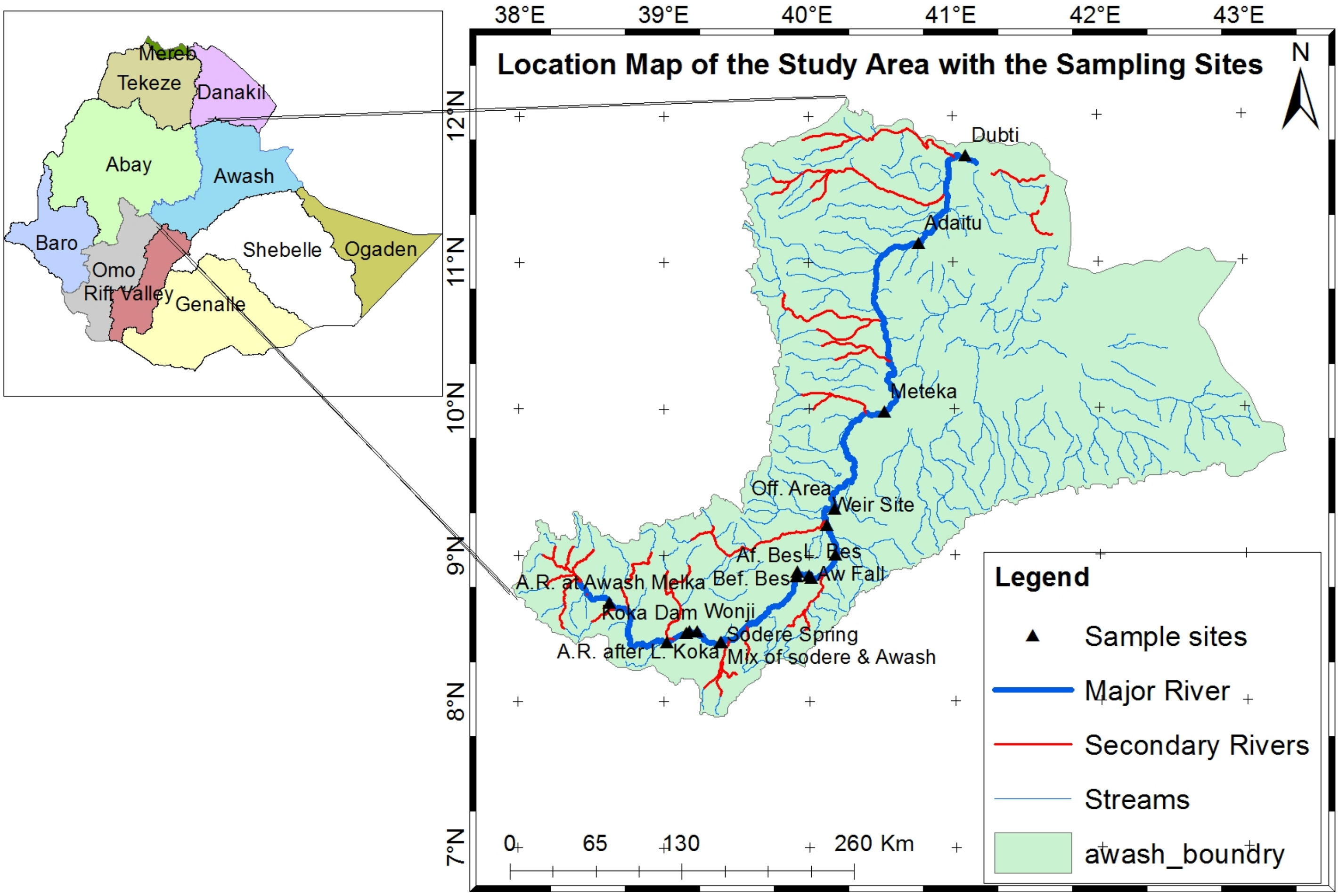

Figure 1. Location map of the study area.

lands used for rain-fed crops, irrigation and grazing. Various crops are cultivated ranging from cereals, vegetables, flowers, cotton to perennial fruit trees and sugarcane (Tessema, 2011; Gedion, 2009). Although the relative surface water resource of the basin is about 4.65 billion m^3, it is the most developed and utilized since 77.4% of the irrigable land in the basin has been cultivated. About 60% of the large-scale irrigated agriculture and more than 65% of the national industries are located in the basin. The rainfall pattern is bimodal with the first being the short season of March to May while the second and the main one is from July to September (Tessema, 2011). Annual average temperature ranges from 16.7 to 29°C and the annual mean relative humidity in the basin varies from 60.2 to 49.7%. While the mean annual wind speed is 0.9 m/s, the mean annual rainfall varies from about 1600 mm at Ankober to 160 mm at Asayita (Berhe et al., 2013).

Data collection, quality control and validation

The sampling process has been designed adequately to decide the exact number, sites and time at which the samples were taken. This was done to attain representativeness of the samples. Multi-parameter (HANNA HI 991300) onsite water quality testing meter, GPS, digital camera, plastic sample containers, plaster, long rope, sample fetching plastic vessel, and ice box were some of the materials taken to the field. Sampling was done in four phases, twice in each of the dry (February 2016 and January 2017) and wet seasons (May 2015 and June 2016). In all the phases, grab samples of water have been taken from 13 sites: three of them in the lower and ten in the middle basin. These were chosen based on accessibility and types of land use (agricultural, urban and industrial) found in the catchment. Samples were taken in triplicate from midpoint (vertically and laterally) of the river by using plastic vessel tied with long rope. Thereafter, samples were collected in polyethylene plastic bottles rinsed with distilled water both for onsite testing and laboratory analyses as shown in Figure 2. All samples for offsite analyses were kept at 4°C in a refrigerator until further use.

When samples were collected, transported, and preserved from the field, quality control (QC) procedures were followed to produce quality data with respect to precision and accuracy. Therefore, field QC samples such as equipment blank and trip blanks were collected to test the presence or absence of errors occurring in the field according to Zhang (2007) procedures. The QC samples that were used for assuring quality during laboratory analysis were duplicates (to know the analytical precision) and blanks (to identify any potential contamination).

EC and total dissolved solids (TDS) were analyzed on site using

Figure 2. Water sample taking from (a) Awash at Adaitu, (b) from Lake Beseka and (c) Onsite Water Quality testing for pH, EC, TDS and T° from Awash at Ziway Road.

the HANNA meter (Figure 2) since they would otherwise have changed during storage and transport while the offsite analyses of water quality parameters of interest were conducted using standard methods for examination of water and wastewater (APHA, 1998). Since the River is being used mainly for irrigation and domestic uses in the basin, parameters such as Turbidity (Turb.), Temperature (Temp.), TDS, Total Solids (TS), Total Hardness (TH), Total Nitrogen (TN), ECo, TC, Alkalinity (Alk.), NH_3, EC, DO, BOD, COD, Na^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, NO_2^-, NO_3^-, CO_3^{2-}, HCO_3^-, and PO_4^{2-} were considered for analysis. The parameters analyzed and methods used for their analyses in this study are illustrated in Table 1.

Water quality analysis for the upper basin (UB) was done by Vitens Evides International Granting Organization of Netherlands together with Oromia Regional Water Office of Ethiopia in seven rounds at about 2.5 months' interval between 26/06/2014 and 30/11/2015. They considered ten sample sites of which only four sites of interest and only those parameters having full data in all the sites were selected. Since a lot of samples were taken from each site, a number of parameters were considered and the choice of sampling sites was strategic enough; this dataset was preferably used for computation of WQI in the sub-basin. There were missing and censored values in the UB water quality dataset marked as 'x', '?', 'empty', 'nil', '<R' and 'TNTC' and were validated by ignoring from calculation of the mean and appropriate substitution. Dixon test, which is based on the ratio of the distance between the potential outlier value and its nearest value to the range of the whole data set (Rangeti et al., 2015), was used to detect the outliers observed in the dataset. Accordingly, out of the selected 28 variables, only turbidity showed outlier at the 17th site.

Since only concentrations of Ca^{2+} and Mg^{2+} were given for the UB, TH indicated in Table 2 was computed as the concentrations of Ca^{2+} and Mg^{2+} expressed as equivalent of $CaCO_3$ (Lenntech, 2014) by using equation (1):

$$[TH] = 2.5 * [Ca^{2+}] + 4.1 * [Mg^{2+}] \quad (1)$$

Soil sodicity, which is expressed by a ratio called Sodium Adsorption Ratio (SAR) and depicted in Table 3, could be calculated from the major cations by using equation (2) (Lesch and Suarez, 2009; Seid and Genanew, 2013; Hussain et al., 2010).

$$SAR\ (meq/L) = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (2)$$

which represents a suitable sodium hazard index for typical irrigation water. However, the guideline of SAR for irrigation, according to Ayers and Westcot (1985), is dependent on the concentration of salinity, which is severely restricted if EC and TDS exceed 3 dS/m and 2000 mg/L respectively since it affects crop water availability. The other chemical index of irrigation water quality importance such as RSC was also calculated from the measured water quality parameters by using equation (3) (Dinka, 2016). The cations and anions, which were expressed in mg/L, were all changed into mili-equivalents per liter (meq/L).

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (3)$$

According to Dinka (2016), RSC >7.5 is unfit, 5.0 to 7.5 is poor, 2.5 to 5.0 is marginal, 0 to 2.5 is fit, and < 0 is very good for irrigation.

Water quality indices (WQI)

WQI practically describes the problem of pollution in a water body and is used to represent measurements of bulk of water quality data in a single number, combines various measurements of different units in a single metric, and facilitates communication of results (CCME, 2001b). It is a very reliable and efficient way for evaluating water quality relative to its desirable state. It also modifies policies thereby developing tools to decide suitability of water sources for their intended use and makes suggestions for a more efficient water resources and River basin management by formulating pollution control strategies (Gibrilla et al., 2011; Barceló-Quintal et al., 2013; Tyagi et al., 2013; Sargaonkar and Deshpande, 2003; CCME, 2001a). Awash River water quality status was evaluated using CCME WQI due to its efficiency and flexibility.

Table 1. Parameters analyzed and the corresponding methods used for their analyses in this study

Par.	Analyses methods used	Par.	Analyses methods used	Par.	Analyses methods used
Turb.	Palintest	TN	Persulfate digestion	Cl^-	Titration & Argentometric
pH	Cyberscan PC 300 pH/EC/TDS/Temp.	Na	Flame photometer	Ca	Titration
Temp.	Cyberscan PC 300 pH/EC/TDS/Temp.	K^+	Tetraphenylborate	Mg	Periodate oxidation
TDS	Gravimetric & Cyberscan PC 300 pH/EC/TDS/Temp.	NO_3^-	Cadmium Reduction	TH	Titration for MLB and Calculated for UB (eqn.1)
TS	Gravimetric	NO_2^-	Diazotization	CO_3^{2-}	Titration
EC	Calorimetric & Cyberscan PC 300 pH/EC/TDS/Temp.	SO_4^{2-}	SulfaVer 4	HCO_3^-	Titration
DO	Titration	Fe	FerroVer M	PO_4^{2-}	Ascorbic acid
BOD	Modified Winkler-Azide dilution	Mn	Periodate Oxidation	Alk.	Titration
COD	Reactor Digestion	F^-	SPADNS	ECo	Membrane Filter
Pb	LeadTrak™ Fast Column Extraction	NH_3	Nessler & Aluminon	TC	Membrane Filter
Zn	Zincon	Cu	Porphyrin	SAR, RSC	calculated for MLB (eqns. 2 & 3)
Cr	Alkaline hypobromite Oxidation	Cl_2	DPD		

Table 2. Mean values of water quality parameters in the four sites of UB[1]

Par.	S14	S15	S16	S17	G1	G2	Par.	S14	S15	S16	S17	G1	G2
Turb.	149	185	556	2675	4	2	SO_4^{2-}	25.1	23.7	24.86	21.3	250	20
pH	7.25	7.46	7.12	7.41	6.5-8.5	8.5	Fe	1.25	1.15	2.55	2.37	0.3	5
Temp.	22.8	23.3	22.9	20.4	15-30	NS	Mn	0.41	0.75	0.24	0.17	0.1	0.2
TDS	169	163	219	167.9	1000	2000	F^-	0.71	0.8	0.59	0.41	1.5	1
EC	338	323	437	335.6	1500	3000	NH_3	1.8	1.56	2.26	4.62	1.5	5
DO	4.21	4.92	3.13	3.67	>5	NS	Cu	7.2	8.8	15.2	6	1	0.2
BOD	8.23	7.59	14.7	14.98	<5	<10	Cl_2	0.11	0.1	0.12	0.5	5	10
COD	36.4	54.8	112	35.2	<30	<60	Cl^-	20.3	18.6	14.3	25	250	355
Pb	3.5	1.25	4	3.33	0.01	5	Ca	98.9	104	163	153	200	400
Zn	0.05	0.05	0.03	0.07	4	2	Mg	78.6	59.1	69.4	50.9	150	61
Cr	0.02	0.02	0.03	0.03	0.05	0.1	TH	569	502	691.8	590	500	NS
TN	2.36	3.44	11.64	6.2	55	5	Alk.	143	138	180	184	400	750
K^+	6.68	5.57	8.17	4.02	20	2	ECo	61.6	86.6	TNTC	180	0	<10
NO_3^-	11.5	7.5	19.48	3.39	50	30	TC	102	96	TNTC	TNTC	0	<50
NO_2^-	0.07	0.04	1.07	0.06	3	NS							

The sites: S14= Awash river after Lake Koka, S15= Awash river at Koka Dam, S16= Awash river before Lake Koka, S17= Awash river at Awash Melka Kuntire, G1= WHO and US EPA Drinking Water Quality Guidelines (DWQG), G2= FAO Irrigation Water Quality Guidelines (IWQG), TNTC= Too Numerous To Count, and NS= No Standard.

[1] All parameters, except Turbidity, EC, Temperature, pH, ECo and TC, were expressed in mg/L. Turbidity, EC and Temperature were measured respectively by NTU, µS/cm, and °C; ECo and TC both in counts/100ml; while pH is unit less.

Table 3. Mean values of water quality parameters in the two dry and two wet months of the middle and lower basins (MLB) of the Awash river

Par	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	G1	G2
TDS	327.7	505.4	569.4	580.7	559.2	610.6	804.7	933.9	2275	240.7	520.0	1445	229.0	1000	2000
TS	722.9	1855	1793	2577	6233	1689	859.8	1457	3621	812.4	704.0	1514	456.0	**NS**	**NS**
NH_3	0.9	1.7	1.4	1.3	2.5	1.7	3.7	1.4	1.3	1.0	0.9	0.7	1.0	1.5	5.0
TH	663.0	959.0	737.0	713.0	610.5	435.0	100.0	520.5	437.0	1071	664.0	635.0	686.5	500.0	**NS**
Na	104.4	153.9	210.6	182.3	180.4	251.2	290.3	423.2	1279	55.6	188.0	557.5	44.6	200.0	220.8
Ca	31.6	32.3	31.4	29.4	27.6	28.0	27.1	27.2	8.6	34.1	30.4	20.7	30.5	200.0	400.0
Mg	7.3	9.3	10.5	8.6	7.3	6.3	6.8	8.7	3.2	6.7	3.4	9.2	7.0	150.0	61.0
F^-	0.7	1.3	2.2	2.3	2.7	2.3	2.7	2.6	2.2	1.3	2.4	5.3	1.6	1.5	1.0
Cl^-	57.9	107.8	92.4	102.8	108.1	153.6	211.1	171.3	211.0	55.0	80.3	181.1	47.3	250.0	355.0
NO_2^-	0.0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.1	3.0	**NS**
NO_3^-	0.2	0.8	0.7	1.0	1.1	2.0	3.2	1.3	2.8	0.5	2.9	1.3	4.3	50.0	30.0
Alk.	655.0	692.5	916.5	903.0	1217	827.0	506.0	827.5	1292	647.0	805.0	1188	572.0	500.0	750
EC	593.7	944.4	1040	1097	980.8	1115	1370	1437	3823	435.8	915.0	2201	405.5	1500	3000
CO_3^{2-}	10.6	10.0	30.9	37.0	102.7	106.3	101.9	85.9	493.0	**ND**	**ND**	288.0	6.8	250.0	180
HCO_3^-	252.2	370.1	434.6	401.2	375.4	457.5	436.8	470.3	982.0	310.2	896.7	1111	334.6	580.0	518.5
PO_4^{2-}	2.3	22.5	9.7	8.3	0.8	4.5	0.4	6.7	3.4	7.6	4.5	0.8	5.6	0.0	2.0
SAR	4.4	6.3	8.3	7.5	7.9	11.7	12.9	17.6	98.3	2.3	8.6	25.7	1.9	**NS**	15.0
RSC	2.3	4.02	5.73	5.64	7.6	9.12	8.65	8.5	31.8	**ND**	**ND**	26	3.6	**NS**	7.5

Where the sites, S1= Dupti, S2= Adaitu, S3= Meteka, S4= Office area, S5= Weir site, S6= Awash water supply, S7= Awash fall, S8= After Beseka, S9= Lake Beseka intake, S10= Before Beseka, S11= Mix of Sodere & Awash, S12= Sodere spring, and S13= Wonji, G1= WHO and US EPA DWQG, G2= FAO IWQG, ND= No Data.

Conceptual framework of CCME WQI

CCME WQI is based on a combination of three factors: scope, frequency and amplitude (Tyagi et al., 2013; CCME, 2001a, b) and is given by:

$$\text{CCME WQI} = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \quad (4)$$

Where, F_1 (Scope) = Number of variables whose objectives are not met.

= [No. of failed variables/Total no. of variables] × 100 (5)

F_2 (Frequency) = Number of times by which the objectives are not met.

= [No. of failed tests/Total no of tests] × 100 (6)

F_3 (Amplitude) = Amount by which the objectives are not met. This can be determined by three steps as follows:

(a) Excursion, e = [Failed test value i /Objective] - 1 (7)
(b) Normalized Sum of Excursions (*nse*):

$$(nse) = \sum_{i=1}^{n} \text{excursions}_i / \text{No of tests} \quad (8)$$

(c) F_3 = nse / (0.01 × nse + 0.01) (9)

is an asymptotic function that scales the normalized sum of excursions from objectives (nse) to yield a range between 0 and 100.

Based on results of index calculation, which was based on exceedances of objectives for key water quality variables, water quality of a water body was ranked as either excellent (95 to 100), good (80 to 94), fair (60 to 79), marginal (45 to 59) or poor (0 to 44) (Tyagi et al., 2013; CCME, 2001a, b; Andrea et al., 2005). Before calculating the index, the water body, variables, and appropriate objectives were defined. Although the time period chosen depends on the amount of data available, here dataset of two years has been used since data from different years can be combined when monitoring of certain years is incomplete (CCME, 2001a, b). Furthermore, WQIs were calculated separately as the dataset used to determine WQI of the UB is quite different from that of the MLB.

RESULTS AND DISCUSSION

Looking at the average (Av) of the overall sites of each parameter, those which failed to meet the WHO DWQG (S), according to WHO (2011, 2017), were turbidity, DO, BOD, COD, Pb, Fe, Mn, NH_3, Cu, TH, ECo and TC in the UB as could be depicted by Figure 3a and b. In the MLB, parameters that do not satisfy the DWQG are TH, Na, F^-, alkalinity, and PO_4^-. Those that are not in harmony with the FAO irrigation water quality guideline, according to Ayers and Westcot (1985), were TN, K^+, SO_4, Mn, NH_3, Cu, Mg, TH, ECo and TC in the UB and Na, Mg, F^-, alkalinity, HCO_3^-, PO_4^-, and SAR in the MLB.

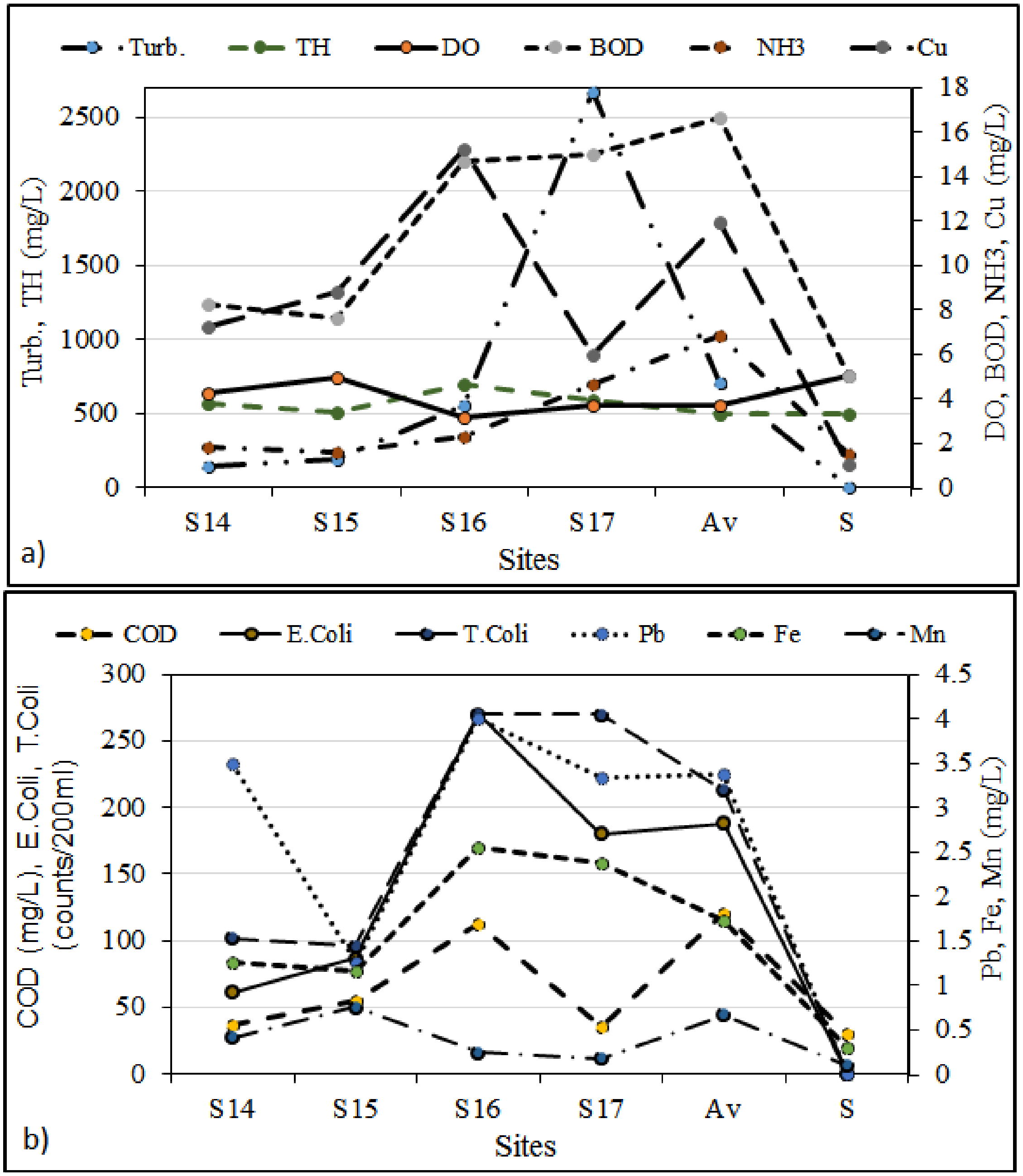

Figure 3. Parameters in the four sites of the UB exceeding the DWQG (S).

Determination of WQI and status of Awash River in the upper basin

Temperature, DO, NO_2^- and TH were excluded from evaluating the irrigation WQI as their guideline values were not available. The calculation of WQI in the UB was done assuming values of TNTC of fecal and total coliforms to be 270 each while nil in the MLB was assumed to be zero. In the calculation of amplitude (F3), the objectives of ECo and TC were assumed to be 1 to prevent an infinity excursion though the actual standard of 0. Here the only parameters in Table 2 considered in the index calculation were those for which the WHO, FAO or US EPA guidelines were specified. The three factors F1, F2, and F3 determining the CCME WQI and the resulting indices were computed for drinking and agricultural uses. The factors in this sub-basin got the respective values of 39.29, 42.31 and 97.08 for drinking

Table 4. WQIs for domestic and irrigation water uses and status of Awash River.

Water Use	Zone	Calculated WQI	Status (With Reference to CCME WQI)
Domestic	UB	34.79	Poor
	MLB	32.25	Poor
Irrigation	UB	46.39	Marginal
	MLB	62.78	Fair

and 36, 27.72 and 80.97 for irrigation uses. The drinking and irrigation WQIs for the basin, which were computed using Equation 4, were found respectively to be 34.79 and 46.39 as could be seen in Table 4.

WQI and status of Awash River in the MLB

Since guideline values for TS and SAR were not available, these parameters were excluded from the calculation of drinking WQI. For the same reason, TS, TH and NO_2^- were ignored in calculating irrigation WQI (Table 3). The total number of tests was reduced by two as there were two no data values of CO_3^{2-} for the tenth and eleventh sites. Taking average values of water quality parameters for the two seasons (dry and wet) in the sub-basins, the three factors F1, F2, and F3 determining the CCME WQI were computed for the respective water uses, drinking and irrigation. Accordingly, their respective values were found to be 60, 33.16 and 95.25 for drinking and 57.14, 24.44 and 17.14 for irrigation uses. As a result the drinking and irrigation WQIs for the basin were computed using Equation 4 and were found respectively to be 32.25 and 62.78 (Table 4).

The drinking and irrigation WQIs of the UB were respectively in the poor and marginal categories of the Canadian water quality classification. The indices of drinking and irrigation in the MLB were respectively in the poor and fair categories of the Canadian water quality ranking. Although the difference in the used water quality dataset of the two cases might contribute for the difference in the indices to some extent, it was generally conceivable that the water quality of the River was below the good rank of the council. The water quality status for irrigation use in the MLB seems to have significantly been improved to fair from the marginal status of the UB. This might be attributed to the natural purification process in the course of the River and the release of relatively smaller amount and less polluted effluent in the MLB. Though it may be difficult to compare due to the fact, for instance, that the bacteriological parameters like ECo and TC having significant impact were not considered in the MLB, it can be clearly seen from Figures 3 and 4 that the upper basin's waste is being stabilized at Lake Koka (S15) after attaining peak values at the 16^{th} site (just before Lake Koka). Alemayehu et al. (2006) also found out that the domestic water quality status seems to have been deteriorated more in the MLB than that in the UB. This might be the impact of the hydro-geochemical nature of the downstream sub-basin, which includes part of the Ethiopian rift valley (Dinka, 2017).

On the other hand, the value of SAR for sites S8, S9 and S12, which were respectively After Beseka, Lake Beseka and Sodere spring, exceeded the FAO guideline and hence these water bodies are not fit for irrigation unless some intervention is exercised at these hotspots. Similarly, RSC for sites S5, S6, S7, S8, S9, and S12 was greater than 7.5 and hence these sites were found to be unfit for irrigation while only S1 and S2 were shown to lie respectively in the fit and marginal ranges (Table 3). This finding is supported by the conclusions of Dinka (2017) and Alemayehu et al. (2006), stating that Lake Beseka's and other rift valley lakes' salinity, sodicity and alkalinity are too high to affect the River.

Means of the commonly analyzed 11 variables (TDS, EC, NO_3^-, NO_2^-, NH_3, F^-, Cl^-, Ca, Mg, TH and alkalinity) were compared between the UB and MLB and between sites in each sub-basin as shown by Figures 4 and 5a and b. The comparison showed that TDS, EC, F^-, Cl^-, and alkalinity were observed to be greater in the MLB than that in the UB. However, NO_3^-, NO_2^-, NH_3, Ca, Mg and TH showed higher values in the UB than in the downstream. This low concentration is in agreement with that studied by Dinka et al. (2015) which may be due to the fact that the upper basin is relatively more dominated by agro-chemicals and hardness. The former is consistent with the fact that the water from Sodere hot spring and Lake Beseka is of exceptionally high TDS and EC values and with previous studies such as that conducted by Reimann et al. (2003) and Halcrow (1989) indicating high fluoride concentration in Awash valley.

Comparison among sites within the UB showed that S16 (Awash River just before Koka Dam) had higher values of almost all parameters than S17 (Melka Kuntire) (Figures 3, 4 and Table 2); that is, as one goes from uplands to downstream, except turbidity, BOD, TC and

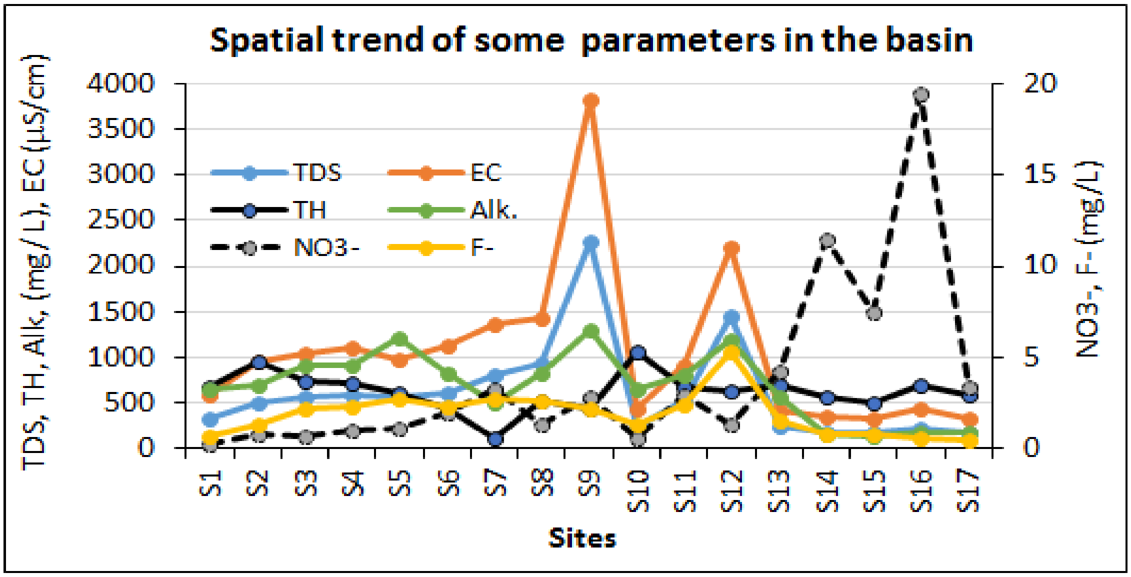

Figure 4. Spatial variation of some parameters in the basin.

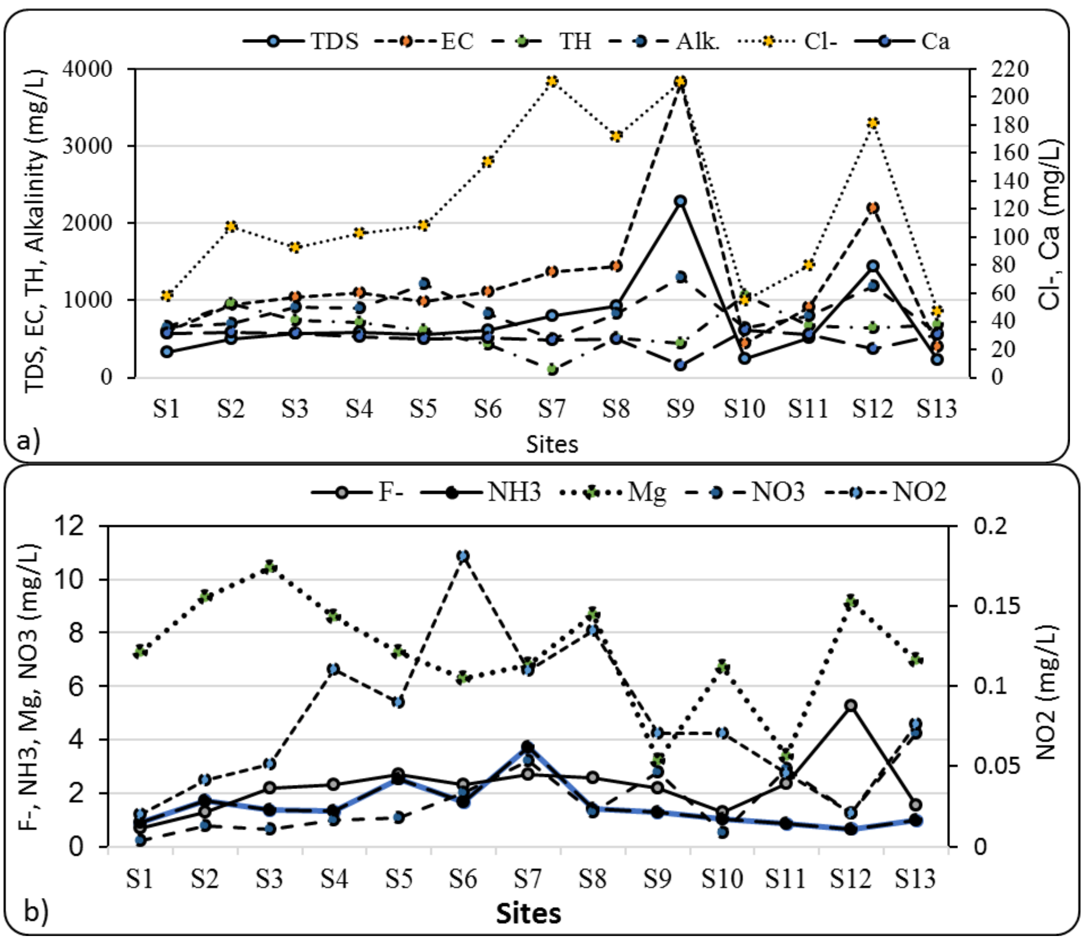

Figure 5. Spatial variation of water quality variables (both a and b) in the MLB.

NH_3, all have shown increasing trends. This can be attributed to effluents discharged from tanneries, oil mill factories, slaughterhouses and poultry farms around Mojo town (discharging their raw effluent directly into the Mojo River-tributary to Awash), similar wastes of Addis Ababa city (through Great and Little Akaki Rivers, which in turn converge to Abasamuel-tributary to Awash) and that of the nearby rural areas concentrated by floriculture and other industrial establishments (Degefu et al., 2013). However, some others such as COD, Fe, ECo, and TC were seen to decrease in the way from the 16th to the 14th site. Comparison among sites within the MLB also indicates some variation with exceptional picks especially of EC, TDS, and alkalinity at S9 and S12 (Lake Beseka and Sodere hot spring respectively) (Figures 4 and 5).

The graphical representations of the spatial variation of the determining parameters indicate clearly why the domestic water quality decreases as one goes from upper to downstream sub-basins and why the opposite is true for irrigation water quality.

Abundance of nutrients in the UB is expected from the ground based on the fact that agricultural activities using intensive nutrients are pronounced more in the UB than in the downstream basins. Hardness, as expected, is higher in the UB since ground water is being utilized and released into the River and discharges of greywater, full of Ca and Mg, from urban centers can potentially raise hardness.

CONCLUSION AND RECOMMENDATIONS

The study evaluated the physico-chemical (throughout the Awash River) and bacteriological (only in its UB) water quality for drinking and irrigation water uses. The water quality analysis results examined from different sites of the River showed that most of the parameters of concern do not comply with the drinking water quality guidelines and hence unsuitable for drinking. It also showed that most parameters need great care to be used even for irrigation. Both the cumulative drinking and irrigation WQIs of the UB and the drinking WQI of the downstream sub-basins lie in the poor range. This calls for protection of the River (especially in the upper and middle basins where intensive socio-economic activities are being observed) since contamination of this River with physical-chemical and biological determinants are attributed to wastewater discharge from urban, industrial, agricultural activities, lakes and hot springs in its catchment. Because one ultimate goal of water resources management in a basin is to implement programs that conserve water quality, it would be imperative to have a long-term monitoring program at selected sites. These programs together with establishment of municipal wastewater and storm-water treatment plants for identified dischargers in the basin would be among the potential solutions to increase the indices, which show improvement of the River water quality.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Hydraulic performance assessment of Tahtay Tsalit small scale irrigation scheme, Tigray, Ethiopia

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Assessment of irrigation performances is very essential while planning and chalking out management strategies for various irrigation. However, in Ethiopia, especially Tigray, performance evaluation of irrigation schemes is rarely conducted. The performance of Tahtay Tsalit irrigation scheme was not assessed yet and hence, this research was undertaken to assess the hydraulic performance of the irrigation scheme. The study was carried out during the irrigation season from September to November, 2016. The field measurements on canal dimensions, water flow measurements and water surface elevation were undertaken at selected sampling points. Simple descriptive statistics was employed for analysis of the data collected from field measurements and observations. However, hydraulic performance indicators were used to evaluate the performance of this irrigation scheme. Several factors such as flooding, sedimentation, design problems, damage of sluice gates, abstraction of irrigation water by unwanted plants has been identified in this irrigation scheme for mal-functional of different irrigation structures. Hydraulic performance of the irrigation system was evaluated using ten hydraulic performance indicators. There was no problem in irrigation adequacy (0.84 fair), equity (fair), dependability (0.057 good) and efficiency (0.77 fair) of irrigation water in this irrigation scheme. The average water surface elevation ratio, delivery performance ratio, and delivery duration ratio of the main canal during the monitoring period was less than one, greater than 5 and 150%, respectively. The highest sediment accumulation was observed at head and middle reaches of the irrigation scheme than the tail reaches. Generally, in this irrigation scheme there were a number of irrigation structures which had mal-functioned, and now required to be remodeled with sustainable solution to improve the performance of the irrigation scheme. Hence, it has been recommended that capacity building and awareness creation for irrigation water users, water committee, Woreda and Kebelle expertise are the main key factor to bring a change in irrigation water managements.

Key words: Hydraulic structures, hydraulic performance, small scale irrigation scheme.

INTRODUCTION

Ethiopia has abundant rainfall and water resources, its agricultural system does not yet fully benefit from the technologies of water management and irrigation (Awulachew et al., 2010). Since it is already suffering

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from food shortage because of the increasing population and chronic drought occurrence in most part of the eastern and northern part of the country. There is a dire need of utilizing these resources on emergent bases particularly, in those areas where the duration of the growing period is short and the precipitation is erratic.

Hence, improving the performance of irrigation schemes through various interventions is considered a key issue for addressing the need for increased productivity of irrigated lands under pressure on water resources. Though much study has been done in Ethiopia on irrigation performance assessment of schemes focusing mainly on the hydraulic, structural, water service and maintenance issues of the irrigation system (Seid, 2012; Henok, 2014; Dejen et al., 2011, 2012, 2015, 2016; Tebebal and Ayana, 2015) such kind of studies are limited in Tigray, particularly in the area where this study has been done.

The farmers found Tahtay Tsalit (T.Tsalit) irrigation scheme is able to irrigate and harvest crops twice per year. However, due to lack of frequent training for water application, management, operation and maintenance, for the Water users and water committee. Additionally, expertise of Woreda and/or development agent didn't estimated the appropriate crop water requirements and irrigation scheduling. Based on these problems farmers spent more hours per day to watering the irrigate field. Therefore, this study was conducted on hydraulic performance assessment of T.Tsalit small scale irrigation (SSI) scheme using internal performance indicators.

The study provides important information to the system managers, farmers, Woreda expertise, scientific community, funding agency and policy makers for better understanding of how a system can be operated and maintained the irrigation structures. Moreover, policy makers can take this opportunity to benefit other farmers who are not part of this study area.

Study objectives

The objectives of this study were:

i) To assess the hydraulic performance of the irrigation scheme.
ii) To evaluate the physical (area based) sustainability of the irrigation scheme.
iii) To identify the main causes and effect of failed hydraulic structures.

MATERIALS AND METHODS

Description of the study area

Tahtay Tsalit irrigation scheme is a perennial flow river which is located at Kola Tembien Woreda Tabia Adiha, at a specific site called Laelay Skein. It is about 120 and 23 km away from the regional town of Mekelle and Woreda town of Abi Adi, respectively and the catchment size is 130 km^2. Geographically, it is situated at latitude 13.740N, and longitude: 39.087E (Figure 1). The average elevation of the area above mean sea level is 1675 m (Tigray Region Water Resource, Mine and Energy Bureau (TRWRME), 2003). Tahtay Tsalit irrigation scheme was constructed in 2003 till 2005 between Laelay Tsalit and Mychew SSI schemes. It covers about 265 ha of which the irrigation potential is 178.5 ha while the remaining 86.5 ha is unsuitable land for irrigation purpose. The total length of the lined canal was 4.25 km and the unlined canal was about 1.05 km. The total irrigation beneficiaries was 269 household head and out of these 20.82% were female and 79.18% was male (Wereda Kola Tembien Agricultural Rural Development Office, 2016). The main crop type sown in this irrigation scheme include fruit trees such as orange (*Citrus sinensis*), and mango (*Mangifera indica*), vegetables (pepper (*Piper nigrum*)), and cereals (maize (*Zea mays*)).

Data collection and sources

For this assessment the data was collected from primary and secondary sources. The primary data was collected through direct measurement from fields. For example overview of the irrigation structures together with their water control and measurements, discharging through the branch off-take canals, actual water surface elevation in the main canal were measured from the field. Comprehensive field survey such as transect walk was held through the different components of the scheme to understand the irrigation practices, sources of irrigation water, its water distribution system and their cropping patterns. Moreover, discuss with the focused group and key informants was undertaken to identify the root causes and effect of failed irrigation structures.

The secondary data were collected from Tigray Regional Water Resource, Mines and Energy Bureau, Woreda Kola Tembien Water Resource, Mine and Energy office, Woreda Kola Tembien Agricultural Rural Development office and National Meteorological Agency of Ethiopia. Design document of the irrigation scheme, irrigated crops, actual command areas and climate data are major data which were utilized in the study.

Irrigation water delivery measurements (IWD)

In the study, the irrigation water in the canal was measured by calibrated Parshall flume and 90 degree V notch. The flow measurements were taken from nine off-take canals which were located at head, middle and tail reach of the irrigation system. The discharge of canals resulting from the depth-flow relationship in parshall flumes were calculated in free flow conditions. The measurements were taken at the branch off-take canals just after abstraction points along the distribution canals. Based on the settled water delivery plan, the measurement of actual discharges in each branch off-take canals were taken on 15 days per three months (five days/month) and then converted into an average monthly rate.

Water surface elevation (WSE) measurements

The actual water surface elevation (AWSE) data was taken along the main canal. The main canal length was divided proportionally in to three segments for analysis. The left and right side of the irrigation canals, AWSE were measured at interval of 300 m for head and middle and 250 m interval for tail reach. Generally, AWSE data were taken from thirty inspection stations along the main canal and secondary canal on both side of the irrigation scheme and these aggregated into fifteen inspection points.

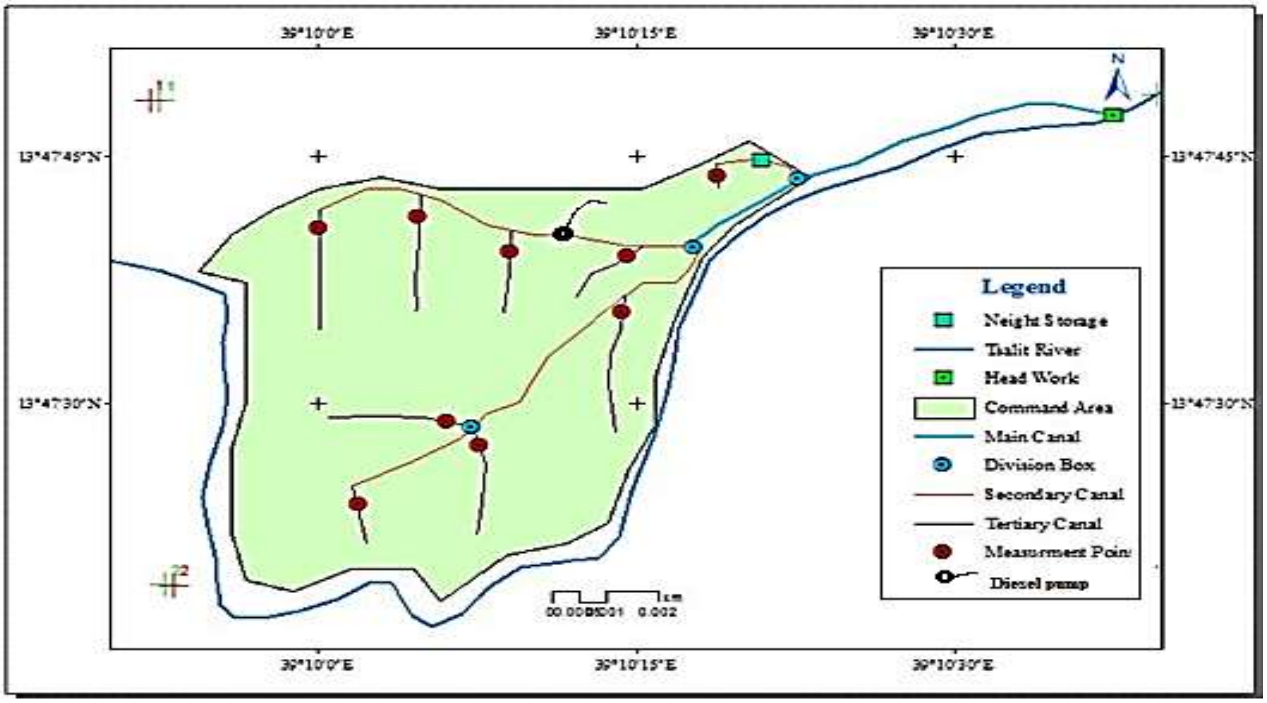

Figure 1. Layout of T.Tsalit SSI scheme.

Measurements of sediment accumulation

Initial depth was measured before cleaning of the canal, while final depth of the canal was taken after cleaning the silt or sedimentation from September 10 to 12, 2016.

Data analysis

Hydraulic performance of the irrigation system was evaluated using ten performance indicators. Performance evaluation using internal indicators contains specifically measuring the extent to which the intended demand required benefits are being achieved. It was investigated based on the data that were collected during September to November, 2016 in one irrigation season. The choice of these months was arranged due to the fact that, in this irrigation scheme most of fields are irrigated. A water delivery performance indicator was designed to evaluate on the main canal at head, middle and tail reaches. The main canal system performance with respect to water delivery indicators was estimated based on the monthly required and delivered discharge.

Hydraulic performance indicators

Water delivery performances at field level were determined according to the indicators of adequacy, equity, dependability and efficiency. The coefficient of variation (CV) was estimated through the ratio of standard deviation to mean. In estimating these indicators, the values of delivered (Q_D), required (Q_R) and intended (Q_{In}) for irrigation scheme were taken as basic variables. The number of irrigations in one season (T) was taken as the time period; and the number of fields (R) was taken as the sub-region. These indicators have been proposed by (Molden and Gates, 1990). The results where compared with Performance standards.

Maintenance indicators

Maintenance performance assessment of irrigation schemes would provide an insight to the future of maintenance situations. It was estimated through the indicators recommended by Bos (1997), Kloezen et al. (1998) and Bos et al. (2005). Maintenance requirements of the system were evaluated by water surface elevation ratio, delivery performance ratio, delivery duration ratio and effectiveness of the infrastructures.

Physical sustainability (Area based) indicators

Sustainability is the performance measure related to upgrading, maintaining, and degrading the environment in the irrigation schemes. Aspects of environmental/physical sustainability that can be affected by irrigation managers and farmer's practices relate primarily to over or under-supply of irrigation water. This leads to negative effect of the irrigation practices that is water logging or salinity. For this study, irrigation ratio and sustainability of irrigated area physical sustainability indicators were used.

RESULTS AND DISCUSSION

Hydraulic performance indicators

There were many different factors that affect irrigation water deliveries in the study area. The community in T.Tsalit SSI scheme both irrigation beneficially and no beneficially use water from Tsalit River, diversion and canals of the irrigation scheme for all water demand purposes particularly in the dry period (Figure 2). As a

Figure 2. Water used for other purpose than irrigation.

Table 1. Average required (Q_R) and delivered (Q_D) discharge on the main canal (m^3 s^{-1}).

	T.Tsalit SSI scheme																	
Month	Head						Middle						Tail					
	Q_{R1}	Q_{D1}	Q_{R2}	Q_{D2}	Q_{R3}	Q_{D3}	Q_{R4}	Q_{D4}	Q_{R5}	Q_{D5}	Q_{R6}	Q_{D6}	Q_{R7}	Q_{D7}	Q_{R8}	Q_{D8}	Q_{R9}	Q_{D9}
Sep	0.14	0.14	0.12	0.10	0.20	0.19	0.19	0.11	0.13	0.12	0.15	0.14	0.11	0.10	0.11	0.10	0.09	0.08
Oct	0.14	0.13	0.12	0.10	0.20	0.16	0.17	0.11	0.13	0.11	0.15	0.13	0.11	0.09	0.11	0.09	0.09	0.09
Nov	0.14	0.12	0.12	0.11	0.20	0.15	0.16	0.11	0.13	0.10	0.15	0.14	0.11	0.09	0.11	0.10	0.09	0.09

Where: Q_{R1}, Q_{R2}, Q_{R3} … Q_{R9} and Q_{D1}, Q_{D2}, Q_{D3} … Q_{D9} required and delivered discharge at 1, 2, 3… 9 of the supply canal incoming across the off -taking canal. N.B: The delivery discharge measurements were taken twice per day and average as the delivery of one day. A total of five days per month was taken.

result, loss of irrigation water from the intended purpose was high in this irrigation scheme.

Based on the investigation, from September to November, 2016 the average values of actual monitored discharge and required in the secondary and branch off-take canals are summarized in Tables 1 and 2, respectively.

Adequacy indicator (P_A)

The adequacy of irrigation water at T.Tsalit irrigation scheme was average temporal value of adequacy are 0.86, 0.80 and 0.87 at head, middle and tail reach of the system, respectively (Table 3). The spatial values of adequacy based on the Table 3 with an average values 0.87, 0.84 and 0.83 in September, October and November, respectively. From these results the spatial and temporal average adequacy of the scheme was 0.84 (fair).

Similar results were obtained by Dejen et al. (2015). The temporal indicators shows that the level of adequacy of water delivery was generally satisfactory at the head and tail reach off-takes, both for 2012 and 2013. However, it was worse at the middle off-takes , which could be explained by the following two factors. First, there was inadequate operation of the night storage reservoir, which causes significant temporal water level fluctuation in the outlet canal from which middle off-takes were supplied. Secondly, off-takes in the middle reach except for one lateral have over flow structures, while the water level regulators were under flow, which makes these off-takes hyper-proportional. Hence any hydrodynamic perturbation in the parent canal generates relatively larger changes in flow of these off-takes.

Equity

Based on the Table 3, equity of water distribution in T.Tsalit SSI scheme at September was fair whereas in the October and November irrigation time equity was good. This is because the irrigation canal in these months were completely cleaned. The water committee as well as the sub leaders started proper function or control the irrigation canal based on the irrigation scheduled.

Dependability

The average dependability values at the head, middle and tail reach of a system is ranging from 0.03 to 0.08 with an overall average dependability of 0.057 (Table 3). Generally, the dependability value of T.Tsalit irrigation scheme lay within the range of 0 - 0.1 (good). When compare on each reaches the tail reach was good reliable than the middle and head. This result shows that, the commitment or agreement of the water committee

Table 2. Average delivered and required discharge in the branch off-take canals ($m^3\ s^{-1}$).

Reach / Month	Head						Middle						Tail					
	Q_{R1}	**Q_{D1}**	**Q_{R2}**	**Q_{D2}**	**Q_{R3}**	**Q_{D3}**	**Q_{R4}**	**Q_{D4}**	**Q_{R5}**	**Q_{D5}**	**Q_{R6}**	**Q_{D6}**	**Q_{R7}**	**Q_{D7}**	**Q_{R8}**	**Q_{D8}**	**Q_{R9}**	**Q_{D9}**
Sep	0.009	0.015	0.009	0.016	0.01	0.014	0.006	0.008	0.006	0.008	0.004	0.009	0.006	0.008	0.007	0.009	0.006	0.006
Oct	0.009	0.015	0.009	0.014	0.01	0.016	0.006	0.008	0.006	0.009	0.004	0.009	0.006	0.009	0.007	0.008	0.006	0.006
Nov	0.009	0.015	0.009	0.013	0.009	0.015	0.006	0.008	0.006	0.008	0.004	0.009	0.006	0.008	0.007	0.008	0.006	0.007

Where: Q_D and Q_R is the delivered and required discharge in the branch off-take canals and in branch off-take of R_1 till R_9 respectively.

Table 3. Average adequacy of water distribution, dependability of water supplied and equity of water distribution on the system.

Month	Head			Middle			Tail			Spatial Average (P_A)	STDEV	CV_R (P_E)
	R1	R2	R3	R4	R5	R6	R7	R8	R9			
Sep	0.96	0.84	0.96	0.56	0.95	0.91	0.85	0.9	0.86	**0.87**	0.12	**0.14**
Oct	0.88	0.83	0.84	0.65	0.89	0.88	0.83	0.86	0.91	**0.84**	0.08	**0.09**
Nov	0.8	0.87	0.75	0.67	0.83	0.89	0.81	0.87	0.94	**0.83**	0.08	**0.1**
Average (Temporal)	0.88	0.85	0.85	0.63	0.89	0.9	0.83	0.88	0.9	0.84		
Average Reach (P_A)		**0.86**			**0.8**			**0.87**		**0.84**		
STDEV	0.08	0.02	0.11	0.06	0.06	0.02	0.02	0.02	0.04	0.02		
CV_T (P_D)	0.09	0.02	0.12	0.09	0.07	0.02	0.03	0.03	0.04			
Ave.CV_T (P_D)		**0.08**			**0.06**			**0.03**		**0.057**		**0.11**

with their irrigation water users (IWUs) to distribute irrigation water was proportional and the communication between them was very stronger.

Gorantiwar and Smout (2005) explained that farmers may be happier with a water delivery system in the irrigation scheme that delivers an inadequate supply which is reliable, than with the adequate supply which is not reliable. If the farmers are sure that the deliveries are according to the schedule communicated to them, they can plan their activities accordingly resulting in higher productivity.

Efficiency

For T.Tsalit irrigation scheme the spatial and temporal average values of irrigation efficiency (P_F) are illustrated in Table 4. The temporal irrigation efficiency was poor at the head in all months; however, good and fair temporally at the tail and middle of the irrigation scheme. This problem was happened due to uncontrolled delivery of water in the first, second and third branch canals. The spatial irrigation efficiency of T.Tsalit SSI scheme was under fair at all months 0.77, 0.78 and 0.77 during September, October and November, respectively.

Generally, similar results were found from different sites; for example, Dejen (2015) aggregated all monthly efficiency indicators values concern the tendency of the whole system to save water for the downstream off-takes. Moreover, Tebebal and Ayana (2015) found similar results at the middle and tail reach of the system over the observation period; while the efficiency of water supplied in the head reach was poor. This problem was transpired due to uncontrolled delivery of water in the first branch canal.

Maintenance indicators

Maintenance performance inspection of irrigation scheme would provide an insight to the feature of maintenance situations. According to Mateos et al. (2002) objectives of maintenance indicators are to keep the system in proper operating conditions, to maximize the life of the system's

Table 4. Average spatial and temporal irrigation efficiency.

Month	Head			Middle			Tail			Spatial Av. P_F
	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	
Sep	0.61	0.57	0.68	0.78	0.73	1	0.82	0.8	0.94	**0.77**
Oct	0.6	0.67	0.61	0.8	0.68	1	0.75	0.88	0.99	**0.78**
Nov	0.61	0.68	0.61	0.78	0.71	1	0.8	0.91	0.86	**0.77**
Average P_F	0.61	0.64	0.63	0.79	0.71	1	0.79	0.86	0.93	
Temporal Av. P_F		**0.63**			**0.83**			**0.86**		**0.77**

Table 5. Water surface elevation ratio (WSER).

Linear distance (m)	Head				Linear distance (m)	Middle				Linear distance (m)	Tail				Overall	
	IWSE (m)	AWSE (m)	DEV. WSE	WSER		IWSE (m)	AWSE (m)	DEV. WSE	WSER		IWSE (m)	AWSE (m)	DEV. WSE	WSER	DEV. WSE	WSER
20	0.8	0.65	0.15	0.81	2020	0.6	0.59	0.01	0.98	4020	0.4	0.31	0.09	0.78		
420	0.8	0.72	0.08	0.9	2420	0.6	0.51	0.09	0.85	4420	0.4	0.36	0.04	0.90		
820	0.75	0.63	0.12	0.84	2820	0.55	0.51	0.04	0.93	4820	0.4	0.36	0.04	0.90		
1220	0.75	0.62	0.13	0.83	3220	0.55	0.53	0.02	0.96	5220	0.4	0.39	0.01	0.98		
1620	0.75	0.69	0.06	0.92	3620	0.55	0.48	0.07	0.87	5300	0.4	0.35	0.05	0.88		
Average		0.66	0.11	0.86			0.52	0.05	0.92			0.35	0.05	0.89	**0.07**	**0.89**
Maximum		0.72	0.15	0.92			0.59	0.09	0.98			0.39	0.09	0.98		

Linear distance is the distance from the intake canal to the monitoring station, DES.WSE = deviation of water surface elevation, DEV.ESE = IWSE – AWSE, and WSER = water surface elevation ratio. N.B: The result was based on average level measurement of water depth at FSL in various main canal sections and the linear distance was the distance from the intake of the irrigation canal.

facilities, and to prevent interruptions in water deliveries. Therefore, maintenance study helps to reflect the management performance of an irrigation schemes.

Water surface elevation ratio (WSER)

The results of WSER are given in Table 5. It was derived from the average value of the ratio of water surface elevation in the prescribed monitoring locations on head, middle and tail reach of the main canal and represents the average WSE below the full surface level (FSL) of the main canal as per the design document. The intended water depth of the main canal from the canal bottom was 0.8 m at FSL with design discharge of 2.3 $m^3 s^{-1}$.

The current average water surface elevation at FSL were 0.66 m, 0.52 m and 0.35 m at the head, middle and tail reach, respectively. The overall average of WSER was 0.89; this shows a seven percent of WSE at FSL was reduced from the intended water depth of the main canal (Table 5). The average WSER of the main canal during the monitoring period was generally less than one, thus the main canal was ineffective by weed and sedimentation problems. Similar result was found by Tebebal and Ayana (2015). The overall average WSER was found to be 0.91. From their estimation, about seven percent of WSE at FSL was reduced from the intended water depth of the main canal.

Delivery performance ratio (DPR)

The delivery performance ratio of irrigation scheme was illustrated in Table 6. The head

Table 6. Delivery performance ratio of canal reach.

Month	Head			Middle			Tail			Spatial average
	R1	R2	R3	R4	R5	R6	R7	R8	R9	
Sep	0.05	0.04	0.05	0.07	0.05	0.05	0.05	0.06	0.07	**0.06**
Oct	0.05	0.08	0.04	0.07	0.05	0.04	0.05	0.06	0.07	**0.06**
Nov	0.04	0.04	0.39	0.07	0.05	0.05	0.05	0.06	0.07	**0.09**
Average (Temp)	0.05	0.06	0.16	0.07	0.05	0.05	0.05	0.06	0.07	
Average		**0.09**			**0.06**			**0.06**		**0.07**

R_1 till R_9 represents samples of off-take canals from which discharge measurements were taken.

Figure 3. Mal-functioned hydraulic structures.

reach of the hydraulic structures DPR was estimated to be 0.09 which is greater than 5%, which needs maintenance and this also agrees with the field observation (Figure 3) and response from the focus group discussions. Part of diversion nearest to the inlet of the main canal was damaged and two sluice gates were flushed by flood during 2011.

The result at head reach was greater than middle and tail which have the same value 0.06 for each reach, this show the head reach of the canals was affected by siltation of the irrigation canals and scouring the downstream of the diversion. Tahtay Tsalit SSI scheme need more maintenance in November than the remained months (September and October).

Delivery duration ratio (DDR)

The value of delivery duration ratio for T.Tsalit SSI scheme as per the design document, the intended duration of water delivery was 16 hours per day. However, because of the expanding of the irrigated land, silting up of the canal systems, mal-functioning of control structures, inappropriate watering of main and secondary canals and shortage of water; mainly for tail end beneficiaries, actual duration of water delivery was increased to 24 h per day. Therefore, DDR for this irrigation scheme is 150%; showing the water distribution system was not dependable and the system maintenance also insufficient. Tebebal and Ayana (2015) at Hara irrigation scheme similarly demonstrated that the water distribution system was not dependable (133.33%) and the system maintenance was also insufficient.

Effectiveness of infrastructure

In Tahtay Tsalit irrigation scheme both the spill way sluice gates at the weir nor the flow control gates at the off-take were functional and hence, are not effective yet. On the other hand, no failure was observed at the main and branch canals. Beyond the mal-functionality of sluice gates, off-takes and other hydraulic structures were also mal-functioned (Table 7).

Based on the design document, the total number of structures that were constructed in T.Tsalit SSI scheme i.e. diversion, intake gate, spillway gate and other irrigation structures built on the main and branch canals were 155, however only 94 structures are currently functional (Table 7). The values of effectiveness of infrastructures was estimated to be 60.65%. This value suggests that the maintenance activity of the system was poor. Similar results and expression given by Tebebal and Ayana, (2015) in Hare irrigation scheme, SNNPR, Ethiopia from 113 constructed irrigation structures only 18 structures were functional and its position was 15.9%.

Table 7. Functional and mal-functioned irrigation structures.

		T. Tsalit SSI scheme			
S/N	**Infrastructures**	**Functional**	**Mal-functioned**	**Total No. of infrastructure**	**Effectiveness of infrastructure (%)**
1	Spill way gate	0	3	3	0
2	Drop structures	45	3	48	93.8
4	Diversion box	3	2	5	60.0
5	Off-take	46	7	53	86.8
6	Sluice gate at the off-take	0	46	46	0
	Total	94	61	155	48.11
	Position (%)	**60.65**	39.35		

Table 8. Environmental sustainability of irrigation scheme (WKTARD, 2016).

SSIS	Irrigable area (ha)	Design capacity (ha)	Irrigated land (ha)	IR	SIA
T.Tsalit	178.5	149.5	161.75	**0.91**	**1.08**

Physical (area based) sustainability indicators

Based on the focus group discussion the physical sustainability of irrigation scheme could be affected by IWUs and irrigation managers. This was related primarily to over or under supply of irrigation water leading to mal-functioning of the hydraulic structures, water logging or salinity.

Irrigation ratio (IR)

In Tahtay Tsalit irrigation scheme from the total irrigable land about 91% was irrigated (Table 8). This is because the irrigation scheme was constructed in 2003 and has relatively the required irrigation infrastructures. Eventhough, it was to expand beyond this value, but shortage of irrigation water was the limiting factor not to irrigate the potentially irrigable land. Moreover, there is no irrigation water fee that promotes farmers to use the irrigation water efficiently so as to increase the irrigable land in the scheme.

Dejen et al. (2012) have similar reasons for the greater irrigation ratio found at Golgota which could be explained by three factors; these are, generous water availability, absence of irrigation water fee and better land productivity encouraging farmers to invest on more areas.

Sustainability of Irrigated Area (SIA)

According to the estimated value of SIA for this irrigation scheme has sustainable irrigated land (Table 8) which can be explained by the expansion of irrigated area from what has been designed initially. Nearly similar result and reasons found in Dejen et al. (2012) that, for Golgota scheme with a value of 1.22; the irrigated area has expanded by about 20% since commissioning. The same reason applies for irrigation ratio. These factors encourage more farmers to come to the area and irrigate lands by leasing or renting from local land owners.

Causes and effect of failed hydraulic structures

The main causes of failure of the hydraulic structures in T.Tsalit SSI scheme could be attributed to the occurrence of high flooding in 2011. During that time a number of sluice gates were damaged by the flood and also more amount of sedimentation entered in to the irrigable lands. After the damage, maintenance was being done routinely using temporary materials such as sand bag, mud and stone to the structures and this further adds siltation to the canals.

Based on the filed observation and focus group discussion; the failure of some irrigation structures was observed to be design problem (Figure 4c). For example, due to the high slope difference between the constructed off-takes and irrigable farm lands (the variation of the off-take and the irrigable land was averagely about 0.5m). As a result, farmers didn’t use this irrigation off-takes as it could erode their farm land and hence, use other alternative off-take faraway from their farm land. This leads into soil erosion, siltation, seepage, deep percolation and mal-functioning of the irrigation structures.

Improper operation and maintenance of canals which was strengthened by poor awareness on water users and water committee were also mentioned as problems, and leads into illegal manipulation of canals and structures.

Figure 4. Main causes of hydraulic structure mal-functioning of T.Tsalit SSI scheme.

Table 9. Sediment deposition of T.Tsalit SSI scheme.

Reach	Sample	Sedimentation (m^3 per 5 m)
Head	S1	1.214
	S2	0.965
Middle	S3	0.931
	S4	0.850
Tail canals on the left side	S5	0.701
	S6	0.483
	S7	0.268
Tail canals on the right side	S8	0.525
	S9	0.532
	S10	0.406
	Average	**0.687**

Due to the stealing of flow control gates from the off-take irrigation canals farmers were forced to use soil and wooden logs (Figure 4a) to control flows of water and this creates siltation problem mainly at the canals. The tertiary unlined canals which were constructed by the individual farmers has a problem in its dimension (very wide) which creates an opportunity of water loss through percolation, evaporation and even flow to unwanted areas (Figure 4b) and additionally leads soil erosion.

Deforestation, free grazing and non-treating the upper catchments by different soil and water conservation structures due to the existing disagreements between *Hagere Selam* and *Kola Tembien* Woredas were also mentioned as the most important source of siltation in the irrigation scheme.

Apart from the structure mal-functioning factors, there were some unwanted plants.these are *Pterolosium stellatum* (Konteftefe), *Ziziphus spinachristi* (geba), *Acacia sieberiana and Acacia seyal* (Tsaeda cheia and Tselim cheia), *Ficus sur* (Sagla), *Balanites eagyptica* (Meki'a), *Syzygium guinensis* (Li'ham) and *Ficus vasta* (Da'ero) where as the planted trees were *Euphorbia tirucalli* (Knchib), *Eucalyptus camaldunesa* (keyh kelamitos), *Gravilia robusta* (Gravila), Susbanyia, and Lusinya) in the farm land that absorbed the irrigation water and they are agents of the irrigation canal to become cracked.

Sediment deposition in the irrigation canals

From the measurements in this irrigation scheme as illustrated Table 9, the sedimentation in T.Tsalit near head canal (main canals) has more amount of sedimentation than the middle and tail canals, that is, (S_1) 1.214 $\frac{m^3}{5m}$ into (S_4) 0.850 $\frac{m^3}{5m}$ and as the distance increases from the head into the tail canals sedimentation decreased from (S_5) 0.701 $\frac{m^3}{5m}$ to (S_7) 0.268 $\frac{m^3}{5m}$..

Moreover, the sedimentation of the right side canal has more sediment accumulation than the left side canals of the irrigation S_8, S_9, and S_{10}0.525$\frac{m^3}{5m}$, 0.532 $\frac{m^3}{5m}$ and

$0.406\frac{m^3}{5m}$, respectively. Because, there was large amount of cultivation land above the canal and the topographic features are undulating.

Conclusions

Improving irrigation water management through identification of factors that hinder for efficient utilization is compulsory. Several factors such as flooding, sedimentation, cracking, stealing of flow control gates, improper operation and maintenance, abstraction of irrigation water by unwanted plants, deforestation, free grazing, lack of watershed treatment/soil water conservation have been identified in this irrigation scheme. The overall irrigation water delivered performance indicators, adequacy value was fair both spatially and temporally. The overall equity value of the delivery system was fair. Regardless of its fair classification, there was high temporal variability. Dependability was classified as good but, there was spatial variation in the canal reach that is tail reach was good and for the head and middle was fair classification. The estimated delivered performance ratio was greater than 5% which needs maintenance. Delivery duration ratio of this scheme has 150%; showing the water distribution system was not dependable and the system maintenance was insufficient. In T.Tsalit irrigation scheme neither the spillway sluice gates at the weir nor at the flow control gates at the off-take were functional and are not effective yet. Beyond the mal-functionality of sluice gates, a considerable number of off-takes were also mal-functioned. On the other hand, no failures were observed at the main and branch canals. There was high irrigation ratio and sustainability of irrigate area in T.Tsalit. Since, sustainable irrigate land which could be explained by the expansion of irrigated areas in this sites from what has been designed initially. Generally, in this irrigation scheme there were a number of irrigation structures which were mal-functioned due to many different reasons and now needs sustainable solution to improve the performance of the irrigation scheme.

RECOMMENDATIONS

i) Awareness creation and capacity building should be given to local administrations, development agent, irrigation water users and farmers on management of irrigation water and irrigation structures.

ii) There should be integration between *Hagere Selam* and *Kola Tembien* Woredas in the watershed development.

iii) All tertiary off-take flow control gates should be constructed so as to control the discharge of the irrigation water and minimized the sedimentation accumulation of the next off-takes.

iv) There should be water fee by-laws for all the irrigation water users; which will later used for maintenance of failed irrigation structures.

v) Watering procedure should be based on the crop water requirement and irrigation scheduling.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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