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Natural and anthropogenic sources of salinity in the Awash River and Lake Beseka (Ethiopia): Modelling impacts of climate change and lake-river interactions

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ABSTRACT

Study region: Awash River Basin, Ethiopia: Study focus: Many river basins in sub-Saharan Africa have become vulnerable due to the impact from climate change, weak governance and high levels of poverty. One of the primary concerns is the elevated salinity and the degradation of water quality in the Awash River. Located in the Great Rift Valley in Ethiopia, the Awash River has unique hydrochemistry due to water-rock interactions. However, in recent years, increasing anthropogenic activities including the discharge from saline Lake Beseka into the Awash River has caused some concern. This study used an Integrated Catchment Model to simulate chloride concentration in the Awash River Basin by taking both natural and anthropogenic sources of salinity into consideration. Future scenarios of climate change and Lake Beseka discharge were examined to assess the impact to the river water quality.

New hydrologic insights: Results show that Lake Beseka has made significant contribution to the rise of the salinity in the Awash River. If the trend of human interference (e.g. increased irrigation and unregulated water transfer) continues, the river downstream of Lake Beseka could see Cl increases up to 200 % in the near future (2006–2030). The modeling results are essential for generating long term plans for proper utilization of water resources especially in the region where the resources and the economic capacity to meet the water demand is lacking.

1. Introduction

Water scarcity is one of the most pressing environmental and societal issues worldwide and affects human health, food security, and ecosystem that potentially lead to mass migration (Brzoska and Fröhlich, 2016; Gray and Mueller, 2012; Mekonnen and Hoekstra, 2016). In sub-Saharan Africa, there are many vulnerable river basins due to the impact from climate change, weak governance and high levels of poverty (Hirpa et al., 2019; Taye et al., 2018). The Awash River Basin is one area of concern as the catchment is subject to

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not only high climatic variability with frequent floods and droughts, but also the impact of the rapid growth of agriculture, industries and urbanization, as well as population growth within the Awash basin (Taye et al., 2018). All of these have placed excessive pressures on the basin's water resources. In addition, the decreases in flow reduce the dilution power in the river system. The growing human population and the expansion of industrial and agricultural activities have contributed point-source and non-point source pollutions to the Awash River that inevitably degrade the water quality (Bussi et al., 2021; Nigussie and Getaneh, 2016).

The hydrochemistry of the Awash River Basin is unique and characterized as wide spatial variations in total dissolved solids (TDS) and ionic concentrations due to differences in water-rock interactions related to geology, groundwater residence time, geomorphological setting and climate (Ayenew, 2005; Darling et al., 1996). In general, the highland waters are homogeneous and characterized by lower TDS (50−1200 mg/L) with the dominantly calcium-magnesium bicarbonate type (Ayenew, 2005). The TDS increases towards the rift valley following the regional groundwater flow directions from areas of high rainfall and low evaporation to the semi-arid rift floor. The rift valley waters are dominantly sodium-bicarbonate type with high TDS (200 and˜73,000 mg/l) and enriched fluoride (Ayenew, 2005; Ayenew et al., 2008). This chemical feature of varied TDS is evident in the Awash River Basin where bicarbonate dominates the upper Awash water and changes to high chloride (Cl) type in the middle and low Awash River due to changes in lithology related to evaporite deposit (Ayenew, 2005).

In addition, Lake Beseka, located within the Awash River Basin, is an exceptional lake that was extremely saline in 1960s with the Cl concentration of over 5,000 mg/L due to its unique geological and hydrogeological settings (Olumana Dinka, 2017; Talling and Talling, 1965). Since then, substantial increase in lake volume, area and depth has been observed. There is concern that the continued growth of Lake Beseka from increased groundwater inflow to the lake resulting from an increase from irrigation activities would eventually make Lake Beseka cross the Awash River catchment boundary and join the river that could result in numerous negative environmental and economic consequences (Dinka, 2017). High salinity of Lake Beseka water would significantly impact the river water chemistry and put another pressure to the already stressed water resources. It could also affect the groundwater system and the aquatic ecosystem downstream. The rise in salinity of the river water could affect the large fertile irrigated farmlands located downstream with soil salinization (Dinka, 2017). This situation is a serious threat to the socio-economic stability of the entire Awash River Basin and it requires regular monitoring and an appropriate management system. Various organizations including the Ministry of Water Irrigation and Electricity of Ethiopia (MoWIE) have tried to control the lake level since the early 2010s by setting up pumps, excavating a canal and discharging the lake water into the river (Teffera et al., 2018) (WWDSE, 2010). However, a comprehensive assessment is still needed to understand the impact to the downstream water quality from mixing the Lake Beseka water with the river water.

In this paper, the influence of human factors, in combination with the natural conditions of climate and geology, on the water quality in the region will be examined. We will use an Integrated Catchment Model to simulate chloride concentration in the Awash River basin (including Lake Beseka) considering both natural and anthropogenic sources of salinity. Future scenarios including climate change and the discharge of Lake Beseka water into the Awash River will be analyzed. This is the first study that uses a semi-distributed model application to assess the river flow, Lake Beseka discharge and its impact on river water quality in a holistic way in the Awash River Basin. Understanding the impact from climate change and increased anthropogenic activities is needed to set up suitable water management policies and regulate the uses of water resources in the Awash River Basin. This study also provides insights into river

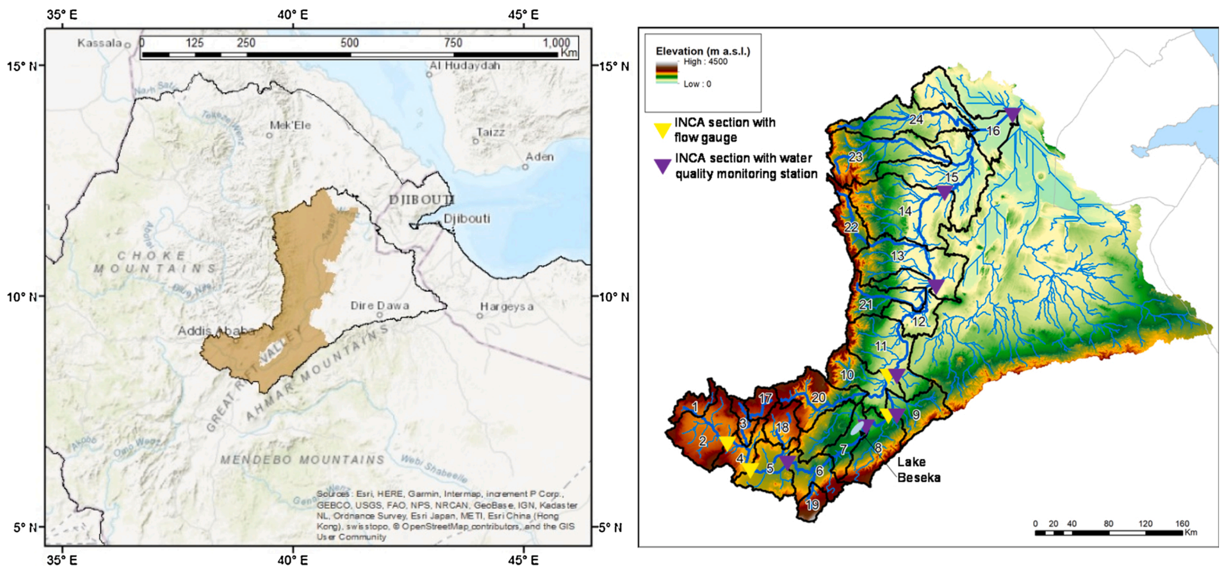

Fig. 1. a) Map of the Awash River Basin draining to the Danakil Plain. The brown-shaded area indicates the INCA modeled Western catchment which is drained by the main Awash River water course (the rest of the catchment does not contribute to the flow of the river due to its arid nature); b) map of the INCA reaches and associated sub-catchments in the Awash River Basin Triangles indicate INCA sections with flow stations and/or water quality monitoring stations.

basin management for other places that face similar issues.

2. Study area and methods

2.1. Study area

The Awash River Basin is one of the twelve river basins of Ethiopia (Fig. 1a). The river, with a length of about 1,200 km, starts from Ginichi town west of the capital Addis Ababa, travels along the Rift Valley and ends in Lake Abe on the border between Ethiopia and Djibouti. The Awash River Basin comprises highlands escarpments and rift valley. The Awash River flows from an altitude of 3,000 m above sea level (m.a.s.l.) to 250 m.a.s.l (Fig. 1b).

The Awash River Basin is part of the Great Rift Valley in Ethiopia and covers a total area of 116,200 km^2. The Western catchment with the size of 70,800 km^2 drains to the main Awash River or its tributaries. The remaining 45,400 km^2, most of which comprises the so-called Eastern catchment, drains into a desert area and does not contribute to the main river course (Nigussie and Getaneh, 2016) (Fig. 2a). Therefore, only the Western catchment was considered in this study (Figs. 1a and 2 a).

In the Ethiopian Rift Valley, the complex tectonic and volcanic processes have resulted in the formation of volcano-tectonic structural depressions that became sites for many rift valley lakes including Lake Beseka in the Awash Basin. Lake Beseka was naturally a closed catchment. Currently, it has inflows from Abadir farm, Nera Era and Fentaile irrigation farms that are located within Lake Beseka catchment. It has a manmade outflow channel constructed by Awash Basin Authority (AwBA) in 2009 and 2010. Near the lake, the Metehara Sugar Estate has developed farmland of about 100 km^2 (Zeleke, 2008). Lake Beseka has been expanding rapidly and the area has increased from 3 km^2 to 40 km^2 from the late 1960s and early 1970s to the early 2000s (MWR, 1999). The lake body was estimated about 54 km^2 in 2015 using the Google Earth image (Shishaye, 2015). A recent land use study showed that the lake body has reached 46.7 km^2 in 2017 (Teffera et al., 2018). The level of the lake rose by 4 m from 1976 to 1997 (Zemedagegnehu and Egizabher, 2004). In contrast to many East African terminal lakes, Lake Beseka has been expanding drastically as a result of an increase in the net groundwater flux into the lake that may have resulted from an increase from irrigation activities in the adjacent farmland (Ayenew, 2004).

The rainfall in the Awash River Basin is highly variable in space and time. The average total rainfall ranges from 1600 mm in the highlands to 160 mm in the lowlands (AWBA, 2017). The climate of the Awash River Basin comes under the influence of the Inter-Tropical Convergence Zone (ITCZ). The rainfall pattern in the basin shows that the main rains occur from July to September and the rest of the year is dry except for a small amount of rainfall during March to May. June is a dry month between the small and the main rainy season.

2.2. INCA-Cl application to the Awash River Basin

The Integrated Catchment Model (INCA) is a dynamic, daily time-step, semi-distributed, process-based water quality model originally created to simulate nitrogen processes and assess sources of nitrogen in catchments (Wade et al., 2002; Whitehead et al., 1998a, b). Over the years, various versions of INCA models (INCA-phosphorus, INCA-sediment, INCA-carbon, INCA-metals, INCA--pathogen and others) have been developed and applied to river catchments (Crossman et al., 2013; Futter et al., 2007; Jackson-Blake et al., 2016; Lu et al., 2017; Whitehead et al., 2009, 2011). The INCA-chloride (INCA-Cl) model was first used to simulate stream Cl concentrations in a single stem river that treats the tributaries as aggregated inputs (Jin et al., 2011). The recent modification to the

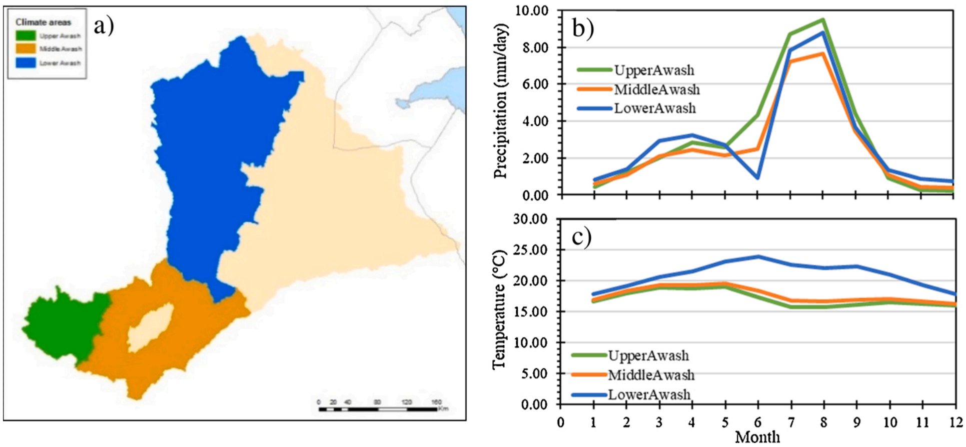

Fig. 2. a) Three Awash River catchment climate areas - Upper (green), Middle (orange) and Lower (blue). Light yellow is the area that drains into a desert area and/or does not contribute to the main river course b) monthly average precipitation for upper Awash, middle Awash and lower Awash between 1981 and 2016; c) monthly average temperature for upper Awash, middle Awash and lower Awash between 1981 and 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

model structure allowed it to simulate the in-stream Cl concentrations in dendritic stream networks (Gutchess et al., 2018). Within the INCA model, Cl is transferred through the catchment by individual processes operating across different land use classes and a multi-branched river network (Jin et al., 2011). Common sources of Cl include atmospheric deposition, road salting, effluent discharge from wastewater treatment plants and groundwater discharge(Gutchess et al., 2018; Kelly et al., 2008).

Hydrological inputs to INCA include daily time series of precipitation, temperature, hydrologically effective rainfall (HER) and soil moisture deficit (SMD). HER and SMD are estimated using the Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport (PERSiST) model, which is a conceptual, daily time-step, semi-distributed model designed primarily for use with the INCA models (Futter et al., 2014). PERSiST simulates water fluxes from precipitation through the terrestrial part of a catchment and into rivers and it allows a broad range of user-specified perceptual models of runoff generation in different climatic regions and landscape types (Futter et al., 2014). In PERSiST, the actual ET is calculated by using a similar approach to Penman's potential evapotranspiration (Durand, 2004). However, instead of using Penman potential ET as the baseline, a degree day evapotranspiration parameter is used, as described by Futter et al. (2014). Other input data to an INCA model requires river network topology, reach characteristics, sub-catchment areas and land uses.

Daily rainfall data was acquired from the Climate Hazards Group Infrared Precipitation with Stations v2.0 (CHIRPS) (Funk et al., 2015; Taye et al., 2018). CHIRPS is a global dataset of rainfall that blends satellite-based and gauge-based rainfall estimates with a 0.05° resolution. Daily temperature data were obtained from a network of local weather stations. Both precipitation and temperature were acquired for the time period between 1981 and 2016. Due to the extreme spatial variability of rainfall within the Awash River Basin, three main areas of homogeneous climate were identified in this study: Upper Awash, Middle Awash and Lower Awash (Fig. 2a). The average daily rainfall and temperature series were computed for each of the three areas between 1981 and 2016 (Fig. 2b and c), by creating a gridded dataset (10 × 10 km) of daily precipitation and temperature and computing the average of all the 10 × 10 km cells within each of the climate areas. Upper and middle Awash have similar monthly temperature, while lower Awash has significantly higher temperature throughout the year (Fig. 2b). For precipitation, three areas generally follow the pattern with wet seasons between June to September. The INCA hydrological input data (daily time series of HER and SMD) between 1981–2016 were then obtained by PERSiST for the Upper, Middle and Lower catchments.

To simulate river flow and Cl in INCA, the Awash River catchment was divided into 24 sub-catchments, shown in Fig. 1. The sub-catchment/reach boundaries were selected at confluences, effluent discharges, flow stations and water quality monitoring stations. Sub-catchments were delineated using a digital elevation model (DEM) in ArcGIS, which was obtained from the Shuttle Radar Topography Mission (SRTM) (Jarvis et al., 2008). SRTM is an international research effort to obtained DEMs on a near-global scale from 56 °S to 60 °N. The land use information was from the GlobCover Portal (Bontemps et al., 2009). GlobCover is an ESA (European Space Agency) initiative whose aim is to develop a service capable of delivering global composites and land cover maps using input

Table 1
A summary of the INCA reach and sub-catchment characteristics.

Reach ID	Sub-catchment area Km^2	Reach Length m	Land use (%) Arable	Grassland/ mixed	Forest	Water	Bare	Urban	Population #	Flow Station	Water Quality Station
1	935	30746	8	84	8	0	0	0	165119		
2	3565	52663	18	72	10	0	0	0	820511	1965-2012	
3	772	84255	19	66	10	0	1	3	1991568		
4	1473	59720	13	82	4	0	1	0	229943	1968-2014	
5	2561	85882	26	61	4	7	2	0	440405		2008-2013
6	2039	96319	7	83	5	0	5	0	540602		
7	1563	72798	0	83	8	3	7	0	198212		2004-2013
8	2998	42439	1	79	18	0	3	0	372767	1975-2009	2004-2013
9	2302	60144	0	74	23	0	3	0	309918		
10	2829	80097	1	74	18	0	7	0	181930	1972-2010	2004-2013
11	4318	78864	1	75	8	0	16	0	234357		
12	2685	132716	1	72	2	3	23	0	75877		2004-2013
13	4651	105260	2	63	5	0	30	0	332269		
14	6262	126622	1	63	9	0	27	0	437035		2004-2013
15	5551	88097	0	49	0	0	51	0	113692		
16	3401	51094	0	32	1	0	67	0	44286		2004-2013
17	884	59665	19	56	14	0	0	10	1457636		
18	1431	34486	47	44	7	1	0	0	383597		
19	845	134347	7	79	13	0	0	0	199819		
20	3017	124297	7	69	23	0	0	0	301241		
21	2142	87518	2	72	16	1	8	0	238638		
22	1701	183533	4	66	30	0	0	0	583313		
23	4427	217153	1	63	23	1	13	0	530968		
24	3791	28600	0	64	3	0	34	0	174401		

observations from the 300 m MERIS sensor on board the ENVISAT satellite mission. The datasets cover two periods: December 2004 - June 2006 and January–December 2009. The most updated dataset from 2009 was used in this study. The percentage of each of six land use classes (arable, grassland/mixed, forest, water, bare, urban), area, and reach length were also calculated for each sub-catchment (Table 1) in ArcGIS which were used as INCA inputs.

River discharge and water quality (Cl) data are available at several stations along the main Awash River managed by the Awash River Water Authority (Table 1). Daily flow data covers from 1960s up to 2014. At the end of the reach 5, the river goes to Koka dam. Water quality data were collected between twice or six times annually from 2004 to 2008 and at a monthly interval from 2009 to 2013. However, a few monthly samples were missing, which resulted in a small number of data available. Based on the availability of observed flow and water quality data, INCA-Cl model calibration was conducted from 2005 to 2014 for 10 years. We calibrated the model against river discharge data as well as the spatial and temporal patterns of river water Cl. INCA model computes the daily flows and Cl concentrations at all reaches along the river system and these values can be compared to observed data using r^2 and the Kling-Gupta efficiency (KGE) to assess the quality of the model (Gupta et al., 2009). The KGE combines the three components of Nash-Sutcliffe efficiency (NSE) of model errors (i.e., correlation, bias, ratio of variances or coefficients of variation) in a more balanced way and it has been widely used in hydrological model calibration in recent years (Gupta et al., 2009; Liu, 2020). We also adopted the same approach as previous studies (Gutchess et al., 2018; Jin et al., 2011) to select flow and Cl related parameters for calibration which include baseflow index, flow parameter a and b, groundwater residence time, direct runoff residence time and initial Cl concentration as well as soil water residence time and initial Cl concentration. The calibrated model has selected parameter set with the highest KGE values.

Main Cl inputs to the model include 1) atmospheric deposition; 2) groundwater discharge; and 3) domestic effluent discharge. For atmospheric deposition, Landtschoote (2017) collected eleven rainfall samples in Northern Ethiopia with chloride concentrations ranging between 0.196 mg/L and 1.548 mg/L (Landtschoote, 2017). An arithmetic-geometric average of 0.55 mg/L was used in the INCA model to represent the mean atmospheric Cl level. Groundwater Cl concentrations varied widely in the Awash River Basin (from 1 mg/L up to 1,000 mg/L) and areal groundwater quality map was developed by Nigussie and Getaneh for the basin (Nigussie and Getaneh, 2016). Thus, different groundwater Cl concentrations were assigned to each sub-catchment based on the groundwater quality map. Specifically, for sub-catchment 1, 2, 4, 5 and 6, groundwater Cl were set at 10 mg/L; for sub-catchment 7, 8, 16 and 24 groundwater Cl were set at 100 mg/L; for sub-catchment 9, 10 and 11 groundwater Cl were set at 250 mg/L; for sub-catchment 12 and 13, groundwater Cl were set at 800 mg/L; for sub-catchment 14, 15, 17, 18, 19, 20, 21, 22 and 23 groundwater Cl were set at 30 mg/L. Lastly, the domestic effluent discharge was calculated based on the population number, water usage and estimated urine Cl level for each sub-catchment.

2.3. Lake Beseka and INCA-Cl application

Lake Beseka is located within the Awash River Basin, central rift valley of Ethiopia at about 200 km southeast of the nation's capital city, Addis Ababa. Lake Beseka water is characterized by a Na-HCO_3-Cl type of water, which is alkaline and saline due to the interaction between the geothermal waters and silicate rocks and the concentration of soluble materials as a consequence of high evaporation rates (Ayenew, 2005; Furi et al., 2012). The similar hydrochemical signature of the groundwater system in the western part of the basin indicates that the groundwater inflow constitutes the major inflow to Lake Beseka in the form of hot springs. The other major component of the lake water is the recharge from adjacent irrigation fields of the sugar farmland (Ayenew, 2004; Kebede and Zewdu, 2019). The recent increase in irrigation recharge has resulted in the decreasing Cl^- concentration due to dilution over the past few decades.

With the expansion of Lake Beseka, it has the potential to join the Awash River in the near future, thereby salinizing the river water, impacting all downstream irrigation developments in the basin and the livelihood of the people depending on the water resources of the basin. In order to reduce the impact, some controlled/regulated discharge from Lake Beseka into the Awash River has been implemented. For example, the Ministry of Water, Irrigation and Electricity of Ethiopia (MoWIE) constructed 8 pumps to discharge lake water into the Awash River at a rate of up to 1.7 m^3/s starting in late 2000s and then the pumps had an unexpected operational issue (WWDSE, 2010). The MoWIE and Water Works Design and Supervision Enterprise (WWDSE) tried to drain the lake water to the Awash River at a rate of up to 10 m^3/s by gravity flow since the end of 2011.

The lack of official record of length and rate of discharge made it impossible to quantify the influence of Lake Beseka water on the Awash River. There would likely be some loss of water during the process. Therefore, a simple Cl mass balance was used to estimate the discharge from the lake using Cl concentrations at locations before the lake and after the lake as a first approximation to estimate the discharge of the lake water to the Awash River. Measured Cl data in the Awash River from 2010 to 2013 showed that the average Cl concentration was 19.6 mg/L and 37.3 mg/L at Reach 7 (before the lake) and Reach 8 (after the lake), respectively. The lake water had the average Cl concentration of 430.0 mg/L from 2010 to 2013. A mixing model (Chapra, 1996) was then used to calculate the percentage of lake water input to the Awash River. The lake water input calculated from Cl mass balance is estimated to be approximately 4.3 %. Given the average baseflow was about 45−50 m^3/s, the inflow from Lake Beseka could be approximately 2 m^3/s with Cl concentrations of 430.0 mg/L.

A one reach INCA model was set up for Lake Beseka. Similar to the Awash River INCA setup, reach characteristics, land uses, and hydrological input (only Middle Catchment) were obtained for the lake and surrounding catchment. The Lake Beseka model was calibrated from 2005 to 2014 using the observed Cl data from the lake. Climate change scenarios were run to understand the long-term change of the lake chemistry, data of which are also used as discharge and concentration input to the Awash River model with different discharge rates (e.g. 1 m^3/s, 2 m^3/s and 5 m^3/s) when assessing the impact to the river water from Lake Beseka in the future.

2.4. Climate change scenarios

In order to assess the impact of climate change to the Awash River watershed, the change factor method was used (Diaz-Nieto and Wilby, 2005). When using this method, atmospheric variables (precipitation and temperature) were analyzed to calculate changes predicted by climate models for the study area. The same changes were then applied to the input time series of the baseline climatic data from 1981 to 2016 to obtain resulting time series of altered climate for the future. In this study, we have adopted the change factors from Taye et al. (Taye et al., 2018), which used three climate models from the Coupled Models Inter-comparison Project phase 5 (CMIP5), three future periods (near future: 2006–2030; mid-future: 2031–2055 and far future: 2056–2080) and the RCP8.5 (representative concentration pathway 8.5) emission scenario (Taye et al., 2018). These three models (GFDL-CM3, MPI-ESM-MR and HadGEM2-AO) among the CMIP5 of 24 global climate models were chosen based on their ability to capture the historical precipitation characteristics in the Awash Basin (Taye et al., 2018). Change factors were estimated in a spatially distributed manner (i.e., over a regular grid - 0.05° x 0.05 °CHIRPS grid) and on a monthly scale. The grids were aggregated into Upper, Middle and Lower catchments when generating future climate data that were used as input for the INCA model to obtain predictions of flow and chloride concentrations under future climate change.

3. Results and discussions

3.1. Awash river INCA flow calibration results

The Awash River is strongly affected by the Inter-Tropical Convergence Zone (ITCZ) and shows clear seasonal pattern with high flows occurring from July to September and low flows during the rest of the year. At the upper catchment, peak flow could rise up to 400 m^3/s and the baseflow remains less than 10 m^3/s (Fig. 3). The magnitude of the peak flow does not change significantly as the river travels downstream, while the baseflow increases due to the discharge from groundwater, domestic effluent and Lake Beseka (Fig. 3).

INCA model was calibrated from 2005 to 2014 using observed daily mean flow at several flow stations within the Awash River Basin. Fig. 3 shows the comparison between observed and simulated daily flow at an upper reach (reach 4) and a middle reach (reach 10). Table 2 shows a summary of model performance statistics. The overall fit has r^2 values from 0.47 to 0.57 (Table 2). The goodness-of-fit indices of the model calibration which was calculated using the Kling-Gupta efficiency (KGE) ranges from 0.32 to 0.70 (Table 2). The INCA model generally reproduces observed flow dynamics quite well. For reach 10, flows are affected by Koka dam and unregulated Lake Beseka input to the Awash River so that the model simulation underperforms. Nonetheless, the model adequately captured the seasonal variations of the flow and the magnitude of the rising and falling limbs (Fig. 3).

3.2. Awash river salinity sources and INCA-Cl calibration results

In general, the Cl levels are largely controlled by mixing of low Cl rainfall and high Cl groundwater. The effluent discharge from domestic waste also contributed Cl to the river. This point source became more important during low flows than during high flows. The model simulation generally matches the observed seasonal variabilities of Cl concentrations, although in some cases, Cl concentrations are under-estimated or over-estimated (Fig. 4). There was generally a satisfactory fit of observed and simulated monthly Cl concentration and load at several monitoring stations on the main Awash River (Table 3). For monthly Cl concentration, r^2 and KGE range from 0.03 to 0.61 and -0.03 to 0.59, respectively. For monthly Cl load, r^2 and KGE range from 0.53 to 0.94 and 0.05 to 0.80, respectively. (Table 3). An example of mean monthly load is given in Fig. 5 at Dubti, the last reach of the Awash River (Reach 16). Previous studies indicate r^2 values greater than 0.5 is considered acceptable for model evaluation (Santhi et al., 2001; Van Liew et al.,

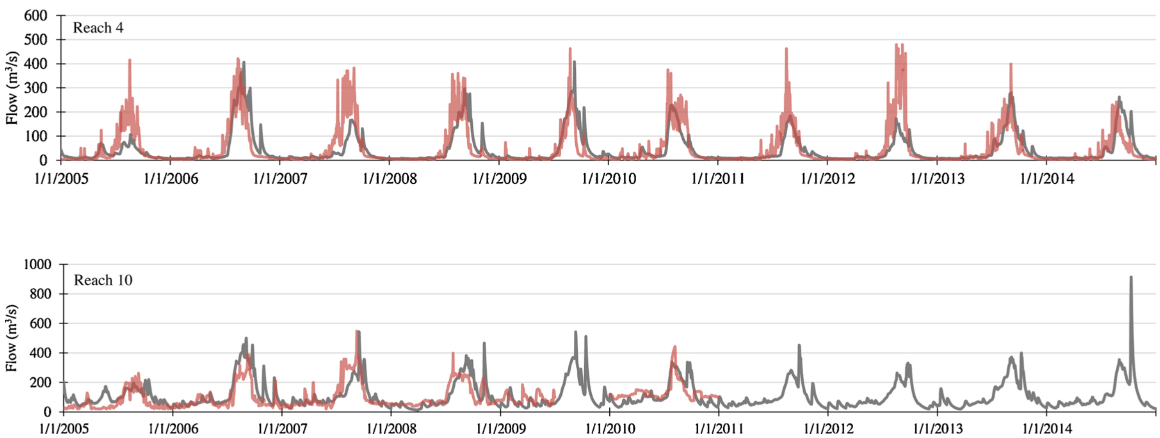

Fig. 3. Observed (red) daily flow and INCA simulated (grey) daily flow at reach 4 and reach 10 from 2005 to 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Goodness-of-fit statistical performance (r^2 and KGE: Kling-Gupta efficiency) (Gupta et al., 2009) showing the comparison between observed and simulated daily flow within the Awash River catchment.

Reach ID	Reach 2	Reach 4	Reach 8	Reach 10
r^2	0.57	0.55	0.58	0.47
KGE	0.32	0.69	0.70	0.66

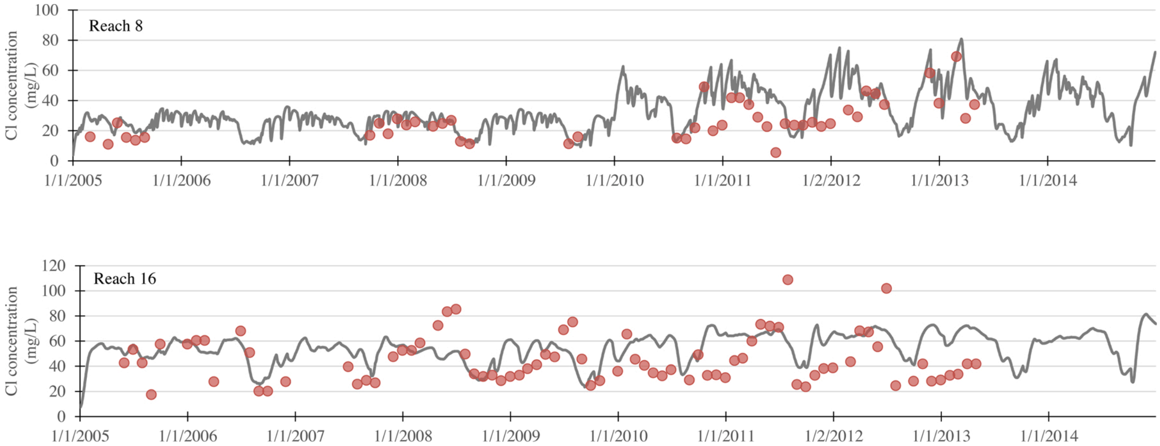

Fig. 4. Times series of Cl concentrations at reach 8 and reach 16. Solid points are observed Cl concentrations and grey lines show INCA modeled daily Cl values.

Table 3
Statistical performance summary (r^2 and KGE) showing the comparison between observed and simulated monthly Cl concentration and load within the Awash River catchment.

Reach ID	Concentration		load	
	r^2	KGE	r^2	KGE
Reach 5	0.03	−0.03	0.53	0.70
Reach 7	0.35	0.41	0.88	0.80
Reach 8	0.61	0.59	0.93	0.76
Reach 10	0.55	0.45	0.60	0.73
Reach 12	0.44	0.42	0.81	0.68
Reach 14	0.54	0.36	0.58	0.05
Reach 16	0.45	0.50	0.84	0.60

2003). Given these statistics' guideline and the process-based nature of the INCA model which accounted for various natural and anthropogenic sources of salinity, the calibrated model was adequate to capture and represent the dominating processes in the Awash River Basin.

As the Awash River flows downstream, Cl concentrations varied greatly which reflects the main controls from groundwater discharge and point source pollution (Figs. 6 and 7). The spatial variation of Cl concentrations in groundwater (from a few mg/L up to 1,000 mg/L) (Nigussie and Getaneh, 2016) manifested itself in the spatial pattern of Cl in the Awash River. For example, the observed mean Cl concentrations increased from 14 mg/L at Reach 5–45 mg/L at Reach 16 (Fig. 6). Furthermore, at the middle reach (e.g. Reach 10), Cl concentrations reached its highest level due to the impact from the discharge of high Cl concentration water from Lake Beseka. The spatial changes in Cl along the Awash River was reproduced by INCA-Cl which gave reasonable estimates of Cl concentrations, although the observed Cl tend to have larger variance comparing to the modeled values (Fig. 6).

Along the main Awash River, the annual mean Cl loads during the calibration period ranged from 1.5×10^6 to 2.0×10^8 kg (Fig. 7a). The area-normalized annual loads varied between 1.5×10^3 and 6.6×10^3 kg/km^2. The annual Cl loads gradually increased at the upper reaches (reach 1–7), while the significant rise in annual Cl loads took place at the middle reaches (reach 8, 9 and 10) due to the contribution of Lake Beseka discharge and increased groundwater discharge (Fig. 7a). After that, the annual Cl loads remained at approximately 2.0×10^8 kg in the rest of the water course (Fig. 7a). This clearly illustrates that the addition of Cl load at the middle reaches have significant impact to the downstream river course by salinizing the river water, impacting downstream irrigation developments and the livelihood of the people who rely on the river water as their drinking water supply. When examining different sources of Cl for each INCA reach along the Awash River, upstream reaches (e.g. reach 1, 2 and 3) were dominated with groundwater discharge, while the downstream reaches' (e.g. reach 14, 15 and 16) primary Cl load came from the prior reach (Fig. 7b). The

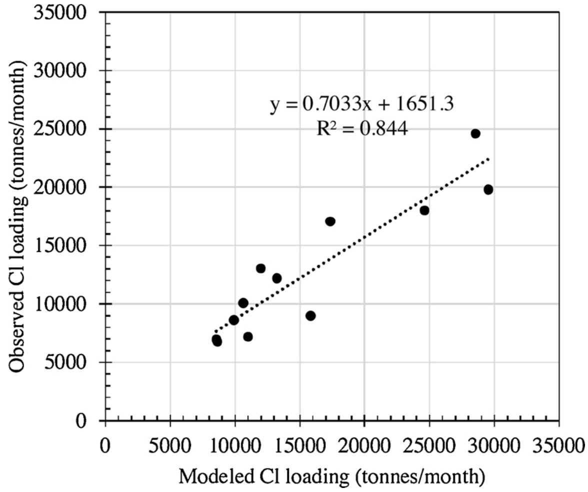

Fig. 5. INCA modeled and observed monthly Cl loads at Dubti, the last reach of the Awash River (Reach 16).

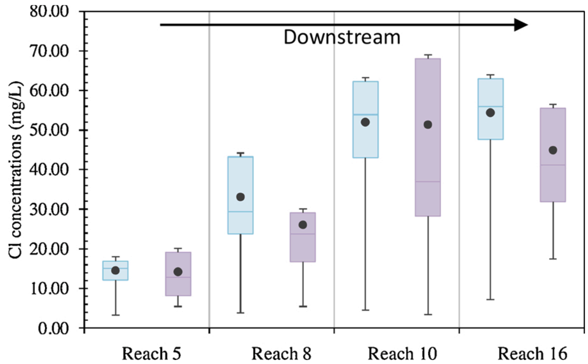

Fig. 6. Comparison of modeled (blue) and observed (purple) Cl concentrations at four reaches along the Awash River from 2005 to 2014. The solid black dots show the mean concentrations of Cl at each location. The top of upper whisker and the bottom of the lower whisker are the maximum value and minimum value. The line through the box is the median value. The top of the box and bottom of the box are the 75th percentile and 25th percentile, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

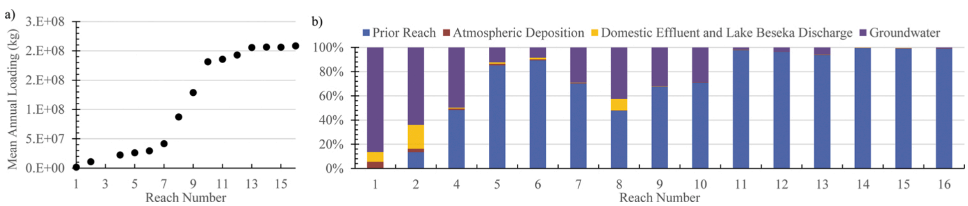

Fig. 7. a) Modeled annual mean Cl loads during the calibration period (2005-2014) at each INCA reach along the main Awash River; b) Percentages of contributions from each main source to annual Cl load at each INCA reach along the main Awash River.

contribution from the domestic effluent to annual Cl load is apparent in reach 2 where the city of Addis Ababa is located (Fig. 7b). For reach 8 where Lake Beseka is discharged into, Lake water and domestic effluent consists almost 10 % of annual Cl load in the river. For the entire catchment, 2.7 % of annual Cl load is estimated to be from atmospheric deposition and 6.1 % of annual Cl load is from point source pollution including domestic effluent and Lake Beseka discharge. The rest comes from groundwater discharge, which contributes a large portion of Cl load.

3.3. Lake Beseka model results

The chemistry of Lake Beseka water has been constantly changing and leading to the reduction of Cl concentration. This variation is related to increase in the inflow due to over-irrigation in the lake catchment. The Cl concentration in the lake water was about 600 mg/

L in 2005 and declined almost 1/3–400 mg/L in 2013 (Fig. 8). Fig. 8 illustrates that INCA model was able to simulate the dilution of chloride concentration and the long-term declining trend in the lake water from 2005 to 2014 when comparing the observed monthly Cl concentrations from the lake with the INCA simulated values. The little variation of daily Cl concentration is due to the long residence time of Lake Beseka. Based on the length of the lake (12 km) and the average discharge of the lake (2 m^3/s), the lake water residence time which is equal to the lake volume divided by discharge, is calculated to be approximately 15 years. The residence time is important as it controls the degree of mixing in the lake and thereby the salinity dynamics. This then controls how long salinity levels will change and more importantly how long salinity levels might take to fall to acceptable concentrations. The major issue of concern with Lake Beseka is that the lake levels are still rising and at some point the lake flow will have to be directed into the Awash River. As the lake water is saline, there is a serious concern that the impacts on the Awash downstream might be severe causing the restricted use of water for both drinking supplies and irrigation. This would create some major issues for the management of the Awash river system.

3.4. Climate change impact to the Awash River and Lake Beseka

Three time periods (near future, mid-future and far future) of climate change impact were analyzed using calibrated Awash River and Lake Beseka models. Monthly mean temperature is projected to increase 0.3–1.0 °C, 0.8–1.5 °C, and 1.3–2.2 °C in the near future, mid-future and far future, respectively, compared to baseline condition (1981–2016). Summer months (June to September) tend to have greater increases in temperature than the rest of the year. Future changes of precipitation vary greatly among different months. Monthly mean precipitation is projected to change from -0.3 to 1.0 mm/day, -0.9 to1.3 mm/day, −1.0–1.7 mm/day in the near future, mid-future and far future, respectively, compared to baseline condition (1981–2016). For the Awash River, without Lake water input, high flows (July to October) at the last reach would be reduced in all three future periods up to 25 % compared to the baseline period (Fig. 9). The flows were projected to continue to decrease from near future to far future. This is due to combined effects from the future changes of temperature and precipitation patterns. During the low flow periods (January-June and November to December), there are mixed results with the increases and decreases in flows. In general, January, February, November and December showed increasing trends into the future, while March to June likely have decreasing flows. The decreasing trend during the low flow periods could likely worsen the issues of water shortage and water security for domestic and agricultural consumptions.

Changes in future Cl concentration in the Awash River are less significant than the flow without the influence from Lake Beseka. The increases are up to 11 % mixed with less than 5 % decreases in Cl at the final reach of the Awash River (Fig. 9). The changing Cl concentrations mainly reflect the future rainfall and flow shifts in the river system.

For Beseka Lake, the Cl concentration level was measured at approximately 400 mg/L in 2013, which fell in the severe restriction of the irrigation water use (>355 mg/L) (Nigussie and Getaneh, 2016). Models using future climate projections indicate the current declining trend would continue into the future. Long term Lake water quality could be largely impacted by extremely heavy rainfall events which would dilute the lake overall iconic concentrations including Cl. Under the current modeling circumstance and projected future climate, the mean Cl of the lake water will likely reach 250 mg/L, which is the Ethiopia Drinking Water Quality Requirement and the National Secondary Drinking Water Regulations from Environmental Protection Agency in the USA, at the year of 2025 (Fig. 10). This reduction of Cl would potentially lessen the irrigation water restriction from severe to slight-moderate (Cl concentrations between 142−355 mg/L) (Nigussie and Getaneh, 2016).

3.5. Combined impact to the Awash River from climate change and Lake Beseka discharge

Due to the growing concern of the expansion of Lake Beseka and its negative impact to the Awash River water and the downstream irrigation developments, regulating Lake Beseka water and manually transferring it into the Awash River at a controlled rate was proposed help mitigate the issue in the last decade (Teffera et al., 2018). If this continues at the current rate (2 m^3/s) into the future, Cl concentration would rise to a much higher level with nearly 20 % increases than the baseline condition at the last reach (Fig. 11). The changes between baseline and future scenarios are greater during low flows than that during high flows due to less dilution. In addition, it is worth noting that the impact is much more significant to the area immediate downstream from Lake Beseka. For example, at reach 8, immediately after Lake Beseka discharge, Cl concentrations could be elevated to about 50 mg/L, which is approximately 70 % increase in the low flow months comparing to the baseline condition (Fig. 11). Therefore, the human activities (e.g. irrigation) are clearly going to affect the Awash River water quality by discharging Lake Beseka water.

Different discharge rates (e.g. 1 m^3/s, 2 m^3/s and 5 m^3/s) from Lake Beseka were also explored to assess its impact to the Awash River water quality. Less inflow from Lake Beseka to the Awash River result in less increases in Cl concentrations along the Awash

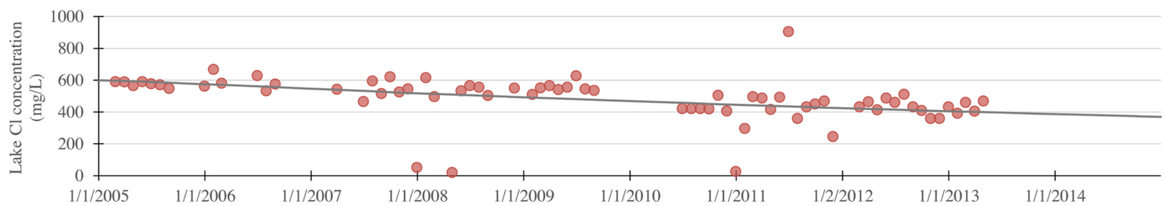

Fig. 8. Lake Beseka Cl calibration from 2005 to 2014. Solid points are observed monthly Cl concentrations in the lake and the grey line shows the INCA modeled daily Cl concentration.

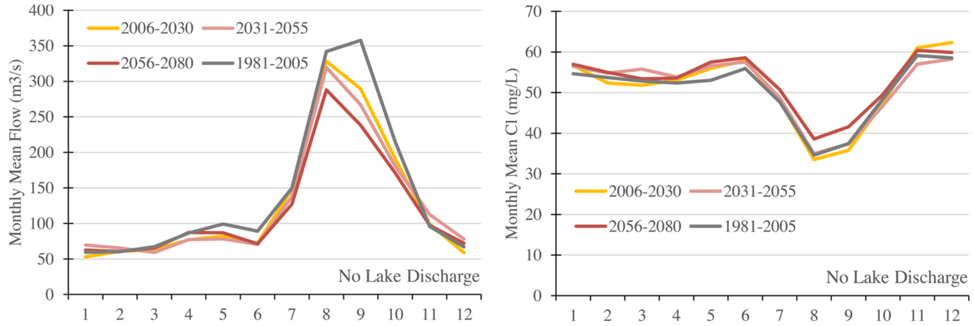

Fig. 9. Monthly mean flow and Cl concentration changes in the near future, mid-future and far future at the last reach of River Awash.

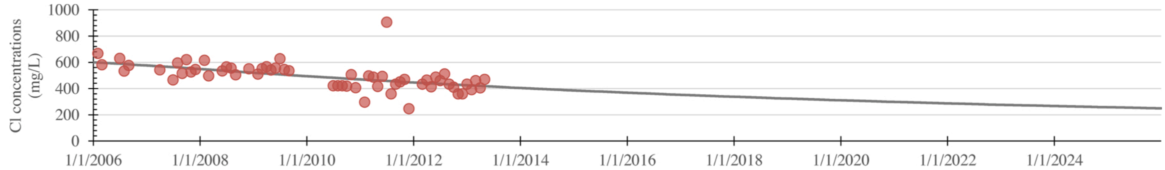

Fig. 10. Cl changes in Lake Beseka into the near future (2006-2025). The grey line is INCA simulated Cl concentration and red dots are observed Cl concentration in Lake Beseka. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

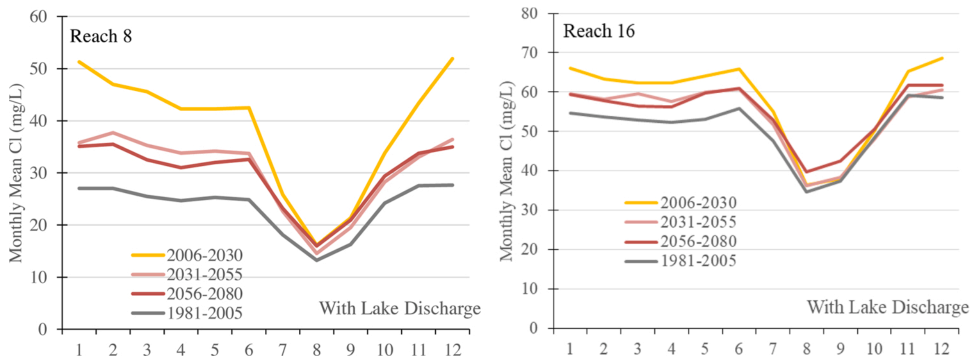

Fig. 11. Variation of monthly Cl concentrations in the Awash River at the mid-section (reach 8) and the bottom-section (reach 16).

River. For example, with the discharge rate of 1 m^3/s from the lake, Cl concentrations in the Awash River are expected to increase about 40 % and 10 % compared to the baseline period in the near future (2006–2030) at reach 8 and reach 16, respectively. With much higher discharge rate from Lake Beseka (5 m^3/s), Cl concentrations would rise substantially at reach 8 which is immediately downstream from the lake. Nearly 200 % increase at reach 8 is possible during low flows in the near future (Fig. 12). The changes however become less significant into far future (2056–2080) as the Cl concentration in Lake Beseka continue to decline over time and its impact would become less (Fig. 12). As Lake Beseka water contains high concentration of Cl, discharge into the Awash River would inevitably increase the Cl concentrations in the Awash River. Long term uses of high salinity water for irrigation would leave salt behind in the soil and lead to soil salinization (Dinka, 2017).

3.6. Model uncertainty and study limitations

A catchment modeling study inevitably involves uncertainty as the models only represent simplifications of reality and would never exactly reproduce flow and water quality dynamics (Jakeman et al., 1993; Wade et al., 2008; Wilby, 2005). However it is possible to create models that capture the long-term trends and main hydrologic/hydrochemical dynamics with the awareness of model uncertainty.

It is recognized that this INCA modeling study has a number of sources of uncertainty that are associated with future projections of flow and Cl concentrations. One area of the uncertainty comes from the choices of the climate change scenarios. This work used three climate models from the CMIP5 ensemble for the region that produced good predications of historical flow under RCP8.5 scenario (worse-case scenario) (Taye et al., 2018). Thus, it is important to be informed that the outcomes of the future flow and Cl

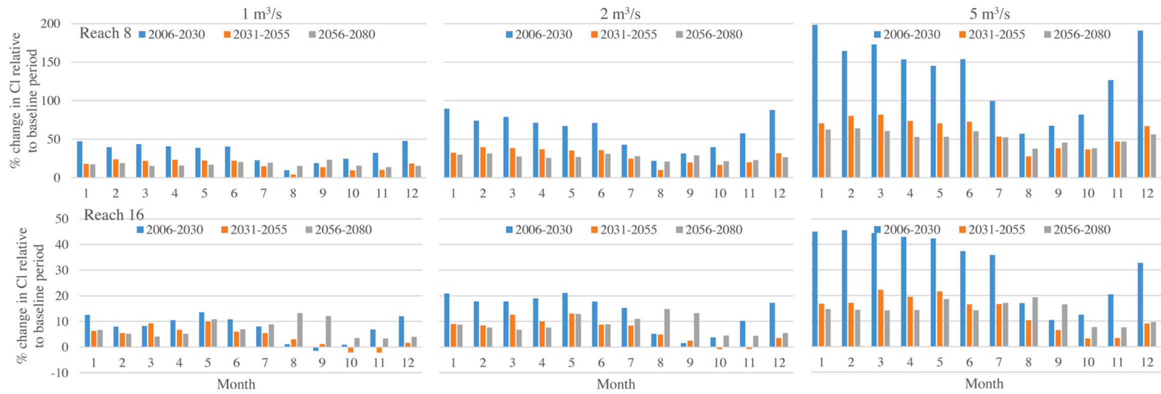

Fig. 12. The impact from Lake Beseka of different discharge rates (e.g. 1 m^3/s, 2 m^3/s and 5 m^3/s) on the Cl concentrations in the Awash River water at reach 8 (top panel) and reach 16 (bottom panel).

concentrations from this study do not represent the full range of future projections.

Another area of uncertainty is associated with input and parametrization of INCA modeling. For example, an arithmetic-geometric average of Cl concentrations from eleven rainfall samples in northern Ethiopia was used as an input in the model for the entire Awash basin (Landtschoote, 2017). The spatial variations of Cl pattern may affect the model performance. Another INCA input of uncertainty is the domestic effluent discharge which was calculated based on human population in each sub-catchment. The effluent discharge estimates did not account for population change over time. As the domestic effluent only contributes a small percentage of Cl to the annual load (<1.5 %) in the study area except reach 1 and 2, the population change during the modelling period is not anticipated to change the results significantly. In addition, a fixed groundwater Cl concentration for each sub-catchment was applied in the model because rapid and drastic groundwater Cl concentration changes across the basin were not expected. Given the large portion of annual Cl load comes from groundwater discharge, a good management and monitoring plan for the regional groundwater resources would be important. While models are helpful to project future changes in water quality, the accuracy of input parameter values and model output should be viewed cautiously.

In this study, a limited number of flow stations and infrequent water quality sampling pose another uncertainty. As model calibration was conducted by comparing observed flow and Cl concentration with simulated values, uncertainty increases with fewer flow and water quality analysis. To reduce this uncertainty, we focused our calibration effort on the sensitive parameters (e.g. flow velocity parameters, groundwater residence time, baseflow index, direct runoff residence time and initial Cl concentration as well as soil water residence time and initial Cl concentration), that were identified by previous INCA studies (Dean et al., 2009; Gutchess et al., 2018; Jin et al., 2011; McIntyre et al., 2005; Wade et al., 2001; Wilby, 2005) and carefully calibrated these parameters by comparing the simulated results to observed values and achieving highest r^2 and KGE. As there is no flow station in the lower Awash River Basin, great care must be taken in interpreting the results of flows in that region. Regarding the infrequent water quality sampling, it is common to have good record of daily flow measurement, while water quality analyses are infrequent (e.g. monthly or quarterly). Because of that, we chose not to divide the Cl dataset into two for model calibration and validation which would cause too few data for each process. Although no validation was performed, the available Cl data were used to calibrate the model and ensure the model capture the main dynamics of the river system. Limited data availability should not hinder the use of the models as the process-based models still remain as the best available approach of understanding the catchment process to the possible future conditions.

This is the first study to assess the sources of the Awash river salinity and analyze the impact from climate change to the river water quality. Comprehensive water quality monitoring program in the Awash River Basin is recommended as it will greatly support modeling applications that provide valuable information for catchment managers and policy makers. Future monitoring program should not only include flow measurement at the lower Awash River Basin but also frequent water quality sampling from both the rivers and groundwater across the basin.

4. Conclusions

Water quality management is a critical component of water resources. Water quality deterioration from point and non-point sources is of great concern in the Awash River Basin due to the diverse polluting activities and its economic significance. Sources of salinity come from both natural processes (high saline Lake Beseka and groundwater) and anthropogenic activities (effluent discharge and Lake Beseka discharge). This paper uses a multi-branched Integrated Catchment Model that incorporates major physical processes to simulate Cl concentration in the Awash River and Lake Beseka. This is the first study that has tried to integrate the whole Awash River system and Lake Beseka. Results show that under climate change, peak flow would reduce in three future periods up to 25 % comparing with the baseline period. Mixed results of increasing and decreasing flows are projected during low flow months (January-June and November to December), which may reduce clean water availability. As for Cl, without considering the discharge from Lake Beseka, changes in Cl concentrations are insignificant and mostly reflect the flow changes. However, with high discharge rates from Lake Beseka, Cl concentration could rise as much as nearly 200 % in the near future in the Awash River water immediately downstream from the lake during low flow conditions. The modeling results clearly showed the impact of the human interference and climate change to the Awash River. The water quality in the Awash River will continue to be affected by both natural process and anthropogenic activities. While modeling study provides insights into future conditions that is valuable for planners and local stakeholders to support strategic decision making, continued water quality monitoring in both the Awash River and Lake Beseka with integrated basin-wide water management practice is essential for future water resources management.

Author statement

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Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100865.

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