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Spatial and Seasonal Water Quality and Heavy Metal Pollution for Irrigation Use in Awash River, Ethiopia

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Abstract: Irrigation water quality impacts the agro-ecosystem, human health, and the overall well-being of the environment. The purpose of this study was to investigate upstream municipal and industrial pollution impacts on irrigated farming and ecosystem health. The suitability indices and Heavy Metal Pollution Index methods have been used to identify the contamination extent and corresponding spatial and seasonal variability. Samples were collected twice per annum, i.e., during the low-flow season and high-flow season (rainy season) in the 2022/23 year. Results showed that during the low-flow season, the salinity hazard was 0.7 dS/m to 2.5 dS/m and medium to high. Sodicity hazards were obtained below <10 for the low-flow season, and for the rainy season, medium (16.63), high (18–26), and very high (>26). The toxic level of chloride for low-flow season showed slight to moderate at 3.6 mg/L and 6.07 mg/L, and toxicity was severe at Deho (14.6 mg/L), slight to moderate at Ambash (4 mg/L), Ertaale Lake (5 mg/L), and Gewanie (4.6 mg/L) in high-flow seasons. No heavy metal contamination was observed for low-flow periods except at Werer Research, which had a Heavy Metal Pollution Index (HPI) > 100. But, during the rainy season, Kesem Dam, Sedi Weir, WARC Pumping, WARC Offtake, and Ambash had a HPI > 100, which implied contamination by metals. Cadmium (Cd) was at moderate to ecological risk at low flow in sites Kesem factory, WARC Offtake, Ertaale, Meteka, and Gewanie, whereas Sedi Weir (Cd and Hg) and WARC Offtake (Cd) were at moderate risk during high flow. To conclude, metal pollution is a serious concern that needs upstream quality monitoring.

Keywords: ecological risk index; heavy metal pollution; irrigation water quality; metal index; salinity hazard; sodium hazard

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1. Introduction

Human activities, such as farming, irrigation, damming rivers, and aquifer extraction, have an impact on watersheds and river systems [1]. These interventions result in the depletion of natural resources and modifications to ecosystem functions [2]. Furthermore, agriculture is the earliest form of human activity that has been used to produce food for consumption [3,4]. Nevertheless, the population's rapid expansion has led to a situation where soil fertility is being reduced, water quality is declining, and ecosystem function is being impacted [5]. In a similar manner, some irrigation waters can directly harm plants, while others harm the structure of the soil [6,7]. Large-scale irrigation project development has improved global food security, especially in dry regions, but it has also been linked to issues with declining soil and water quality [8].

Awash Basin is the most developed basin in Ethiopia due to the availability of land suitable for agriculture, water resources that can be easily tapped, and its strategic location [9]. Furthermore, many of the big agro-industries and highly populated cities and towns in the country are found inside the Awash River Basin [8]. Hence, this basin is the most utilized river basin in Ethiopia, with a number of small-, medium-, and large-scale irrigation schemes (e.g., Fental–Tibila, Metahara, Kesem, Amibara, and Gewan) with a land potential of 200,000 ha of farmland [10].

However, inappropriate irrigation practices and poor-quality irrigation water resulted in the development of salt affected soil, a decline in production, a degradation of natural habitats and ecosystems, and abandoned agricultural lands [1,11,12]. In addition, the mismanagement of irrigation water, in the absence of a complementary drainage system, gave rise to waterlogging, the salinization of productive areas, and considerable losses in crop yields [13]. Thus, the use of poor-quality water for irrigation can create problems like toxicity, poor water infiltration, the degradation of soil's physical properties, and other problems that lead to a reduction in crop production [4,14,15]. Even good-quality irrigation water with an electrical conductivity (ECw) of 0.15 dS m-1 adds one ton/ha of soil after an application of 1 m depth of water [4,16,17]. Since potential crop yield reductions are expected from the use of saline water, the regular monitoring of irrigation water quality needs to be undertaken [18,19]. On the other hand, soils that are not naturally salt-affected soils can also experience high salt accumulation due to unsustainable management practices, including the use of low-quality irrigation water, inadequate irrigation methods, poor drainage, the removal of deep-rooted vegetation resulting in raised water table, the mismanagement of agricultural soil changes, and fertilizer use [17]. In addition, ecosystem change included climate change (affecting water supply and timing of flows), land use change (expanding agriculture increases water demand), and demographic change (growing population increases water demand), urbanization wastewater, and industrial wastewater [15,20].

Recently, the accumulation of toxic metals in irrigated soils and the discharge of wastewater into the river basin concerns the impact of the agro-ecosystem, human health, and environmental pollution [21]. Therefore, a water quality index is an indicator of the quality of water obtained by aggregating several water quality measurements into one number [18]. These assess changes in the quality of the water resource, identifying water quality problems for which special studies are needed and evaluating the performance of pollution control programs [15,16].

For this particular study, water quality was assessed based on its suitability standards and indices for irrigation use. Salinity is the most important criterion for evaluating the quality of irrigation water because of the potential crop yield reductions [14,22,23]. Furthermore, heavy metal pollution of irrigation water has become a serious environmental problem, mainly in upper Awash, with high industrialization and rapid growth leading to the destruction of the balance of the ecosystem [21,24]. At the same time, it enters the human body through the food chain and other channels and accumulates in the human body, endangering human health [25]. Therefore, heavy metals (boron, arsenic, copper, chromium, lead, zinc, manganese, mercury and nickel) need to be assessed for their degree of pollution in the basin using the standard pollution index and hazard classification [20,26].

2. Materials and Methods

2.1. Study Area Description

The Awash River Basin is situated between 7°53′42″ and 12°07′20″ north latitude and 37°56′56″ and 43°17′04″ east longitude. It is bordered by the Danakil, Abbay, Omo-Gibe, and Rift Valley lakes, and Wabi Shebele Basin, as well as the Republic of Djibouti. The river originates near Ginchi in the central highlands of Ethiopia and flows northeast through the northern section of the Rift Valley, eventually discharging into Lake Abbe near the Djibouti border, covering a distance of approximately 1200 km. The basin has a total catchment area of about 115,906 square kilometers (Figure 1). The Awash River Basin is the only region in Ethiopia with extensive water resource development and offers the best potential for large-scale agricultural expansion, with an irrigable land potential of 206,000 hectares and a mean annual river flow of 4.9 billion cubic meters (BCM) [10].

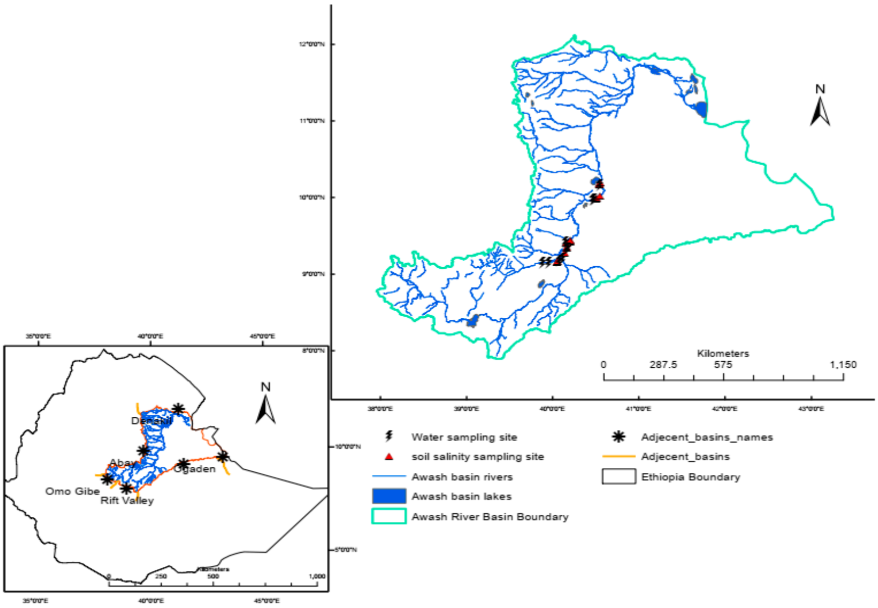

Figure 1. Study area and sampling locations.

2.2. Sampling Design

Water sampling and collection were conducted twice a year: (i) during the middle of the dry season and (ii) during the middle of the main rainy season. Irrigation water samples were collected using two-liter polyethylene bottles, which were acid-washed and rinsed prior to use. Sampling was carried out at 10 locations along the river course and other water bodies within the basin, including dams, hot springs, and lakes. To ensure representative sampling, a total of 20 water samples were collected using the grab method, combining multiple sub-samples taken at 5 min intervals. At each sampling site, two-liter acid-washed polyethylene bottles were used to collect irrigation water samples.

2.3. Analysis of Water Quality Parameters

2.3.1. Measurement of Physico-Chemical Parameters

The collected water samples were subjected to detailed laboratory analysis to evaluate a range of physico-chemical parameters. These included pH, electrical conductivity (EC), concentrations of dissolved cations (calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+})), anions (bicarbonate (HCO_3^{-}), carbonate (CO_3^{2-}), chloride (Cl^{-}), sulfate (SO_4^{2-}), and nitrate (NO_3^{-})), as well as alkalinity. Based on these measurements, key irrigation water quality indices, such as the sodium adsorption ratio (SAR) and residual sodium carbonate (RSC), were calculated. The pH of the water samples was measured using a digital pH meter, while the electrical conductivity (ECw) was determined using a conductivity meter [27]. The pH of the water samples was measured using a digital pH meter, while electrical conductivity (ECw) was determined using a conductivity meter. These measurements provided insights into the water's acidity/alkalinity and salinity levels, respectively. Alkalinity, which reflects the concentration of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, was measured within 12 to 24 h after sample collection. This was achieved by titrating the samples with a standard acid solution until a pH of 4.5 was reached. Chloride (Cl^-) concentration was quantified using the silver nitrate titrimetric method, which involves the reaction of chloride ions with silver nitrate to form a precipitate. Sulfate (SO_4^{2-}) concentration was assessed using either the barium sulfate turbidimetric method or the gravimetric method, depending on the laboratory setup [4,27]. Nitrate (NO_3^-) concentration was determined following the standardized procedures outlined in the United Nations Food and Agricultural Organization (FAO) Irrigation and Drainage Report 29 Rev 1.

This method ensures the accurate and consistent measurement of nitrate levels, which is critical for assessing water suitability for irrigation. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions were detected using an atomic absorption spectrophotometer (AAS), which provides precise measurements of these cations. Sodium (Na^+) and potassium (K^+) ions were evaluated using a flame photometer, which measures the intensity of light emitted by these elements when excited in a flame. Total dissolved salts (TDSs) were determined by summing the concentrations of all individual ions measured in the water samples. For solutions with an EC range of 0.1 to 5.0 mmhos/cm, TDS (in mg/L or ppm) was estimated by multiplying the EC value (in mmhos/cm) by a conversion factor of 640 [17,28].

The sodium adsorption ratio (SAR) was calculated using Equation (1). SAR is a critical parameter for evaluating the sodium hazard in irrigation water and is calculated as follows: Here, the concentrations of sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) are expressed in milliequivalents per liter (meq/L). The SAR value indicates the relative proportion of sodium ions to calcium and magnesium ions in the water, which is essential for assessing its suitability for irrigation [4]. The residual sodium carbonate (RSC) was calculated using Equation (2). RSC is a measure of the excess carbonate and bicarbonate ions over calcium and magnesium ions and is computed as follows: Here, the concentrations of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) are expressed in milliequivalents per liter (meq/L). RSC is used to assess the potential for sodium accumulation in soils, which can affect soil structure and crop growth [27]. By analyzing these parameters and computing SAR and RSC, this study provides a comprehensive evaluation of the water quality in the Awash River Basin, particularly for its suitability for irrigation and agricultural purposes.

$$SAR = \frac{\left[Na^{+}\right]}{\left(Ca^{2+} + Mg^{2+}\right)^{0.5}} \tag{1}$$

$$RSC = \left(HCO_3^{-} + CO_2^{3}\right) - \left(Ca^{2-} + Mg^{2+}\right) \tag{2}$$

Finally, the quality and suitability of irrigation water were evaluated based on the analyzed parameters. The classification of water into various appropriateness categories was conducted using the standards established by the US Salinity Laboratory Staff, which are widely adopted by many countries as a benchmark for assessing irrigation water quality. These standards provide a framework for determining the suitability of water for different uses. It is important to note that Ethiopia does not have its own specific standards for irrigation water quality suitability and hazard limits. Therefore, the assessment relied on the outputs of the analysis and the US Salinity Laboratory Staff's guidelines to classify the water into appropriate categories [27].

2.3.2. Irrigation Water Quality Indices

The quality of water for various applications, such as human and livestock consumption, crop irrigation, and other uses, is determined by the concentration and composition of soluble salts present in it [27]. As a result, water quality is a critical factor in the sustainable utilization of water for irrigated agriculture, especially in regions where salinity is expected to become a concern [4]. Key challenges associated with irrigation water include salinity, sodicity, and ion toxicity. To assess water quality for irrigation, essential parameters such as water salinity (measured by electrical conductivity, EC), sodium hazard (evaluated through the sodium adsorption ratio, SAR), residual sodium carbonates (RSCs), and ion toxicity are considered. Additionally, plant toxicity related to boron and chloride levels is also taken into account, as highlighted in [4,22,27,28].

Salinity levels are a primary concern in most irrigation systems, as excessive salts can adversely affect both soil structure and crop productivity [29]. Additionally, irrigation water often contains various trace elements that may restrict its suitability for agricultural use [30]. Assessing irrigation water quality and selecting appropriate management strategies involve evaluating multiple factors, with salinity risk being a key consideration [28]. To classify irrigation water quality, parameters such as electrical conductivity (EC), the sodium adsorption ratio (SAR), residual sodium carbonate (RSC), pH, chloride, hardness, and alkalinity were evaluated using the standards established by the US Salinity Laboratory (USSL) [4,18,27].

A significant issue arises when irrigation water contains high salt concentrations, particularly due to the impact of sodium on soil properties, which is referred to as the sodium hazard. The sodium adsorption ratio (SAR) is a widely used indicator to quantify the sodium hazard [31]. SAR is calculated based on the ratio of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in the water, as outlined in [27]. This metric helps determine the potential for sodium-induced soil degradation and guides the selection of appropriate irrigation practices.

2.3.3. Heavy Metal Analysis Indices

The concentrations of heavy metals (Cr, Cd, Zn, Fe, Pb, As, Mn, Cu, Hg, Ni, Co, and B) in the water samples were measured using an Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES). To assess the potential risks associated with heavy metal contamination, several pollution indices were employed, including the Heavy Metal Pollution Index (HPI) Equation (3), the metal index (MI) Equation (4), and the Ecological Risk Index (ER) and Risk Index (RI) Equation (5) [32,33]. These indices provide a comprehensive evaluation of the environmental and ecological risks posed by heavy metals in the water.

$$HPI = \sum\nolimits_{n}^{i=0} \left(\frac{W_i Q_i}{W_i} \right) \tag{3}$$

$$MI = \sum_{n}^{i=0} \left(\frac{C_i}{MAC_i} \right) \tag{4}$$

$$RI = \sum\nolimits_{1}^{n} ER_i, \quad ER_i = T_i \times \left(\frac{C_i}{Cb_i} \right) \tag{5}$$

where HPI: Heavy Metal Pollution Index, W_i Q_i: weighted average heavy metal concentration, W_i: concentration factor MI: single metal pollution index, C_i: concentration of metal, MAC_i: maximum allowable metal concentration, RI: Ecological Risk Index, ER_i: ecological pollution index for heavy metal, i, and T_i is the toxic response coefficient for the metal i.

3. Results

3.1. Irrigation Water Quality (IWQ)

3.1.1. Salinity Hazard and Salinity Class

This study revealed that the salinity status, classes, and hazards of irrigation water in the Middle Awash Basin ranged from C2 (medium salinity hazard) to C3 (high salinity hazard) during both the low-flow and high-flow seasons, as illustrated in Figures 2–4.

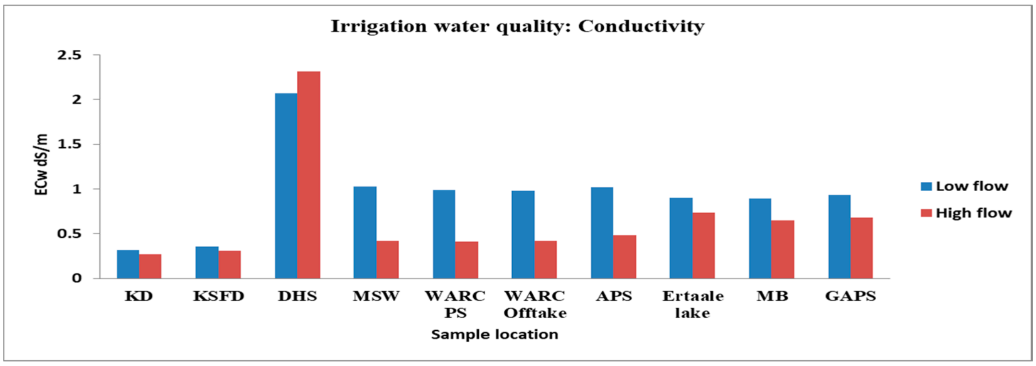

Figure 2. Irrigation water conductivity at middle Awash Basin for low_flow and high_flow season 2022/23.

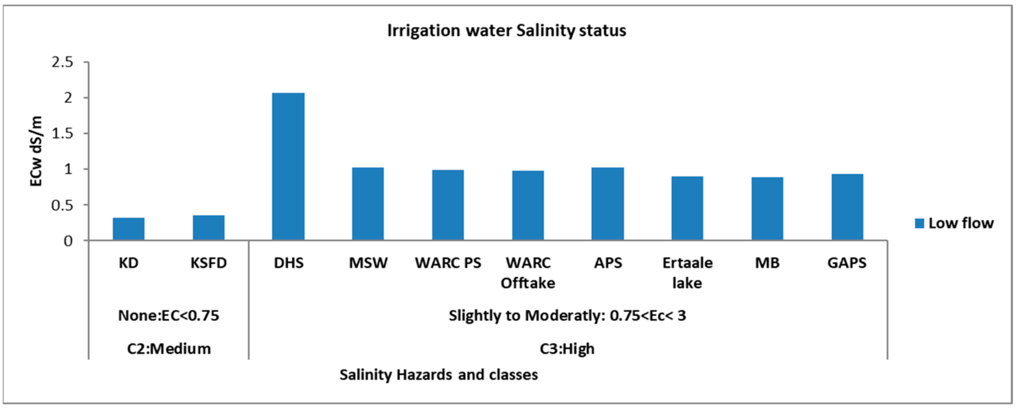

Figure 3. Salinity classes and hazards of irrigation water at middle Awash Basin for low-flow season 2022/23.

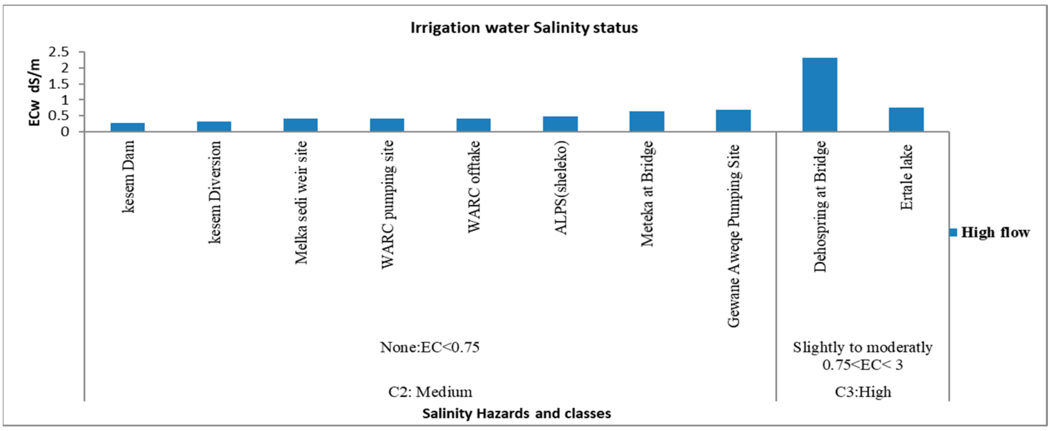

Figure 4. Salinity classes and hazards of irrigation water at middle Awash Basin for high-flow season 2022/23.

During the low-flow season, measurements at Kesem Dam (0.32 dS/m) and Kesem Sugar Factory Diversion (0.36 dS/m) indicated a medium salinity hazard (EC < 0.75 dS/m), as shown in Figure 2. These locations exhibited relatively low electrical conductivity (EC) values, suggesting a lower risk of salinity-related issues for irrigation. However, at other locations within the middle Awash Basin, EC values ranged from 0.7 to 2.5 dS/m, signaling a significant salinity risk (Figure 2). These locations included the following: Deho Hot Spring (DH); Melka Sedi Weir (MSW); Werer Research Pumping Station (WARCPS); Werer Research Offtake (WARC Offtake); Ambash Pumping Station (APS); Ertaale Lake; Meteka (MB); Gewanie Pumping Station (GAPS). Despite the variability in EC values, most locations fell within salinity classes C2 and C3, indicating a medium to high salinity hazard; Figures 3 and 4. While these levels pose some risk, the water remains generally suitable for irrigation, provided appropriate management practices are implemented to mitigate salinity-related issues.

During the high-flow season, Deho Hot Spring recorded the highest conductivity value of 2.31 dS/m, while Ertaale Lake had the lowest EC value of 0.76 dS/m. Other locations exhibited lower EC values, including the following: Kesem Dam (0.27 dS/m); Kesem Sugar Factory (0.31 dS/m); Melka Sedi Weir (0.42 dS/m); Werer Research Pumping Station (0.41 dS/m); Werer Research Offtake (0.42 dS/m); Ambash Pumping Station (0.48 dS/m); Meteka at Bridge (0.65 dS/m); Gewanie Aweqe Pumping Station (0.68 dS/m). These lower EC values during the high-flow season reflect a reduced salinity hazard compared to the low-flow season, as depicted in Figure 2.

The fluctuation in EC values is closely tied to seasonal rainfall patterns, which influence the volume of water entering the river system. During the rainy season (high flow), the dilution effect of increased water flow typically reduces salinity levels, resulting in lower EC values and a reduced salinity hazard (Figure 4). Conversely, during the dry season (low flow), reduced water flow leads to higher concentrations of dissolved salts, increasing the salinity hazard (Figure 3). This seasonal variability underscores the dynamic nature of water quality in the middle Awash Basin.

The findings highlight the importance of considering seasonal changes when assessing water suitability for irrigation and implementing adaptive water management strategies to address salinity risks effectively. This study also highlighted that the middle course of the Awash Basin has been categorized as having slight to moderate salinity risks, consistent with previous research. These studies have indicated that salinity risks in the area have been increasing since the introduction of irrigation practices, as referenced in studies [34].

High electrical conductivity (ECw) in irrigation water, often referred to as salinity hazard, poses significant challenges for agricultural productivity. As EC levels rise, the osmotic pressure of the soil solution increases, creating a physiological drought condition. This occurs because plants can only absorb "pure" water, and the presence of excessive salts in the soil solution makes it harder for plants to compete with ions for water uptake. As a result, even if the soil appears moist, plants may wilt due to the inability to access sufficient water, leading to reduced crop yields. The relationship between water transpiration and crop yield is well established, with higher salinity levels directly impacting the amount of water transpired by plants [35]. This, in turn, reduces yield potential, as highlighted in studies [36–38]. Furthermore, excessive salt accumulation in the soil can degrade soil structure, reduce water infiltration rates, and hinder root development, exacerbating the negative effects on crop growth [36,37,39–41].

3.1.2. Sodium Hazard and Sodium Class of Irrigation Water

During the low-flow season, all locations exhibited low sodicity hazard, with SAR values consistently below 10. These results fall under the sodicity class S1, indicating that the water in these areas is safe for irrigation with a minimal risk of soil sodicity issues. However, the situation changes during the high-flow season, where higher SAR values were observed, leading to increased sodicity hazards. In Kesem Dam (KD), SAR values ranged between 10 and 18, indicating a medium sodicity hazard. This places Kesem Dam in the sodicity class S2, suggesting a moderate risk of soil sodicity, which may require careful management if used for irrigation (Table 1).

Table 1. Sodium classes and sodium hazard of irrigation water at middle Awash River Basin in 2022/23.

Water Quality Indices	Range	Sodicity Class	Sodicity Hazard	Locations and Sampling Seasons	
				Low Flow	High Flow
Sodium Absorption Ratio (SAR)	<10	S1	Low	ALL	None
	10–18	S2	Medium	None	KD
	18–26	S3	High	None	KSFD, MSW, WARC Offtake
	>26	S4	Very High	None	DHS, WARC PS, APS, Ertalale, MB, GAPS
Residual Sodium Carbonate (RSC)	<1.25		Safe	KD, KSF	KD, KSFD, MSW, WARC PS, WARC Offtake
	1.25–2.5		Marginal	None	APS, MB, GAPS
	>2.5		Unsuitable	DHS, MSW, WARC PS, WARC Offtake, APS, Ertalale, MB, GAPS	DHS, Ertaale Lake

KD: Kesem Dam, KSFD: Kesem Sugar Factory Diversion, DHS: Deho Hot Spring, WARC PS: Werer Agricultural Research Center Pumping Station, WARC Offtake: Werer Agricultural Research Center Offtake, APS: Ambash Pumping Station, MB: Meteka at Bridge, GAPS: Gewnaie Aweqe Farm Pumping Station.

In contrast, locations such as KSFD, MSW, and WARC Offtake recorded SAR values between 18 and 26, indicating a high sodicity hazard. These areas were classified under the sodicity class S3, signifying a significant risk of soil degradation due to high sodium content. Irrigation with such water could lead to soil structure deterioration and reduced permeability, necessitating mitigation measures. Furthermore, several locations exhibited very high sodicity hazards, with SAR values exceeding 26. These areas include DHS, WARC PS, APS, Ertalale, MB, and GAPS, which were categorized under the sodicity class S4 during the high-flow season (Table 1). Water with such high SAR values is considered unsuitable for irrigation due to the severe risk of soil sodicity, which can lead to long-term soil damage and reduced agricultural productivity.

In summary, while all locations were safe for irrigation during the low-flow season ($SAR < 10$, class S1), the high-flow season revealed significant variations in sodicity hazards (Table 1). Areas like KD showed moderate risk (SAR 10–18, class S2), while KSFD, MSW, and WARC Offtake faced high risk (SAR 18–26, class S3). The most critical areas, such as DHS, WARC PS, APS, Ertalale, MB, and GAPS, had very high sodicity hazards ($SAR > 26$, class S4), rendering the water unsuitable for irrigation.

These findings underscore the importance of monitoring and managing irrigation water quality, particularly in regions like the middle Awash Basin, where seasonal variations significantly influence water chemistry. This study highlights the need for adaptive irrigation strategies during the high-flow season to mitigate the risks associated with increased sodicity and ensure sustainable agricultural practices [42–44].

3.1.3. pH Levels and Implications for Crop Sensitivity

The analysis of water quality in the study area revealed that pH levels consistently exceeded the limits recommended by the Food and Agriculture Organization (FAO) for irrigation water, as illustrated in Figure 5. During the low-flow season, pH values along the Awash River ranged from a minimum of 7.82 to a maximum of 9.28, indicating a predominantly alkaline environment. Specifically, $pH > 8.5$ was recorded at several locations, including at the following: Kesem Dam (8.74); Deho Hot Spring (9.28); Melka Sedi Weir (8.87); Werer Agricultural Research Center (WARC) Pumping Station (8.89); WARC Offtake (8.81); Ambash Pumping Station (8.62); Ertaale Lake (8.53); Gewanie Pumping Station (8.84); $8.0 < pH \leq 8.5$ was observed at Meteka (8.38). The lowest pH value of 7.82 was recorded at Kesem Sugar Factory Diversion; Figure 5. These elevated pH levels suggest that the water in the middle Awash Basin is highly alkaline, which can negatively impact crops sensitive to pH variations. Alkaline conditions can lead to nutrient imbalances, the reduced availability of essential micronutrients (such as iron, zinc, and phosphorus), and impaired root function, ultimately reducing crop yields. During the high-flow season, pH levels showed some variation but remained predominantly alkaline. Key observations include the following: $pH > 8.5$ was recorded at Deho Hot Spring (9.44) and Ertaale Lake (8.76). At other locations, pH values in the range of $8.0 < pH \leq 8.5$, as shown in Table 2.

The relatively lower pH values during the high-flow season can be attributed to the dilution effect of rainfall, which reduces the concentration of alkaline substances in the water. However, even during this period, the pH levels remained above the optimal range for irrigation water, indicating that the water quality is still unsuitable for pH-sensitive crops. The findings highlight that the water quality in the middle Awash Basin poses a significant risk to pH-sensitive crops. Crops such as beans, potatoes, and certain fruits are particularly vulnerable to alkaline conditions, which can lead to high pH levels which can limit the availability of essential nutrients, leading to deficiencies that impair plant growth and development. Alkaline water can cause physiological stress in plants, reducing their ability to absorb water and nutrients, ultimately lowering crop yields. The prolonged use of alkaline irrigation water can lead to soil alkalization, further exacerbating nutrient imbalances and reducing soil fertility over time. The study also emphasizes the seasonal variability in water quality, with pH levels being more alkaline during the low-flow season and slightly lower during the high-flow season. This variability is primarily driven by the volume of rainfall, which dilutes alkaline substances in the river during the rainy season. However, even during the high-flow season, the pH levels remain above the safe threshold for irrigation, indicating that the water quality in the middle Awash Basin is consistently unsuitable for pH-sensitive crops. The findings emphasize the need for adaptive irrigation strategies, such as the use of acidifying agents or the selection of pH-tolerant crop varieties, to mitigate the adverse effects of alkaline water on crop production. Additionally, the continuous monitoring and management of water quality are essential to ensure sustainable agricultural practices in the region.

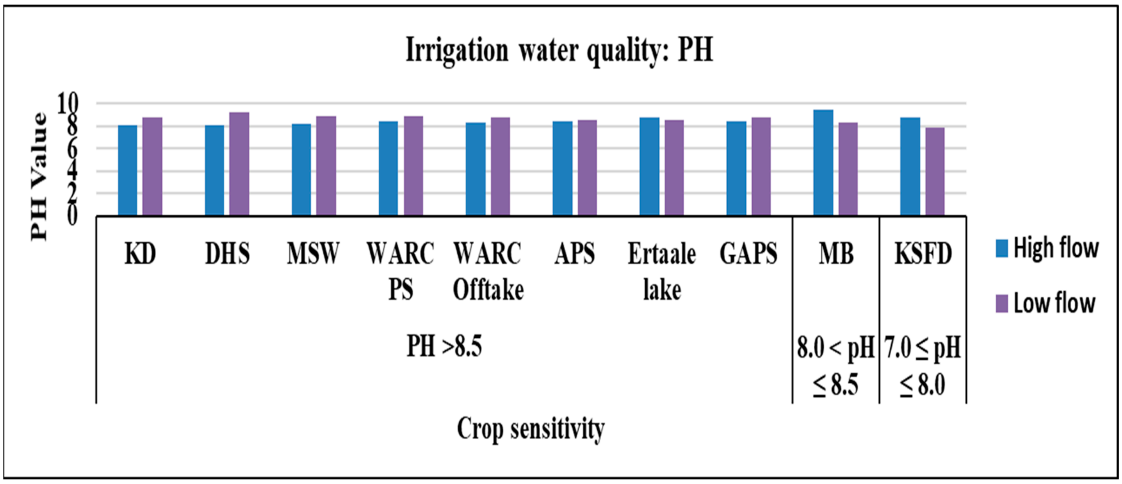

Figure 5. Water pH at middle Awash Basin for low- and high-flow season 2022/23.

Table 2. Crop sensitivity and toxicity hazards of irrigation water at middle Awash River Basin for low- and high-flow season in 2022/23.

Irrigation Water Quality (IWQ) Indices Crop Sensitivity	**Parameter**	**Range**	**Hazard**	**Locations and Sampling Seasons**	
				Low Flow	**High Flow**
	PH	$7.0 \leq pH \leq 8.0$	Slight to moderate	KSFD	None
		$8.0 < pH \leq 8.5$	Severe	Meteka	KD, KSFD, MSW, WARCPS, WARCD, APS, Meteka, and GAPS
		$pH > 8.5$	Highly severe	KD, DHS, MSW, WARCPS, WARCD, APS, Eratale Lake, and GAPS	DHS, Ertaale Lake
	Nitrate Nitrogen (mg/L)	$NO^{3-} < 5.0$	None	KD, DHS, WARCPS, WARCD, and APS	None
		$5.0 \leq NO^{3-} \leq 30.0$	Slight to moderate	None	KD, KSFD, and DHS
		$NO^{3-} > 30.0$	Severe	KSFD, MSW, Ertaale Lake, Meteka, and GAPS	MSW, WARCPS, WARCD, APS, Ertaale Lake, and Meteka, GAPS

Table 2. *Cont.*

Irrigation Water Quality (IWQ) Indices Crop Sensitivity	Parameter	Range	Hazard	Locations and Sampling Seasons	
				Low Flow	High Flow
	Alkalinity (mg/L)	Alkalinity < 90	None	None	None
		90 ≤ alkalinity ≤ 500	Slight to moderate	KD, KSFD, MSW, WARCPS, WARCD, Ertaale Lake, Meteka, and GAPS	KD, KSFD, and Ertaale Lake
		Alkalinity > 500	Severe	DHS	DHS, MSW, WARCPS, WARCD, Ertaale Lake, and Meteka, GAPS

KD: Kesem Dam, KSFD: Kesem Sugar Factory Diversion, DHS: Deho Hot Spring, WARCPS: Werer Agricultural Research Center Pumping Station, WARC Offtake: Werer Agricultural Research Center Offtake, APS: Ambash Pumping Station, MB: Meteka at Bridge, GAPS: Gewnaie Aweqe Farm Pumping Station.

3.1.4. Chloride Toxicity

The analysis of chloride concentrations in the study area showed varying levels of chloride toxicity across different locations during both the low- and high-flow seasons. During the low-flow season, chloride toxicity levels ranged from modest to moderate at several locations: Melka Sedi Weir recorded a chloride concentration of 6.07 mg/L, and WARC Pumping Station showed a chloride concentration of 4.1 mg/L (Figure 4). In contrast, Deho Hot Spring exhibited severe chloride toxicity with a concentration of 14.6 mg/L, while other locations such as Ambash Pumping Station (4 mg/L), Ertaale Lake (5 mg/L), and Gewanie Pumping Station (4.6 mg/L) displayed slight to moderate toxicity. Chloride concentrations at all other locations were below 4 mg/L, indicating non-toxic conditions (Figure 6). However, during the high-flow season, chloride toxicity levels were generally lower, with no locations exhibiting potentially hazardous concentrations. This reduction in chloride levels can be attributed to the dilution effect of increased rainfall, which lowers the concentration of dissolved salts in the water (Figure 6). As a result, elevated chloride levels in irrigation water can lead to chloride ion accumulation in plant tissues, causing leaf burn, reduced growth, and yield loss. Additionally, chloride toxicity can exacerbate the effects of salinity, further impairing crop performance and soil health [45,46].

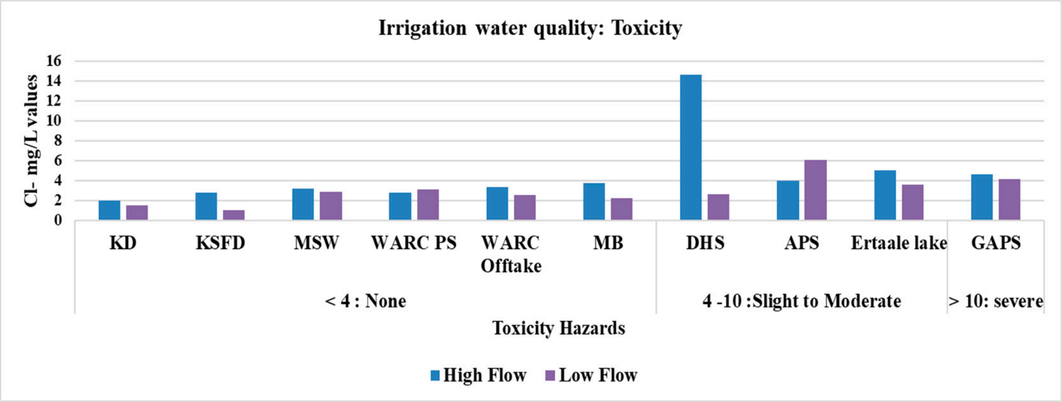

Figure 6. Toxic ion level of irrigation water quality at middle Awash River Basin for high_flow and low_flow seasons in 2022/23.

3.2. Irrigation Water's Heavy Metal Pollution Index and Ecological Risk Index

3.2.1. Heavy Metal Pollution Index (HPI)

This study revealed significant heavy metal contamination in the irrigation water of the middle Awash River Basin (ARB), during both the low- and high-flow season. Therefore, heavy metal contamination was detected at nearly all sampling locations across the study basin, with the exception of the Werer Research Pumping Station (WARC PS), which recorded a Heavy Metal Pollution Index (HPI) below 100, indicating relatively lower contamination levels (Figure 7). During the high-flow season, elevated HPI values (above 100) were observed at several locations, including Kesem Dam, Melka Sedi Weir (MWS Weir), WARC Pumping Station, WARC Offtake, and Ambash Pumping Station, confirming the presence of heavy metal contamination in the river (Figure 8). These findings highlight the persistence of heavy metal pollution in the basin, regardless of seasonal variations [21,24]. The persistent presence of heavy metals in the irrigation water of the middle Awash Basin poses significant risks to agricultural productivity, soil health, and human health.

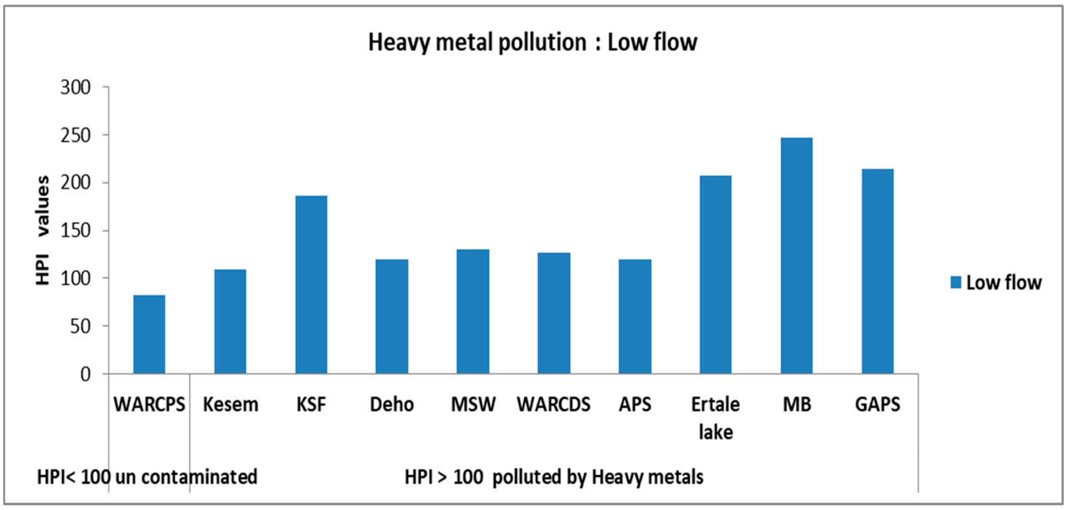

Figure 7. Heavy metal index of irrigation water at middle Awash River Basin during low_flow seasons in 2022/23.

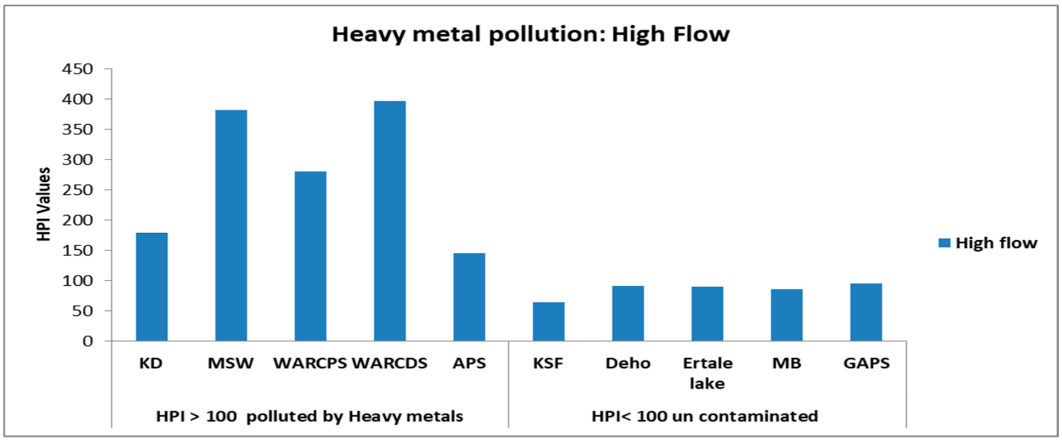

Figure 8. Heavy metal index of irrigation water at middle Awash River Basin for high_flow seasons in 2022/23.

The metal index (MI) was used to further assess the degree of heavy metal contamination in irrigation water. During the low-flow season, the MI values indicated varying levels of contamination: pure (Kesem Dam); slightly affected (Kesem Sugar Factory, Deho Hot Spring, Melka Sedi Weir, WARC DC, Ambash Pumping Station, Ertaale Lake, Meteka, and Gewanie Pumping Station); and strongly affected (WARC Pumping Station) (Figure 9). During the high-flow season, the MI values showed a similar trend but with some variations: moderately affected (Kesem Sugar Factory, Deho Hot Spring, Ertaale Lake, and Meteka); severely affected (Ambash and Gewanie Pumping Stations); slightly affected (Kesem Dam); and severely affected (Melka Sedi Weir, WARC Pumping Station, and WARC Offtake) (Figure 10). These results demonstrate that the middle Awash River is polluted with heavy metals throughout both flow seasons, with varying degrees of contamination across different locations. This study identified the presence of various heavy metals, including arsenic (As), boron (B), cadmium (Cd), cobalt (Co), copper (Cu), chromium (Cr), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn). These metals are known to have detrimental effects on human health, ecological systems, and plant growth [47]. For instance, heavy metals can accumulate in soil and water, leading to bioaccumulation in crops, which poses risks to human health when consumed.

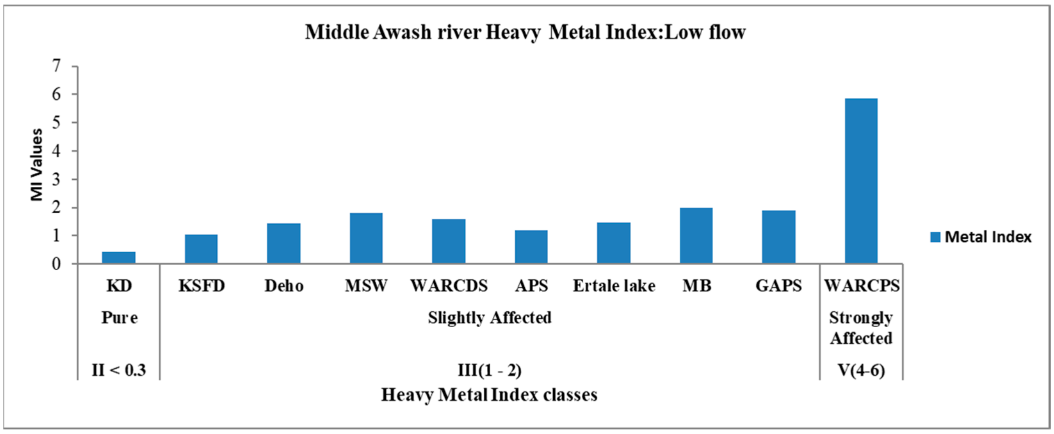

Figure 9. Individual metal pollution classes at middle Awash River Basin during low_flow seasons in 2022/23.

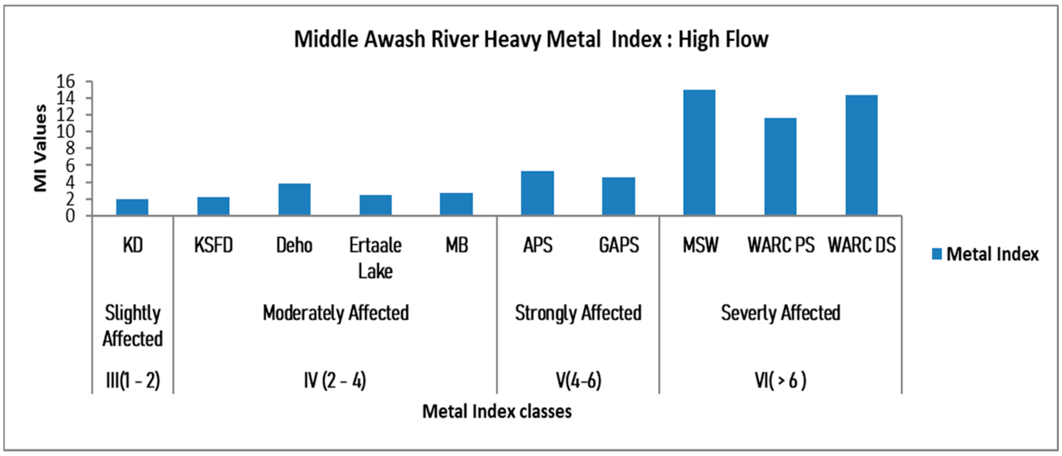

Figure 10. Individual metal pollution classes of irrigation water at middle Awash River Basin for high_flow seasons in 2022/23.

3.2.2. Ecological Risk Index

During the low-flow season, the Ecological Risk Index (ERI) for individual metals indicated low risk (ER < 40) at most sampling sites (Table 3). However, moderate risk was observed for cadmium (Cd) at the following locations: Kesem Sugar Factory (KSF) (ERI: 68); WARC Offtake (ERI: 40); Ertaale Lake (ERI: 76); Meteka (ERI: 80); Gewanie Pumping Station (ERI: 76). During the high-flow season, the Ecological Risk Index (ERI) for individual metals indicated low risk (ER < 40) at most sites (Table 3). However, moderate risk was observed for cadmium (Cd) and mercury (Hg) at the following locations: Melka Sedi Weir (Cd: 55.976; Hg: 42.73) and WARC Offtake (Cd: 60.32). Similar results were obtained and concluded ecological risks in the study area.

Table 3. Potential Ecological Risk Index of middle Awash River (low and high flow).

Locations	ER Low-Flow Season			ER High-Flow Season		
	ER < 40	**40 ≤ RI < 80**	**Ecological Risk of Individual Metal**	**ER < 40**	**40 ≤ ER < 80**	**Ecological Risk of Individual Metal**
Kesem	All		Low	All		Low
KSF	All except Cd	Cd: 68	Moderate risk (Cd)	All		Low
Deho	All		Low	All		Low
MSWeir	All except Cd and Hg		Low	All except Cd and Hg	Cd: 55.976 and Hg: 42.73	Moderate risk
WARCPS	All		Low	All		Low
WARCDS	All except Cd	Cd: 40	Moderate risk (Cd)	All except Cd	Cd: 60.32	Moderate risk
Ambash PS	All		Low	All		Low
Ertaale Lake	All except Cd	Cd: 76	Moderate risk (Cd)	All		Low
Meteka	All except Cd	Cd: 80	Moderate risk (Cd)	All		Low
Gewanie PS	All except Cd	Cd: 76	Moderate risk (Cd)	All		Low

KSF: Kesem Sugar Factory; WARCPS: Werer Agricultural Research Center Pumping Station; WARC Offtake: Werer Agricultural Research Center Offtake; Ambash PS: Ambash Pumping Station; Gewanie PS: Gewanie Aweqe Fentie Farm Pumping Station.

The Risk Index (RI), which assesses the cumulative ecological risk of multiple heavy metals, also indicated low risk (RI < 112.5) at most sites during low-flow seasons (Table 4). However, moderate risk was observed at the following: Ertaale Lake (RI: 118.19); Meteka (RI: 136.95); Gewanie Pumping Station (RI: 122.093). These findings suggest that while most sites posed a low ecological risk during the low-flow season, certain locations exhibited moderate risk due to elevated levels of cadmium (Cd) and other heavy metals such as arsenic (As), boron (B), cobalt (Co), copper (Cu), chromium (Cr), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn). Similarly, during high-flow season, the Risk Index (RI) indicated low risk (RI < 112.5) at most sites, but moderate risk was observed at the following: Melka Sedi Weir (RI: 149.81) and WARC Offtake (RI: 158.05) (Table 4). These results highlight that, despite the dilution effect of increased water flow during the high-flow season, certain locations still exhibited moderate ecological risk due to the presence of heavy metals.

Table 4. Pollution risk index of middle Awash River (low and high flow).

Locations	**RI Low-Flow Season**			**RI High-Flow Season**		
	RI < 112.5	**112.5 ≤ RI < 225**	**Ecological Risk of Single Metal**	**RI < 112.5**	**112.5 ≤ RI < 225**	**Ecological Risk of Single Metal**
Kesem	53.5		Low	2.49		Low
KSF	99.94		Low	25.76		Low
Deho	108.52		Low	110.1		Low
MSWeir	81.82		Low		149.81	Moderate risk
WARCPS	59.91		Low	110.76		
WARCDS	80.91		Low		158.05	Moderate risk
AmbashPS	75.95		Low	73.38		Low
Ertaale lake		118.19	Moderate	54.78		Low
Meteka		136.95	Moderate	42.78		Low
Gewanie PS		122.093	Moderate	47.08		Low

KSF: Kesem Sugar Factory; WARCPS: Werer Agricultural Research Center pumping station; WARC Offtake: Werer Agricultural Research Center Offtake; Ambash PS: Ambash Pumping Station; Gewanie PS: Gewanie Aweqe Fentie Farm Pumping Station.

The presence of heavy metals such as As, B, Cd, Co, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn in the middle Awash River Basin poses significant risks to the following: Ecosystems: Heavy metals can disrupt aquatic ecosystems, harm biodiversity, and degrade water quality [21,24,47–49]. For example, cadmium and mercury are highly toxic to aquatic organisms, leading to reduced populations and altered ecosystem dynamics. Plants: Heavy metals can impair nutrient uptake, reduce crop yields, and cause physiological stress in plants. Cadmium, in particular, is known to inhibit root growth and reduce photosynthesis. Human Health: Heavy metals can accumulate in crops and enter the food chain, posing risks such as toxicity, organ damage, and chronic diseases. For instance, cadmium exposure is linked to kidney damage and bone disorders, while mercury exposure can cause neurological and developmental issues.

4. Discussion

4.1. Irrigation Water Quality

The assessment of irrigation water quality is a critical step in understanding the suitability of water for agricultural use, especially in regions with seasonal and temporary variations in water availability. Methods such as salinity classification and hazard assessment are widely used to evaluate water quality and its impact on crop production and soil health [13,16,50]. In the middle Awash Basin, water quality varied between medium salinity (C2) and high salinity (C3), indicating significant salt accumulation that renders the water unsuitable for irrigation during both low- and high-flow seasons. This finding aligns with previous studies [24,34,51,52], which also highlighted the adverse effects of salinity on water quality and agricultural productivity.

Therefore, during the low-flow season, Kesem Dam and Kesem Sugar Factory Diversion exhibited medium salinity hazards (below 0.7 dS/m), while other locations showed high salinity hazards (0.7 to 2.5 dS/m). In contrast, during the high-flow season, only Deho Hot Spring had high salinity (2.31 dS/m), with other sites falling under medium salinity hazards. This seasonal variation in salinity is influenced by rainfall and the volume of water entering the river from its tributaries. High salinity (ECw) in irrigation water negatively impacts crop yields by creating a physiological drought condition, where plants struggle to absorb water due to increased osmotic pressure in the soil solution [45,52]. Even when the soil appears moist, high salinity reduces the availability of water to plants, directly affecting crop productivity [19,53]. Chloride toxicity further exacerbates these challenges, with high levels observed at Deho Hot Spring, moderate levels at Ambash Pumping Station, Ertaale Lake, and Gewanie Pumping Station, and non-toxic levels at other locations.

This study also found that pH levels in the middle Awash Basin exceeded the FAO-recommended range of 6.0–8.0, with values ranging from 7.82 to 9.28 during the low-flow season. Elevated pH levels during the high-flow season further impacted pH-sensitive crops, reducing yields. These findings underscore the need for the careful management of irrigation water to mitigate salinity, chloride toxicity, and pH-related challenges.

The analysis of the Sodium Absorption Ratio (SAR) across different locations and seasons reveals significant variations in sodicity hazards, which are critical for assessing the suitability of water for irrigation. The results demonstrate a clear distinction between the low-flow and high-flow seasons, with implications for agricultural practices and soil health. During the low-flow season, all locations exhibited low sodicity hazard (SAR < 10), falling under the sodicity class S1. This indicates that the water in these areas is safe for irrigation with a minimal risk of soil sodicity issues. The low SAR values suggest that sodium levels are within acceptable limits, posing no immediate threat to soil structure or permeability. This is an ideal scenario for agricultural activities, as it ensures that irrigation will not lead to soil degradation or reduced crop productivity.

In contrast, the high-flow season showed a marked increase in SAR values, leading to higher sodicity hazards across various locations. This seasonal variation highlights the influence of external factors such as increased runoff, changes in water sources, or contamination during periods of high rainfall or flooding. Area like Kesem Dam recorded SAR values between 10 and 18, placing it in the sodicity class S2 (medium hazard). While this poses a moderate risk of soil sodicity, it can still be managed with careful irrigation practices, such as the application of gypsum or other soil amendments to mitigate sodium accumulation. Locations like KSFD, MSW, and WARC Offtake exhibited SAR values between 18 and 26, categorizing them under sodicity class S3 (high hazard). This level of sodicity poses a significant risk to soil health, as high sodium content can disrupt soil structure, reduce permeability, and hinder root growth. Irrigation in these areas requires stringent management strategies, including the use of leaching practices and organic matter to improve soil conditions. The most critical areas, including DHS, WARC PS, APS, Ertalale, MB, and GAPS, recorded SAR values exceeding 26, placing them in the sodicity class S4 (very high hazard). Water with such high SAR values is considered unsuitable for irrigation due to the severe risk of soil sodicity. The prolonged use of such water can lead to irreversible soil damage, including soil hardening, reduced fertility, and decreased agricultural productivity. These areas require alternative water sources or advanced treatment methods before irrigation can be considered.

The RSC results underscore the importance of monitoring and managing irrigation water quality to prevent sodium-induced soil degradation. High RSC values can lead to soil sodicity, which reduces soil permeability, inhibits root growth, and decreases crop productivity. In areas with unsuitable RSC values, alternative water sources or soil amendment practices, such as the application of gypsum or organic matter, may be necessary to mitigate the effects of sodium accumulation. In contrast, areas with safe or marginal RSC values can be used for irrigation, provided that appropriate management practices, such as leaching and the cultivation of salt-tolerant crops, are implemented. The seasonal variability in RSC values also highlights the influence of rainfall and water flow on water quality, with the high-flow season generally showing improved conditions due to the dilution effect of increased water volume.

4.2. Heavy Metal Pollution Index (HPI) and Metal Index (MI)

Heavy metal contamination was prevalent in the middle Awash Basin, particularly during the low-flow season. The Heavy Metal Pollution Index (HPI) indicated contamination at all sampling locations except WARC Pumping Station (HPI < 100). During the high-flow season, heavy metal contamination (HPI > 100) was observed at Kesem Dam, Melka Sedi Weir, WARC Pumping Station, WARC Offtake, and Ambash Pumping Station. In contrast, Kesem Sugar Factory Diversion, Deho Hot Spring, Ertaale Lake, and Gewanie Pumping Station showed HPI values below 100, indicating lower contamination levels.

The Metal Index (MI) further confirmed heavy metal pollution, with varying degrees of contamination across sites. During the low-flow season, Kesem Dam was classified as non-affected, while other sites ranged from slightly affected (Kesem Sugar Factory, Deho Hot Spring, Melka Sedi Weir, Ambash Pumping Station, Ertaale Lake, Meteka, and Gewanie Pumping Station) to strongly affected (WARC Pumping Station). During the high-flow season, contamination levels ranged from slightly affected (Kesem Dam) to severely affected (Melka Sedi Weir, WARC Pumping Station, and WARC Offtake).

Heavy metals such as As, B, Cd, Co, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn pose significant risks to human health, ecosystems, and plant growth. Their presence in irrigation water can lead to bioaccumulation in crops, soil degradation, and ecological imbalances, necessitating urgent monitoring and mitigation efforts.

4.3. Ecological Risk Index (ERI)

The Ecological Risk Index (ERI) and Risk Index (RI) assessments revealed low ecological risk (ER < 40, RI < 112.5) at most sites during both low- and high-flow seasons. However, moderate risks were observed for cadmium (Cd) at Kesem Sugar Factory, WARC Offtake, Ertaale Lake, Meteka, and Gewanie Pumping Station during the low-flow season. Similarly, moderate risks were identified at Ertaale Lake, Meteka, and Gewanie Pumping Station based on the Risk Index.

During the high-flow season, low ecological risks were observed at most sites, except for Melka Sedi Weir (Cd: 55.976; Hg: 42.73) and WARC Offtake (Cd: 60.32), which showed moderate risks. The RI also indicated moderate risks at Melka Sedi Weir (149.81) and WARC Offtake (158.05). These findings highlight the persistent ecological risks posed by heavy metals in the middle Awash Basin, particularly during periods of high contamination.

5. Conclusions

5.1. General Findings on Water Quality

This study focused on assessing the current state of water pollution and contamination in the middle Awash Basin using suitability indices, the Heavy Metal Pollution Index (HPI), and the Ecological Risk Index (ERI). The results revealed significant issues related to salinity accumulation and heavy metal contamination, which limit the suitability of water for irrigation in the area. The primary source of heavy metal contamination was identified as upstream wastewater discharge and effluents entering the river system.

5.2. Salinity Hazards

The analysis showed that irrigation water quality in the middle Awash Basin ranged from medium-salinity (C2) to high salinity (C3), indicating contamination by salt accumulation. This makes the water unsuitable for irrigation, posing risks of environmental pollution and potential yield reduction during both low- and high-flow seasons. While medium-salinity water (C2) can be used with moderate leaching and salt-tolerant crops, high-salinity water (C3) is unsuitable for soils with restricted drainage. During the low-flow season, Kesem Dam and Kesem Sugar Factory Diversion exhibited medium salinity hazards (below 0.7 dS/m), while all other sites showed high salinity hazards (0.7 to 2.5 dS/m). In contrast, during the high-flow season, only Deho Hot Spring had high salinity (2.31 dS/m), with other sites falling under medium salinity hazards. Salinity levels fluctuated with seasonal rainfall and water volume from tributaries.

5.3. pH Levels and Chloride Toxicity

This study found that the pH levels in the middle Awash Basin exceeded the FAO-recommended range of 6.0–8.0 for safe irrigation water. During both low- and high-flow seasons, pH values surpassed 8.5, negatively impacting pH-sensitive crops and reducing yields. Chloride toxicity was highest at Deho Hot Spring, moderate at Ambash Pumping Station, Ertaale Lake, and Gewanie Pumping Station, and non-toxic at other locations such as Kesem Dam, Kesem Sugar Factory, Melka Sedi Weir, Werer Research Pumping Station, Werer Research Offtake, and Meteka.

5.4. Heavy Metal Contamination

Heavy metal pollution was prevalent during the low-flow season, with all sites except WARC Pumping Station (HPI < 100) showing contamination. The Metal Index (MI) indicated that most sites were slightly to strongly affected by heavy metals, with Kesem Dam being the only non-affected location. During the high-flow season, heavy metal contamination (HPI > 100) was observed at Kesem Dam, Melka Sedi Weir, WARC Pumping Station, WARC Offtake, and Ambash Pumping Station. The MI results further confirmed widespread pollution, with sites ranging from slightly affected (Kesem Dam) to severely affected (Melka Sedi Weir, WARC Pumping Station, and WARC Offtake).

5.5. Ecological Risk Assessment

The Ecological Risk Index (ERI) and Risk Index (RI) revealed low ecological risk (ER < 40, RI < 112.5) at most sites during the low-flow season. However, moderate risks were observed for cadmium (Cd) at Kesem Sugar Factory, WARC Offtake, Ertaale Lake, Meteka, and Gewanie Pumping Station. Similarly, moderate ecological risks were identified at Ertaale Lake, Meteka, and Gewanie Pumping Station based on the RI. During the high-flow season, low ecological risks were observed at most sites, except for Melka Sedi Weir (Cd: 55.976; Hg: 42.73) and WARC Offtake (Cd: 60.32), which showed moderate risks. The RI also indicated moderate risks at Melka Sedi Weir (149.81) and WARC Offtake (158.05).

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T.A.A. and S.G.G.; project administration: T.A.A., S.G.G. and K.J.C.; funding acquisition: T.A.A., S.G.G. and K.J.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: This research has been conducted by obeying scientific ethics and has no conflicts between individuals, organizations, and other bodies. The authors are fully responsible for the research results and outcomes.

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