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Salinity impact assessment on crop yield for Wadi Laba spate irrigation system in Eritrea

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ABSTRACT

Spate irrigation is a floodwater harvesting and management system. In the Wadi Laba (ephemeral stream) spate irrigation system, unpredictable and potentially destructive floods are currently the only source of irrigation water used to grow sorghum (*Sorghum bicolor*) and maize (*Zea mays*) on about 2600 ha. From about 1900 to 2000, farmers harnessed floods with indigenous brushwood and earthen dams. Large floods (>100 m^3/s) frequently damaged the structures. In 2000, the Government of Eritrea installed a concrete headwork. The objective was to divert large floods of up to 265 m^3/s and to irrigate annually all the Wadi Laba fields thereby doubling production. This was done without considering the potential salinity problems. In 2002 and 2003, we determined the salinity of the floodwaters and found that it increased with the flood discharges. For floods that exceed 100 m^3/s, the average rootzone salinities, estimated for leaching fractions ranging from 0.1 to 0.3, could result in yield reductions; particularly for maize the yield reduction ranges from 30 to 100%. The main conclusion to be drawn from the study is that the water management reforms cannot double crop production (especially of maize) unless the management and allocations of floodwaters takes into account the need to control soil salinity.

1. Introduction

Spate irrigation is locally known as Jerif in Eritrea. In the context of Eritrea, spate irrigation can be defined as a method that directs large quantities of floodwater induced by rainfall in the upper catchments, which is emitted through wadis (ephemeral streams) to irrigate fields in the low-lying areas (Mehari et al., 2005a). Spate irrigation requires mountainous or hilly topography that generates the runoff and adjacent low-lying fields with deep soils that are able to store ample water for the crops during the periods with no rain (Mehari et al., 2005a; Van Steenbergen, 1997). Spate irrigation is a pre-planting system, where the flood season precedes the crop production period. In most spate irrigation systems in Eritrea the major floods occur between June and September, which is the time of heavy rainfall in the upper catchments, and crop growth takes place between October and April completely depending on the water stored in the soil (Mehari et al., 2005a).

There are no archaeological findings or artifacts that could with certainty answer the question: when did spate irrigation start in Eritrea? Based on interviews with elderly farmers, however, it can be deduced that the Yemenis introduced the system around 100 years ago (Mehari et al., 2005b). Although spate irrigation is believed to be the oldest among the irrigation systems in Eritrea, it is the least understood system among many irrigation experts and other scholars in the country. Spate irrigation is not taught as a separate subject in the University of Asmara – the only university in Eritrea – it is only briefly mentioned in the introductory irrigation courses.

In Eritrea, there are 11 spate irrigation systems that cover about 56% of the 28,000 ha currently under irrigation, and nearly 35% of the estimated 300,000 ha of potential irrigable

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land (International Fund for Agricultural Development, 1995). They are the major sources of food production for about 20% of the rural poor communities that make up 80% of the 4.5 million population of Eritrea. In spate irrigation systems, uncertainties and risks are a given. Uncertainties include the timing, volume and duration of the floodwater, and the risks to crop production include the destructive nature of floods. These risks and uncertainties are a particular concern in Eritrea. Unlike the spate irrigation systems in many other countries where conjunctive use of floodwater and groundwater is practiced, in all the spate irrigation systems in Eritrea the sole source of irrigation is floodwater. Groundwater is only abstracted from a few scattered wells along the banks of the Wadi Laba for drinking water. Some of these wells produce saline water (>3 dS/m), whereas others do not (<1 dS/m). Groundwater resources have not yet been studied and consequently there is no reliable estimate of their potential (quality and quantity). Moreover, rainfall has a negligible contribution for crop production. The mean annual rainfall in all spate-irrigated areas is estimated at less than 150 mm (Halcrow, 1997). The rainfall is highly erratic and mainly occurs between December and March, which is the late season and harvest time for sorghum (*Sorghum bicolor*) and maize (*Zea mays*)—the major crops grown under spate irrigation.

For the past 100 years, the farmers have relied on indigenous brushwood, earthen and stone structures, locally known as *Agims* and *Musghas,* to divert and distribute the floodwaters to their low-lying fields. *Agims* divert and distribute water from the wadi to the main and secondary canals; *musghas* distribute water to the tertiary canals and fields (Mehari et al., 2005c). Weir type and deflector type bunds were the two commonly used water diversion structures. In the weir type bund, an *Agim* is constructed almost perpendicular to the wadi banks, extending over the whole width to divert the entire flow. In the deflector type, a 30–60 m long *Agim* is extended in the wadi parallel to the flow to divert part of the flow (Mehari et al., 2005c). At field level, the floodwater is conveyed from head to tail end and from field-to-field. In Wadi Laba, the fields have no individual intakes, but 400–600 ha upstream and midstream, as well as midstream and downstream areas share a common intake.

Given the destructive nature of the floods, timely maintenance and rehabilitation of the *Agims* and *Musghas* is vital in the indigenous spate irrigation systems: without it there may simply not be irrigation in the next year. To cope with these challenges, the farmers established effective organizations and introduced a collective water management approach guided by customary rights and rules. They have not, however, been fully successful in mitigating the unpredictability and uncertainty of the floods. Medium (25–50 m^3/s) and larger floods have frequently damaged their structures resulting in tremendous water losses. As a result, good and bad production years occurred and most of the farming households have remained poor.

In 2000, in an effort to improve production and farmers livelihood, the Government of Eritrea, with financial and technical assistance from the International Fund for Agricultural Development (IFAD), replaced the main *Agims* and *Musghas* of the Wadi Laba spate irrigation system with more permanent and stronger concrete and gabion headworks. Among the specific targets were to minimize the failure of the indigenous structures, to divert larger floods up to 265 m^3/s in a controlled and managed manner, and to double the annually irrigated area from 1200 to 2600 ha. While giving proper attention to the water 'quantity' management, water quality management has been ignored and the risk of soil salinization has not been assessed. Salinity is among the major problems threatening the sustainability of irrigated agriculture—particularly in the arid and semi-arid regions of the world to which the Wadi Laba area belongs (Van Hofwegen and Svendsen, 2000).

A salinity problem exists if salt accumulates in the rootzone to a concentration that causes a loss in crop yield (Maas and Grattan, 1999). Water soluble and readily transportable salts are the ones that contribute to a salinity problem. Generally, in irrigated areas, these salts often originate from a saline, shallow groundwater table (within 2 m of the surface), or from salts in the applied water (Ayers and Westcot, 1985; Tanji, 1990). In the Wadi Laba irrigated fields, the groundwater table lies between 10 and 20 m (Natural Resources Consulting Engineering, 1996) and hence the only source of salinity, if any, is the floodwater.

There is a widely shared perception among the majority of the farmers and the irrigation specialists that the flash floods supplied by the Wadi Laba are a source of good quality irrigation water, which does not cause soil salinization to a level that would reduce the yields of sorghum (*Sorghum bicolor*) and maize (*Zea mays*). This assertion is merely based on the assumption that salinity related symptoms have not been observed during the non-drought times. These symptoms are similar to that of drought, such as wilting, or a darker, bluish-green color and sometimes thicker, waxier leaves (Ayers and Westcot, 1985). Soil salinization can take several years to reach levels that have a noticeable effect. Moreover, moderate salt effects could go entirely unnoticed because of a uniform reduction in growth across an entire field. Therefore, could it be that the moderately large and smaller floods (<100 m^3/s) that have been mainly utilized in the indigenous system of the Wadi Laba have low or at most medium salinity levels? And do the large (>100 m^3/s) floods that have been utilized since 2000 have medium to high salinity, but that the time of their utilization has been too short to have a noticeable impact? These questions could only be addressed by a systematic salinity analysis of the floods and the irrigated fields. The authors undertook such a study with the following objectives: (1) to investigate the salinity level in the rootzone that can be induced by a long-term use of the different categories of Wadi Laba floods, (2) to assess the potential impact of soil salinity on crop yields and (3) to recommend, if necessary, appropriate land, water and crop management practices that can minimize salinity problems at field level.

2. Materials and methods

2.1. Study area description

This study was conducted in the Wadi Laba spate irrigation system, which is presumed to have been established in Eritrea at the beginning of the nineteenth century (Mehari et al.,

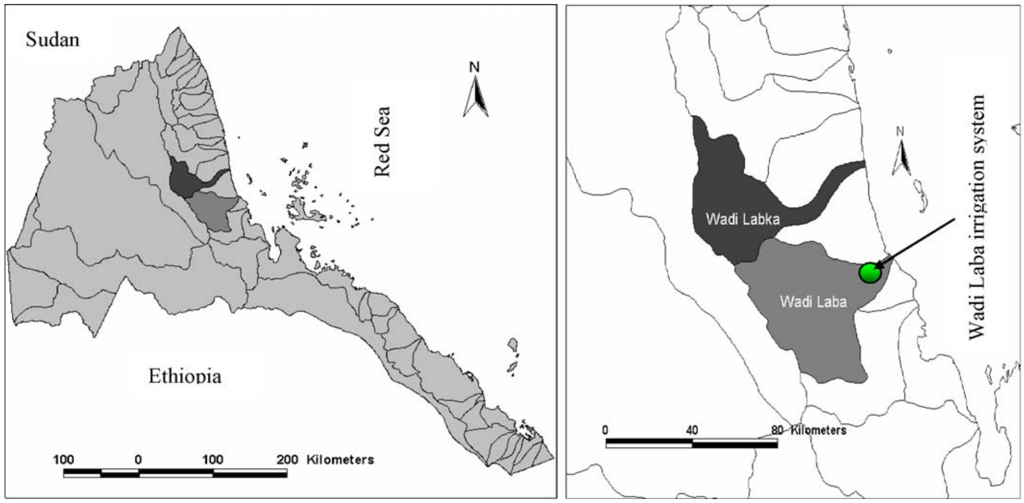

Fig. 1 – Location map of Eritrea and the Wadi Laba catchment and irrigation system.

2005b). Both the local and national irrigation authorities believe that in the past 100 years, the Wadi Laba farmers have acquired a wealth of experience in floodwater management. This may be one of the main reasons that led the authorities to select the Wadi Laba system to pioneer spate irrigation development activities.

The Wadi Laba system is located on the coastal plains of Eritrea (altitude of 300 m) in the lower section of the Wadi Laba catchment (Fig. 1). This lower section has an area of nearly 60,000 ha or about one quarter of the 240,000 ha, the area of the whole catchment. The climate is hot and arid with a maximum daily temperature ranging from 30 °C in January to 45 °C in August. The mean annual rainfall is below 150 mm and the potential evapotranspiration is estimated to be greater than 2000 mm/year (Halcrow, 1997). The upper section of the catchment (180,000 ha), the source of floodwaters for the low-lying fields is hilly and mountainous with elevations ranging from 1000 to 3000 m. The climate is warm to mild with an average annual temperature of about 22 °C. The average annual rainfall ranges from 400 to 600 mm and is erratic in nature (Ogbazghi, 2001).

The current irrigable area in the Wadi Laba is approximately 2600 ha with a potential of 5000 ha (Mehari et al., 2005b). The total number of farming households that rely mainly on the spate irrigation system for their livelihood is 3200 (Daniel, 1997). The family size of a household ranges from five to seven persons. Using an average of six persons per household, the farming population would be about 19,000.

The major crop in Wadi Laba irrigation system is sorghum (*Sorghum bicolor*), followed by maize (*Zea mays*). *Hijeri*, a local sorghum variety, is the most widely grown crop because it is well adapted to the local climate and has a well-branched root system, which is very efficient at extracting residual moisture from deep soil layers (Mehari et al., 2005b). Maize is usually grown as the second crop in the sequence. The preferred local variety is *Berhe*, which has a short growth period (<90 days) and can provide some yield with the limited soil moisture left over from sorghum.

The Wadi Laba farmers categorize the spate floods into six types: very small, small, medium, moderately large, large and very large based on the surface area the floods cover in the Wadi and on some natural height measuring elements such as huge trees and historical large stones. The very large floods are known as *Reka* (Mehari et al., 2005b), a *Tigre* (local) term which means generosity of water from God that irrigates all the fields together. Discharge estimates were done of several very small, small, medium, moderately large and large category floods using the velocity–area method (Boiten, 2000), and they have been found to roughly correspond to smaller than 10 and the range of 10–25, 25–50, 50–100 and 100–200 m^3/s. Moreover, all the measured spates displayed some common flow characteristics, namely a rapid increase of the discharge in the first half hour and a peak with a short duration of about 10 min. The peak was followed by a sharp decline in discharge for nearly half to 1 h and a gradual decline and recession that extends from several hours to 3–4 days (Fig. 2). Consequently, the floods provide a source of water for only a short period, and depending on the volume of the peak, they can destroy diversion structures. This, coupled with the unpredictability in timing and volume of the floods, makes floodwater management a challenging task.

Based on the number of floods, the farmers classify the flood seasons into excellent, good, average and dry, which correspond to the occurrence of above 25, 20–25, 10–20, and

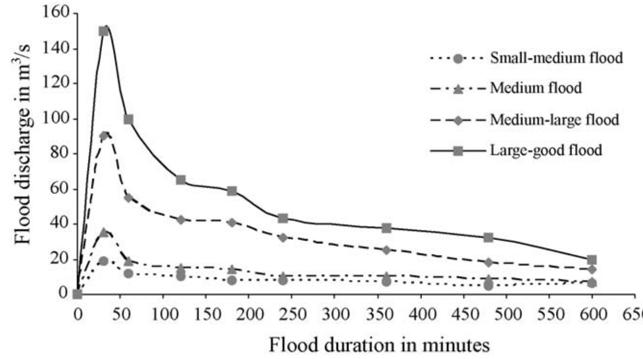

Fig. 2 – Hydrographs of the Wadi Laba floods (Mehari et al., 2005b).

Table 1 – The Wadi Laba flood categories between 1992 and 2003 (Mehari et al., 2005c)

Year	Flood season category	Number of floods that occurred						
		Very small (<10 m^3/s)	Small (10–25 m^3/s)	Medium (25–50 m^3/s)	Moderately large (50–100 m^3/s)	Large (100–200 m^3/s)	Very Large (>200 m^3/s)	Total
1992	Excellent	6	5	13	4	3	1	32
1993	Good	7	3	10	2	1	–	23
1994	Average	3	2	6	1	–	–	12
1995	Dry	2	1	3	2	–	1	9
1996	Dry	3	–	5	–	1	–	9
1997	Average	4	4	5	1	1	–	15
1998	Average	3	2	7	2	1	1	15
1999	Good	4	5	9	2	4	–	24
2000	Average	3	1	6	3	1	–	14
2001	Average	2	3	5	4	–	1	15
2002	Dry	1	1	3	3	–	1	9
2003	Excellent	4	5	12	4	2	1	28
Total number of floods		42	32	84	28	114	6	205

below 10 spates per season, respectively. A 12-year record (Mehari et al., 2005c) indicates that the medium floods account for 33–56% of the total number of floods (Table 1). From Table 1 follows that very large floods (>200 m^3/s) occur about once every 2 years, large floods occur once a year and the moderately large floods occur at least twice a year.

2.2. *Research methodologies*

Out of the 37 floods that occurred in 2002 and 2003 (Table 1), the discharge of 19 floods was measured using the velocity–area method (Boiten, 2000). The two largest floods (>200 m^3/s) were laden with debris, shrubs and tree, making velocity measurements extremely dangerous. Smaller floods (<10 m^3/s) were not measured because they are too small to supply any water to the most upstream fields. Floods that occurred between 2:00 and 3:00 a.m. were not measured since, for security reasons, no one was allowed to work in the field at that time of the night.

To determine the salinity of the Wadi Laba floods, water samples were taken at relative water depths of 0.2, 0.6 and 0.8 from the surface along the right bank, the deepest part of the cross-section. Eight samples were taken during the first 10 h of the flow (Fig. 2)—at an interval of half an hour in the first hour, then every hour for the next 3 and at 2 h interval for the remaining time. They were mixed to form one composite sample of 0.5 L; then the sample was thoroughly mixed and the salinity (ECw, dS/m) was determined with an electrical conductivity (EC) meter after the value remained constant for at least 5 min. ECw increased linearly with increasing discharge rate, D (m^3/s); $ECw = 0.01 \times D + 0.12$; $R^2 = 0.95$. This equation was used to estimate ECw for the very large floods (>200 m^3/s).

The chemical composition of the suspended sediments (solids) of the 19 composite flood samples was determined using standard laboratory methods. The suspended solids were separated from the water using suction pump and ammonium acetate solution buffered to pH 7.0 was used to extract the exchangeable ions in the solids (Thomas, 1982). The analyses were done using the flame absorption and the flame emission photometry respectively (Knudsen et al., 1982; Soltanpour et al., 1982) in the case of calcium (Ca) and magnesium (Mg), and potassium (K) and sodium (Na) cations. Colorimetric, turbidimetric and tiration methods (U.S. Salinity Laboratory Staff, 1954; Kruis, 2002 and American Public Health Organization, 1992) were applied for the chloride (Cl), sulphate (SO_4) and bicarbonate (HCO_3) anions. The cations and anions exhibited a linear relationship ($y = ax + b$) with the flood discharge (Fig. 3). This relationship was used to estimate the chemical composition of the very large floods.

The electrical conductivities of extracts obtained from saturated-soil pastes were determined (Robbins and Wiegand, 1990) on soil samples taken from twelve randomly selected irrigated fields—four in each of the upstream, midstream and downstream sites was measured. In an effort to have a representative sample, each of the selected fields (1 ha in size) was divided into 25 small rectangles. One sample for the topsoil (0–30 cm depth) and one for the sub-soil (30 cm to 2 m depth) were collected from each of the small rectangles using a core sampler. Field observations have shown that 2 m is the effective root depth of sorghum and maize. The soil samples

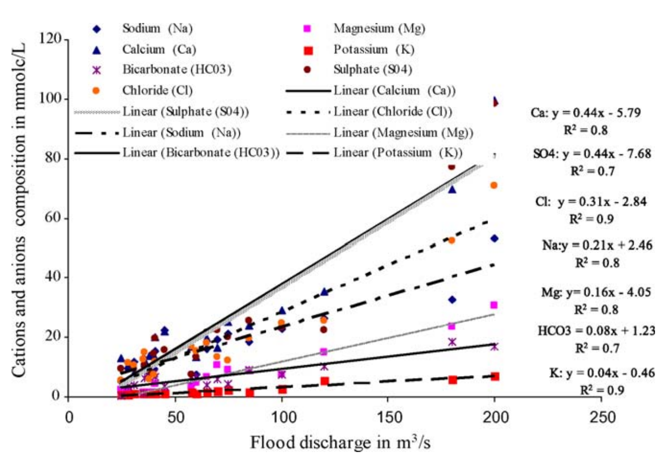

Fig. 3 – Relationship between the flood discharge, and the soluble cations and anions composition of the Wadi Laba floods. *N.B. The concentration of the exchangeable ions determined using ammonium extraction method was negligible.*

Table 2 – Measured and calculated electrical conductivity of Wadi Laba flood samples (ECw)

Flood category	Discharge, D (m^3/s)	ECw (dS/m)	Salinity hazard[a]
Medium	25	0.15	None
	28	0.29	
	31	0.37	
	35	0.45	
	36	0.50	
	38	0.38	
	40	0.47	
	41	0.48	
	45	0.50	
Moderately large	58	0.65	Slight
	60	0.71	
	65	0.75	
	70	0.81	
	75	0.72	
	85	0.83	
	100	0.90	
Large	120	1.33	Slight to moderate
	180	1.44	
	200	1.88	
Very large	205	2.17[b]	Slight to moderate
	225	2.37[b]	
	245	2.57[b]	
	265	2.77[b]	

[a] Classification is based on the irrigation water quality guidelines given in Table 3, Ayers and Westcot, 1985.
[b] *ECw calculated from the linear equation* ($ECw = 0.01 \times D + 0.12$; $R^2 = 0.95$) obtained from an ECw–D graph of the medium, moderately large and large floods.

were mixed thoroughly to get one composite sample for the topsoil and another for the sub-soil.

3. Results and discussion

3.1. *Salinities of the floodwater and the suspended sediments*

The salinity guidelines (Table 1, Ayers and Westcot, 1985) together with the measured ECw of the medium, moderately large and large floods, and the calculated ECw of the very large floods (Table 2), indicate that:

- the medium floods (25–50 m^3/s) have no salinity hazard whereas the moderately large floods (60–100 m^3/s) have a slight salinity hazard; and
- all the large floods (100–200 m^3/s) and the very large floods (>200 m^3/s) have a slight to moderate salinity hazard.

The high salinity of the large floods may be attributed to the composition of the Wadi Laba upper catchment. Another reason could be the salinization of the wadi banks consequent to the wetting by the frequent small floods and the subsequent concentration of salts as the banks dry. As the flow increases, erosion of the banks and in turn the suspended solids in the flow increase and the dissolution of the entrained salts on and within the suspended solids.

According to the interviews held with the farmers and personal observations during a number of flood events, floods with a discharge greater than 50 m^3/s occur when there is rainfall on the highest altitudes (3000 m). Floods with a discharge between 10 and 50 m^3/s happen when the hilly sections of the catchment at low to medium altitude (1000–2000 m) receive rainfall. The high salinity level in the large floods indicates that the mountainous area is relatively richer in salt bearing minerals than the hilly areas. This is not a wild assumption. As compared to the typical analytical data for different types of salt affected soils (Table 10.3, Smedema et al., 2004), the chemical compositions of the water phase (the exchangeable ions were found to be negligible) of the large floods presented in Table 3 suggest that the floods originated from a saline area.. The content of each of the cations (Ca^{++}, Mg^{++}, Na^+ and K^+) and anions (Cl^-, SO_4^- and HCO_3^-) was found to be greater than 130 mmolc/L. Cl^- and SO_4^-, the two major sources of salinity accounted for nearly 66 and 50 mmolc/L, respectively.

3.2. *The average soil-water salinity in the rootzones of sorghum and maize*

Following irrigation with saline water, salt concentration builds up due to plants extracting water but leaving salts behind in a greatly reduced volume of soil-water. As crops use water, the upper rootzone becomes depleted and the zone of readily available water moves toward the deeper parts as the time interval between irrigations is extended. The crop does not respond to the extreme low or high salinity levels in the root zone but integrates water availability and takes water from wherever it is most readily available. For crops irrigated infrequently, as is normal in spate irrigation systems, the crop yield is best correlated with the average soil-water salinity of the rootzone (Grattan, 1999; Shalhevet, 1994).

The average electrical conductivity of saturated paste extracts, ECe, which could develop in the rootzone was estimated from the ECw values in Table 2. Since rainfall on the irrigated lands is insignificant, the ECe was estimated by using concentration factors (Table 3, Ayers and Westcot, 1985) to predict the soil salinity from the salinity of the irrigation water and the leaching fraction. This prediction required an estimate of the leaching fractions based on the total applied amount of water and the evapotranspiration, ETc.

- The annual ETc for an optimum crop yield is approximately 870 mm. This is in line with the Wadi Laba farmer's practice where two sorghum harvests (seeded and ratoon) or one sorghum and one maize harvest/year occur. The ETo values have been calculated by Penman–Monteith (Allen et al., 1998) on the basis of 10 year climatic data of the study area and have been directly measured using a Class A pan in 2002 and 2003. The pan coefficients k_{pan} is 0.65 for the mean relative humidity (RH) between 40 and 70% and k_{pan} is 0.75 for RH larger than 70% (see Table 5, Allen et al., 1998). From these data, it follows that the average net ETc for one harvest of seeded sorghum, sorghum ratoon and maize second crop is 450, 400 and 440 mm, respectively (Table 4). Thus, the estimate of the annual ETc ranges from 850 to 890 mm. The average, 870 mm was used here. Based on this average ETc

Table 3 – Chemical composition of the water phase of the suspended sediments of the different Wadi Laba flood categories[a]

Flood category	Discharge (m^3/s)[b]	Sodium (Na)[b]	Calcium (Ca)[b]	Magnesium (Mg)[b]	Potassium (K)[b]	Total cations[b]	Bicarbonate (HCO_3)[b]	Sulphate (SO_4)[b]	Chloride (Cl)[b]	Total anions[b]	Sodium adsorption ratio[c] (SAR)
Medium	25.0	5.1	2.3	12.8	0.7	20.9	0.5	9.5	5.6	15.6	1.9
	28.0	9.3	1.8	10.8	0.6	22.5	3.5	11.4	11.3	26.2	3.7
	31.0	11.7	0.7	7.9	1.0	21.3	3.8	9.4	10.5	23.7	5.6
	35.0	13.0	1.4	9.0	1.1	24.5	1.3	12.5	12.6	26.4	5.7
	36.0	10.3	1.4	12.3	1.1	25.1	6.4	10.8	14.8	32.0	3.9
	38.0	8.3	1.5	13.8	1.0	24.6	8.4	8.6	5.9	22.9	3.0
	40.0	9.6	1.4	13.6	1.3	25.9	8.0	14.5	7.5	30.0	3.5
	41.0	15.2	4.4	20.0	1.1	40.7	6.8	19.5	11.8	38.1	4.4
	45.0	22.3	1.6	22.2	1.1	47.2	3.5	15.8	12.5	31.8	6.5
Average	35.4	11.6	1.8	13.6	1.0	28.1*	4.7	12.4	10.3	27.4*	4.2
Moderately large	58.0	4.0	3.2	16.9	1.6	25.7	6.8	7.6	16.8	31.2	1.3
	60.0	7.5	4.9	13.5	1.3	27.2	6.5	13.4	15.3	35.2	2.5
	65.0	16.2	6.5	19.6	1.7	44.0	4.0	21.6	18.1	43.7	4.5
	70.0	19.3	10.8	16.6	1.9	48.6	5.8	22.4	13.5	41.7	5.2
	75.0	21.3	8.9	25.1	2.5	57.8	4.3	19.9	12.3	36.5	5.2
	85.0	18.5	8.6	23.9	1.4	52.4	9.2	25.5	19.8	54.5	4.6
	100.0	23.0	7.5	29.0	2.7	62.2	7.5	23.3	24.6	55.4	5.4
Average	73.3	15.7	7.2	20.7	1.9	45.4*	6.3	19.1	17.2	42.6**	4.2
Large	120.0	26.5	15.0	35.3	5.4	82.2	10.3	22.5	25.7	58.5	5.3
	180.0	32.8	23.5	69.8	6.0	132.1	18.4	77.3	52.5	148.2	4.8
	200.0	53.3	30.8	99.7	7.2	191.0	17.1	98.5	70.9	186.5	6.6
Average	166.7	37.5	23.1	68.3	6.2	135.1**	15.3	66.1	49.7	131.1**	5.6
Very large ***	205.0	45.5	28.8	84.2	7.7	166.2	17.6	82.5	62.3	162.5	6.1
	225.0	49.7	32.0	93.0	8.5	183.2	19.2	91.3	68.5	179.1	6.3
	245.0	53.9	35.2	101.8	9.3	200.2	20.8	100.1	74.7	195.7	6.5
	265.0	58.1	38.4	110.6	10.1	217.2	22.4	108.9	80.9	212.3	6.7
Average	245.0	53.9	35.2	101.8	9.3	191.7**	20.8	100.1	74.7	187.4**	6.5

As compared to the typical analytical data for different salt affected soils, Table 10.3, Smedema et al., 2004; * are non-saline where as ** are saline; *** chemical composition estimated from Fig. 3.

[a] The concentration of the exchangeable ions determined using ammonium acetate extraction method was negligible.

[b] Expressed in mmolc/L.

[c] $SAR(Na/\sqrt{(Ca + mg)/2}) < 9$ mmolc/L indicates non-sodic soils (Table 1, Ayers and Westcot, 1985).

Table 4 – Estimated net water requirement (ETc) of sorghum and maize in the Wadi Laba irrigated fields

Crop type	Growth stage	Growth period		ETo1[a]		ETo2[b]		Max. K_c values[c]	ETc1 ($ETo1 \times K_c$)	ETc2 ($ETo2 \times K_c$)	Average ETc (ETc1 + ETc2)/2
		Date	Days	mm/day	mm	mm/day	mm		mm	mm	mm
Sorghum (*Hijeri* local variety) seeded crop	Initial	21/9–9/10	19	7	133	6	114	0.40	53	46	49
	Development	10/10–10/11	32	6	192	5	160	0.75	144	120	132
	Mid season	11/11–16/12	36	5	180	4	144	1.15	207	166	186
	Late season	17/12–11/01	26	4	104	4	104	0.80	83	83	83
Total			113		609		522		487	414	451
Sorghum (*Hijeri* local variety) ratoon crop	Initial	25/1–9/2	8	4	32	5	40	0.40	13	16	14
	Development	10/2–9/3	29	5	145	5	145	0.75	109	109	109
	Mid season	8/3–6/4	30	6	180	6	180	1.15	207	207	207
	Late season	4/4–17/04	14	7	98	6	84	0.80	78	67	73
Total			81		455	0	449		407	399	403
Maize (*Berhe* local variety)	Initial	1/2–15/2	16	4	64	4	64	0.50	32	32	32
	Development	16/2–14/3	28	5	140	5	140	0.85	119	119	119
	Mid season	15/3–12/4	29	6	174	6	174	1.20	209	209	209
	Late season	17/4–30/04	14	7	98	6	84	0.90	88	76	82
Total			87		476		462		448	435	442

[a] Estimated using Penman–Monteith on the basis of a 10-year climatic data of the study area.
[b] Obtained from Class A pan measurements. Pan Coefficients: K_{pan} 0.65 for mean relative humidity, RH, of 40–70%, and K_{pan} 0.75 for RH > 70% (Table 5, Allen et al., 1998 were used). In Wadi Laba, RH ranges from 40 to 70% in September and October, and is >70% for the rest of the crop production period.
[c] Adapted from Brower and Heibloem (1986).

Table 5 – Percentage of sorghum and maize crop yield relative to the yield for the same conditions without salinity (assumed 100%), at 0.1 and 0.3 LF and irrigation by the different Wadi Laba flood categories

Flood category	Discharge (m^3/s)	Average rootzone salinity, ECe (dS/m)		Yield sorghum, Y_r (%)		Yield maize, Y_r (%)	
		0.1 LF	0.3 LF	0.1 LF	0.3 LF	0.1 LF	0.3 LF
Medium	25	0.63	0.32	100	100	100	100
	28	1.18	0.60	100	100	100	100
	31	1.52	0.77	100	100	100	100
	35	1.85	0.94	100	100	98	100
	36	2.04	1.03	100	100	96	100
	38	1.55	0.79	100	100	100	100
	40	1.93	0.98	100	100	97	100
	41	1.99	1.01	100	100	97	100
	45	2.05	1.04	100	100	96	100
Moderately large	58	2.68	1.36	100	100	88	100
	60	2.92	1.48	100	100	85	100
	65	3.06	1.55	100	100	84	100
	70	3.33	1.69	100	100	80	100
	75	2.94	1.49	100	100	85	100
	85	3.39	1.71	100	100	80	100
	100	3.68	1.86	100	100	76	98
Large	120	5.47	2.77	100	100	55	87
	180	5.92	3.00	100	100	49	84
	200	7.73	3.91	85	100	28	73
Very large	205	8.91	4.51	66	100	13	66
	225	9.73	4.92	53	100	4	61
	245	10.55	5.34	40	100	0	56
	265	11.37	5.75	27	100	0	51

and a reasonable range in depths of applied water, a choice of leaching fractions, LF, from 0.1 to 0.3 seems to be realistic.

This range in LF is consistent with the present irrigation practices in Wadi Laba. The farmers consider a certain field to be 'fully' irrigated if it receives at least three irrigation turns of 50 cm depth each. An applied water depth of 1,500 mm and the average ETc of 870 mm result in a leaching fraction of about 0.4 ((1500 − 870)/1500). A 'partially' irrigated field gets one to two turns of 50 cm depth each, which result in a leaching fraction of 0.1 ((1000 − 870)/1000).

3.3. *Predicted impact of the ECe on the sorghum and maize yield*

The long-term impact of ECe on the grain yields of sorghum and maize (Table 5) was assessed by using Eq. (1) (Maas and Grattan, 1999).

$$Y_r = 100 - s(\mathrm{ECe} - t) \quad (1)$$

where Y_r is crop yield relative to the maximum crop yield for non-saline conditions in percent, t the threshold salinity in dS/m, s the yield loss per unit increase in salinity above t in percent per dS/m and ECe is the average salinity of a saturated paste extract in the rootzone in dS/m.

For the same crop, there are different s and t figures developed (Ayers and Westcot, 1985; Maas and Grattan, 1999) to reflect the various climatic factors under which the crop is grown. Most crops can tolerate greater salt stress if the weather is cool and humid than when it is hot and dry. To get the most accurate estimate of the possible yield reduction, the s and t values after Maas and Grattan (1999) were used in this research. These figures were developed for hot-arid coastal areas, which have similar climatic conditions to that of the Wadi Laba irrigated area. According to Maas and Grattan (1999), sorghum belongs to the moderately salt-tolerant group and has t and s values of 6.8 dS/m and 16% per dS/m, respectively; maize is categorized as moderately sensitive with respective t and s values of 1.7 dS/m and 12% per dS/m.

To estimate the average salinity of the rootzone as a function of the leaching fraction (LF), the concentration factors have been used as given by Ayers and Westcot (Table 3; 1985). The concentration factor for a LF of 0.1 is 2.1 and that for a LF of 0.3 is 1. In other words, the average ECe in the rootzone of a crop that is irrigated in such a way that the LF is 0.1 will be 2.1 times the ECsw; and if the LF is 0.3, then the average ECe will be equal to ECsw. When using this method to estimate the ECe the following assumptions have been made, namely that the rainfall is not a source of water for the crop, sufficient water has been applied to establish a steady state salinity distribution throughout the rootzone during the crop season, and that the salinity of the applied water does not change with time. This method of estimating the average salinity in the rootzone tends to be conservative, unless the average soil salinity in the rootzone when the crop is planted is higher than the estimated salinity that is obtained by using the concentration factors. Because of these assumptions, the estimated average ECe values usually exceed what actually occurs, i.e. the estimates of yield reduction are greater than what actually will occur (Shalhevet, 1994).

In the fields that receive two turns of irrigation water (0.1 LF), the following salinity impact assessment can be made from Table 5:

Table 6 – Measured soil-water salinity of the root zone, ECe of selected Wadi Laba fields (average of three measurements of each of the top and sub-soil samples)

	Upstream fields					Midstream fields					Downstream fields				
	1	2	3	4	Average	1	2	3	4	Average	1	2	3	4	Average
ECe (dS/m)	1.15	1.25	1.60	1.55	1.4	2.10	2.55	2.70	2.75	2.53	3.5	3.85	4.7	4.15	4.05

- Medium floods can be utilized for sorghum and maize production without any risk of yield loss.
- Moderately large floods, while not of any concern in the case of sorghum, could reduce the yield of maize by 25%.
- The large floods could reduce sorghum yields by 15%, which may be considered acceptable. In the case of maize, however, the loss could be 70%. Even at 0.3 LF, the floods could incur a yield loss of 25% and may thus be considered unsuitable for maize production.
- The very large floods could cause 75 and 100% yield reduction of sorghum and maize, respectively. These floods may be used for sorghum production only in those fields that receive three irrigation turns. They are not suitable for maize since even at 0.3 LF, the salinity in the rootzone will half the yield.

The presented analysis, however, assumes that a field is irrigated by one single flood-category. Although the practicality of this assumption cannot be ruled out, the relatively more likely event is that a field is irrigated by a combination of two or three different flood categories. The newly built structures have not changed the water-sharing arrangements among the farmers. Therefore, one needs to consider the consequences of indigenous water rights in the salinity assessment. These water rights allocate the small and medium floods, and occasionally the moderate-large floods to the upstream fields; the moderate-large and sometimes the large floods to the midstream fields, and the large and very large floods to the downstream fields. Based on these allocations some additional salinity impacts can be deduced (Table 5):

- Sorghum and maize yields in the upstream fields will not decline regardless of whether they are irrigated twice or three times.
- Sorghum yield in the midstream fields that receive two irrigation turns may not decrease, but maize yield could decline by 30–50%. If the fields get three irrigation turns, the maximum maize yield loss would be about 10%, assuming that two third of the yield comes from the moderate-large and one third from the large floods.
- The downstream fields will be the most affected fields by salinity. With two irrigation turns using only very large floods, the sorghum and maize yields may decrease 70 and 100%, respectively; if equal quantities of large and very large floods are utilized, the yield losses would be 45 and 85%; while if only large floods are used, the losses would be 15 and 70%. With three irrigation turns, there would be no sorghum yield losses; but the maize yield could decline by 50% when very large floods are the only source, 35 and 45% if large and very large floods are applied in a 2:1 and 1:2 ratios; and 30% if the large floods should supply all three irrigation turns.

This analysis shows that a strict adherence to the existing water sharing arrangements could contribute to high maize and sorghum yield losses in the downstream fields. However, violation of the present arrangements could have a much larger negative effect. The field-to-field water distribution is convenient for the upstream and downstream farmers to utilize the few large floods, especially in times of drought. This practice leaves many downstream fields dry and at best, partially irrigated, thereby exposing them to the highest yield losses. Therefore, some changes in the field layout are necessary to provide the downstream fields with separate intakes and to enable them to divert directly water from the canals and even the wadi. This intervention could have an added value for the wet season; some downstream fields may be able to harness moderately large floods. Apart from this, it is recommended to introduce some practical salinity measures by strengthening the farmers' awareness so that they grow only sorghum in the fields irrigated by large floods; by introducing a water management policy of discharging the very large floods to the wadi and by convincing the farmers not to utilize these very large floods. Besides the high impact they have on the maize and sorghum yields, the very large floods are the most destructive and the scarcest floods. Moreover, should the need arise to introduce new crops; at least those moderately tolerant to salinity would have to be preferred.

It is worth noting that the *s* and *t* values for all crops are based on a research where salinity was artificially imposed after the crop was established in a non-saline soil medium (ECe < 4 dS/m). Three field experiments, which used grain sorghum as an important dry land summer crop on the saline Liverpool Plains in Northern New South Wales, have shown that the yield was reduced by 50% at irrigation water induced ECe levels of as low as 2.8 dS/m (Daniells et al., 2001). As mentioned before, the advisory literature indicated a salinity threshold (no yield reduction) for sorghum at 6.8 dS/m. The Wadi Laba fields were, however, non-saline in 2002 (Table 6). Hence, it may be assumed that the actual yield reductions could not be higher than the ones indicated in Table 5.

It is also clear from Table 6 that after a century of spate irrigation, the actual (measured) ECe of the fields is far lower than the predicted ECe values (Table 5). This may not be due to an allocation of larger amount of water for leaching than that used in Table 5. As acknowledged by the farmers, even during an excellent flood season that has a probability of occurrence of only 20% (Table 1), a maximum of 70% of all the Wadi Laba fields have been fully or partially irrigated. The more reasonable explanation may thus be that till the year 2000 the Wadi Laba system relied on earthen and brushwood diversion structures that could withstand (without failing) floods of a maximum of 100 m^3/s. Thus, the large and very large floods, which are relatively rare in occurrence as compared to the other flood categories, may have only seldom made their way to the fields.

4. Conclusion

The fact that the indigenous water management system was not able to divert large floods (>100 m^3/s) may have cost substantial maize and sorghum production in the Wadi Laba area, and at times incurred livelihood hardships to the farmers. However, a positive aspect is that the indigenous water management system has maintained the salinity of the fields at sustainable levels.

The water management reform that focused on diverting large floods in a controlled manner may not attain its intended objective of doubling the yields (especially of maize) unless the salinity problem is adequately addressed. The slightly to moderately saline large floods, which supply water mainly to the downstream fields, may have a significant impact on the maize yield, but also on that of sorghum. In the worst scenario, when a field receives two irrigation turns from the very large (200–260 m^3/s) floods, sorghum and maize yields could decrease 75 and 100%, respectively; in the case of large floods (100–200 m^3/s), by 15 and 70%. In the best scenario, when a field is irrigated trice with the large floods, only maize yield could decline by 30%. Some of the recommendations to minimize yield loses include the provision of separate intakes for the downstream farmers in view of their right on large floods; the growth of maize only on the fields that are irrigated by small to moderately large floods (<100 m^3/s) and the restriction of large floods for sorghum. Other recommendations are the diversion of very large floods to the wadi and the prioritization of moderately salt tolerant, new crops. It is remarkable to mention that even the small and moderately large floods with an average ECw of about 0.6 dS/m, when applied at the rate of 8700 m^3/ha/year, may add 5 tonens of salt to the soil. If this is not flushed out of the rootzone, salinity problems could rapidly build up. Thus, budgeting at least 10% of the applied floodwater for leaching is a must-do water management task.

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