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DETERMINATION OF WATER REQUIREMENTS FOR PRODUCING IRRIGATED RICE AND OTHER CROPS IN THE AFRAM RIVER VALLEY BOTTOM AT AFRAMSO, GHANA

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Abstract

The Valley Bottom Rice Development Project (VBRDP) was started in Ghana in 1990 under the Agricultural Sector Rehabilitation Programme of the Ministry of Food and Agriculture. To assess the quantity and quality of water for rice irrigation at the Aframso project site (from 1993-1996), three methods were applied. Firstly, the Nathan's (1997) effective precipitation index (EPI) was used to evaluate rainfall recharge of the Afram River. Secondly, basic statistical parameters (1986 -1995) were used to evaluate river flow characteristics. Finally, the river water quality was assessed on the basis of Ayers & Westcot (1985) water quality guidelines for irrigation. Both the EPI and river flow characteristics revealed sufficient quantity of surface water for irrigated rice at Aframso throughout the growing season. Again, the mean values of essential parameters of river water, e.g. total dissolved solids (73.00 mg l^{-1}), conductivity (0.094 dS cm^{-1}), adjusted sodium adsorption ratio (0.32), *p*H (6.5), HCO_3^- (0.60 meq l^{-1}) and N-NO_3^- (1.06 mg l^{-1}) showed that the Afram River water has no immediate quality problems that are likely to adversely affect irrigated rice-based cropping in the area.

Résumé

Opoku-Duah, S., Kankam-Yeboah, K. & Mensah, F. K.: *Détermination de besoins d'eau pour la production de riz irrigué et d'autres produits au fond de vallée de la rivière Afram à Aframso au Ghana.* Le Projet de Développement de Riz au fond de Vallée (PDRFV) était commencé au Ghana en 1990 sous le programme de réhabilitation du secteur agricole du Ministère de l'alimentation et l'agriculture. Pour estimer la quantité et la qualité d'eau pour irrigation au site de Projet d'Aframso (de 1993-1996), trois modalités étaient appliquées. D'abord, l'index de précipitation efficace (IPE) de Nathan (1997) était utilisé pour évaluer le rechargement de pluie de la rivière Afram. Deuxièment, les paramètres statistiques de base (1986-1995) étaient utilisés pour évaluer les caractérisques de courant de la rivière. Enfin, la qualité d'eau de la rivière était évaluée en se basant sur las lignes directrices de la qualité d'eau pour irrigation d'Ayers & Westcot (1985). IPE et les caractéristiques de courant de rivière révélaient de quantité suffisante d'eau de surface pour le riz irrigué à Aframso durant toute la saison de pousse. Encore, les valeurs moyennes des paramètres essentiels d'eau de rivière, ex. Totale de solides dissous (73.00 mg l^{-1}) conductivité (0.094 dS cm^{-1}), proportion d'adsorption de sodium ajusté (0.32), *p*H (6.5), $HC0_3^-$ (0.60 meq l^{-1}) et N-$N0_3^-$ (1.06 mg l^{-1}) montraient que l'eau de la rivière Afram n'avait pas de problèmes immédiats de qualité qui pourraient influencer défavorablement la culture basée sur le riz irrigué dans la zone.

Introduction

The Valley Bottom Rice Development Project (VBRDP) was initiated by the Ministry of Food and Agriculture (MOFA) in 1990. The project was conceived within the framework of the Government of Ghana's Agricultural Sector Rehabilitation Programme (ASRP), supported by some international donor agencies including the World Bank.

To satisfy the water aspects of the project, the Water Research Institute (WRI) of the Council for Scientific and Industrial Research (CSIR) was tasked to carry out research studies into the hydrology and water resources of selected valley bottoms capable of supporting rice production in those area, in collaboration with related national research institutions and university departments.

Generally, rice production in Ghana is an upland activity by subsistent farmers and a few commercial and co-operative growers. The production system is mainly rainfed, often hampered by erratic rainfall, for instance, wide variations in both the temporal and spatial distribution, and low precipitation amounts. Besides, tropical upland soils are often poor, due mainly as a result of soil erosion, also resulting from the interactive effect of high rainfall intensity and continuous seasonal cropping (nutrient mining). The above situation, coupled with poor on-farm water management techniques, lead to the low average yield of rice (< 3.5 t ha^{-1}) in Ghana. Apart from this, the need for more agricultural lands due to increasing population requires the conversion of less favourable lands (e.g. inland valleys) into farming plots. The use of inland valleys (i.e. valley bottoms) for rice production presents a particularly viable option for three main reasons. Firstly, water is available in valley bottoms for most part of the year in Ghana. Secondly, rice has enormous capacity to thrive in waterlogged conditions. Finally, inland valleys are naturally fertile.

Despite the inherent adequacy of water and fertility potential of tropical lowlands, Drissen & Dudal (1991) reported that soils of valley bottoms are extremely fragile and for them (soils) to support intensive paddy rice cultivation, satisfactory irrigation and drainage techniques need to be applied. In fact, high soil moisture levels of val-

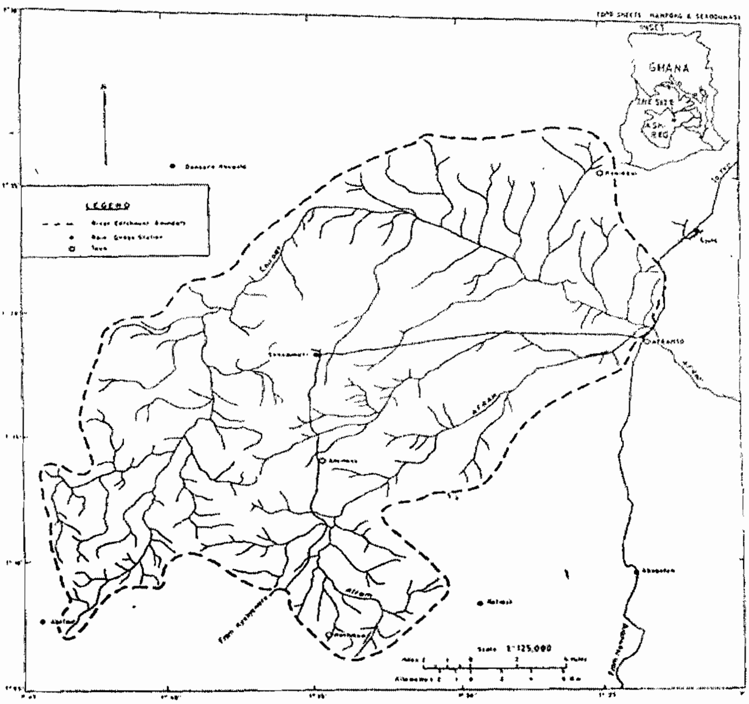

Fig. 1. Drainage basin of the Afram river

ley bottoms may not only present hydro-physical problems (e.g. flooding, slumping, crusting, etc.) but also water quality constraints like soil salinity, poor root permeability and specific ion toxicity to crops.

The objective of the present study was, therefore, to asses the quantitiative and qualitative suitability of surface water sources of the Afram River valley bottom at Aframso for irrigating rice and other locally-suitable crops.

TABLE 1

Mean daily discharge data of Afram river at Aframso (1988/89-1995/96)

Year	*Mean* (m^3 s^{-1})	*Maximum* (m^3 s^{-1})	*Minimum* (m^3 s^{-1})	*Total run-off* × 10^6 m^3
1990/91	0.098	0.530	0.041	3.077
1991/92	0.176	0.617	0.074	5.567
1992/93	0.130	0.198	0.075	1.597
1993/94	0.131	0.168	0.116	1.646
1994/95	0.124	0.392	0.074	3.895

Experimental

The study area

The study was carried out between 1993 and 1996 at Aframso, a small farming community (population: <500) in the Ejura-Sekyedumasi District of the Ashanti Region in Ghana (Fig. 1). The study site covers an area of about 216 ha.

The climate is tropical with bi-modal rainfall peaks. The mean annual rainfalll is 1420 mm. The relative humidity ranges from 64 to 84 per cent in January and August, respectively. Natural vegetation is virtually non-existent in the area with marked changes occurring northwards from thick closed secondary forest (5-50 m high) to open forest-savanna with tall grasses.

The area is underlain by rocks of the Upper Voltaian formation (Obosum bed) which is made up of the Afram shales with sandstone and layers of conglomerates and mudstone (Kesse, 1985). The rocks are generally fine-grained and are weathered by variable natural and artificial agents into residual sandy and sandy-clay soils that overlie decomposing sections of the bedrock. The thickness of the weathered zone varies from 0 to 10 m.

The area is drained by the perennial Afram River and its seasonal tributaries (Fig. 1) including the Chirade, Onwam, Asuboni and Chirimfa, covering a total basin of 895 km^2 (Kankam-Yeboah & Mensah, 1997). Table 1 shows a summary of the river flow information from 1988 to 1996. The mean daily discharge ranges from 0.04 to 0.73 m^3 s^{-1}. In the wet season, large surface runoff occurs, resulting in extensive floods up to about 50 cm.

Groundwater mainly occurs within the sandstones and conglomerates at depths ranging between 17 and 55 mm. Duah, Dapaah-Siakwan & Adzaku (Unpublished) indicate that groundwater yield ranges from 0.5 to 10 m^3 h^{-1} from wells drilled up to 90 m into the aquifer.

Irrigation water

Assessment of water quantity. Rainfall and river water are the most important sources of water for irrigation in Ghana. One useful method for evaluating the sufficiency (quantity) of rain water for irrigation is the application of the effective precipitation index (EPI) suggested by Nathan (1997). Crop (irrigation) water requirement and river flow statistics are other important indicators. Irrigation water requirement (mm) is particularly helpful in the computation of volumetric (water) needs of crops which may be evaluated from the supply side. For example, the FAO (1987) reports that a relatively simple linear relation exists between annual rainfall and crop water requirement of tropical cereals, including rice. Assuming an irrigation efficiency of about 50 per cent (no water control), the water requirement (w) can be represented by the following relation:

$$w = 1672 \exp(-4.98 \times 10^{-4} R) \quad (1)$$

where R is the average annual rainfall in mm. The above also provides enough basis for understanding the EPI concept. Thus, if the total surface water delivery exceeds the irrigation requirements, evapotranspiration losses, infiltration, etc. there is water surplus, and *vice versa*.

Assessment of water quality. For most agricultural water quality studies, major physico-chemical parameters that can be measured have been provided in detail by Kandiah (1990). This paper focuses only on some of the most important parameters that are likely to influence soil salinity, permeability and specific ion toxicity problems in the Afram river valley bottom. The parameters include total dissolved solids (TDS), sodium (Na^+), calcium (Ca^{2+}), potassium (K^+) and magnesium (Mg^{2+}). Other parameters are chloride (Cl^-), bicarbonate (HCO_3^-), nitrate (NO_3^-), hydrogen ion concentration (*p*H) and electrical conductivity (EC_w).

Total salt concentration (for all practical purposes,TDS) is one of the most important agri-

TABLE 2

Guidelines for the interpretation of water quality for irrigation

Potential irrigation Problem	*Units*	*Degree of minimum use* None	*Slight to moderate*	*Severe*
Salinity				
EC_w	dS cm^{-1}	< 70.0	70.0-300.0	> 300.0
TDS	mg l^{-1}	< 450	450-2000	> 2000
Infiltration				
ASAR	-	< 6.0	6.0-24.0	> 24.0
Ec	dS cm^{-1}	>50.0	50.0-200.0	< 200.0
Speccific ion toxicity				
Sodium (Na)	ASAR			
Surface irrigation		< 3.0	3.0-9.0	9.0
Sprinkler irrigation		< 3.0	>3.0	
Chloride (Cl)	meq 1^{-1}			
Surface irrigation		< 4.0	4.0-10.0	> 10
Sprinkler irrigation		< 3.0	> 3.0	
Boroo (B)	mg 1^{-1}	< 0.7	0.7-3.0	> 3.0
Miscellaneous effects				
Nitrogen (N-$N0_3$)	mg 1^{-1}	< 5.0	5.0-30.0	>30.0
Bicarbonate (HCO_3)	meq 1^{-1}	< 1.5	1.5-8.5	> 8.5
*p*H			6.4-8.5	

Source: Modified from Ayers & Westcot (1976 & 1985); FAO (1985) cultural water quality parameters. According to Pescod (1992), dissolved salts increase the osmotic potential and pressure of soil solution, thereby increasing substantially the amount of energy that crops should expend to take up water. As a result, respiration is increased and the growth and yield of most crops (including rice) decline progressively. Pescod (1992) has also noted that the rate of accumulation of salts in the soil (soil salinization) is directly affected by the salinity of the irrigation water. Besides, irrigation water that contains ions of boron, chloride and sodium above recommended values (Table 2) can cause rice toxicity depending on the stage of crop growth, climate and soil conditions.

Sodium is a unique cation because of its effect on soil. When present in the soil in exchangeable form, it can cause adverse physico-chemical changes particularly to soil structure. It possesses the ability to disperse soil, when present above a certain threshold value, relative to the concentration of TDS. Soil dispersion results in reduced infiltration rates of water and air into the soil. When dried, dispersed soil forms crusts that are hard to till and interfere with seed germination and emergence of rice seedlings. Irrigation water could be a source of excess sodium in the soil solution and, hence, it should be evaluated. The most reliable index of sodium hazard of irrigation water to soil is the sodium adsorption ratio (SAR) defined by the following equation:

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

where the ionic concentrations are expressed in meq l^{-1}.

Since rainfall in the study area is considerably high and affinity between Ca^{2+} and both CO_2 and HCO_3^- is chemically high, the use of Equation 1 has been extended to take account of calcium solubility by calculating the adjusted sodium adsorption ratio (ASAR) according to procedures outlined by Ayers & Westcot (1976, 1985) and Tchobanoblous & Burton (1991). ASAR is defined by Equation 3

$$ASAR = SAR * \{1 + (8.4 - pHc)\} \quad (3)$$

where *p*Hc is a variable derived factor from Ayers & Westcot (1985) in reference to the alkalinity and concentrations of sodium, potassium, calcium and magnesium ions of irrigation water.

Electrical conductivity is widely used to indicate the total ionized constituents of water. It is directly related to the sum of the cations (or anions) as determined chemically and is closely correlated, in general, with the total salt concentration. Electrical conductivity can be rapidly and precisely determined and values are always expressed at a standard temperature of 25 °C to enable comparison or readings taken under varying climatic conditions (Kandiah, 1990). It should be noted that electrical conductivity of solutions increases with approximately 2 per cent per °C increase in temperature. Electrical conductivity has been expressed as dS cm^{-1}.

Hydrogen ion concentration (*p*H) is an indicator of the acidity or alkalinity of water but it is seldom a problem by itself. The normal range for irrigation water is from 6.5 to 8.4 (Ayers & Westcot, 1976, 1985). The *p*H values outside this range are a good warning that water may have unsatisfactory quality.

Data collection and analyses

A 30-year rainfall data (1966 - 1995 inclusive) was obtained from the Meteorological Services Department and statistically analyzed. Reference crop evapotranspiration of the Aframso area was computed for the mean year with the aid of the software Cropwat (Smith, 1992).

Two methods were applied for assessing the quantity of water available for irrigating rice in the Aframso river basin. Firstly, the Nathan (1997) effective precipitation index (EPI) (defined as the net rainfall that is available for river recharge and irrigation) was used to evaluate monthly rainfall (precipitation) and evapotranspiration data. the EPI is given as in Equation 4:

$$EPI = (P - PET) / P_a \quad (4)$$

where P is rainfall (mm), PET is reference crop evapotranspiration (mm) and P_a is total annual rainfall (mm). To get rid of the negative sign when PET > P, Equation 4 above can be re-written as follows:

$$EPI = \{(P - PET)/P_a\} + 1.0 \quad (5)$$

and which then leads to three situations:

EPI > 1.0 (surplus water);
EPI = 1.0 (enough water), and
EPI < 1.0 (water deficit).

urements. The data was then statistically analyzed. The analysis took account of the following fundamental assumptions:

1. Rainfall is the main source of river recharge at Aframso.
2. Groundwater contribution to river volume is negligible in the short term (the underlying Obosum shales have low porosity and are highly non-fractured).
3. The overall influence of evapotranspiration is considered in the EPI calculations.

TABLE 3
Some hydrometeorological information of the Afram river basin (1986-1995)

Month	*Total rainfall (mm)*	*Evapo-transpiration (mm)*	*Humid days*	*Rainfall surplus (mm)*	*EPI*
January	2.4	122.3	-	-	0.908
February	23.1	105.3	-	-	0.937
March	98.2	106.2	-	-	0.994
April	125.8	114.8	30	11.0	1.008
May	155.4	105.4	31	50.0	1.039
June	197.2	102.9	30	94.3	1.073
July	147.2	103.4	31	43.8	1.034
August	70.0	115.5	-	-	0.965
September	226.9	112.9	30	114.0	1.088
October	186.6	112.0	31	74.6	1.057
November	31.0	100.8	-	-	0.946
December	33.8	123.7	-	-	0.931
Total	1,297.6	1,325.2	183		

EPI: Effective precipitation index

For rainfed rice-based production, the first situation is the most important while the second suggests sufficient water for irrigation. The actual depth of water can, therefore, be derived from Equation 6:

$$P - PET = (EPI * P_a) - P_a \quad (6)$$

Secondly, river flow data collected from the Hydro Division of the Ministry of Works and Housing was validated through minimum *in situ* meas-

For river water quality assessment, a total of 48 water samples (collected monthly from 1994 till 1997) were analyzed based on relevant physico-chemical parameters.

Sampling was done using 1-litre plastic bottles which were thoroughly washed and rinsed with river water. Physico-chemical analysis of water was carried out at the Environmental Chemistry Laboratory of the Water Research Institute regarding the following indicators: total dissolved

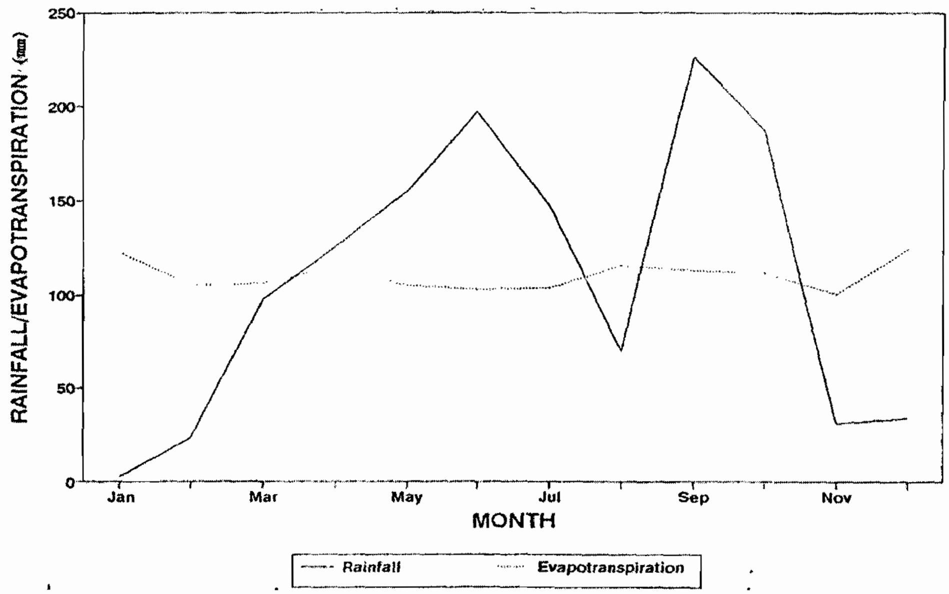

Fig. 2. Water balance at Aframso

solids (TDS), sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-), nitrate (NO_3^-), hydrogen ion concentration (*p*H) and electrical conductivity (EC_w).

The above analysis was carried out based on the standard methods as described in APHA (1985). Again the Ayers & Westcot (1985) irrigation water quality guidelines were used in the evaluation of the water quality for irrigation.

Results and discussion

Quantity of water for irrigation

Table 3 and Fig. 2 give relevant hydrological information about the Afram basin. Whereas total annual rainfall deficit of about 25 - 30 mm yr^{-1} exists (which needs to be compensated for by irrigation), the main wet season (April- September) shows a total rainfall surplus of over 350 mm. The surplus corresponds with the main rice-growing period at the project site. But is this an indication of adequate water for irrigating rice in the Aframso area?

Table 3 shows the EPI values for the Aframso area. There is sufficient irrigation water (i.e. EPI $\geq$ 1.0) for most part of the rice-growing season (May - September). This period also coincides with the wet season but the EPI < 1.0 in August confirms the usual dry spell for that period. The evaluation of the irrigation requirement (Table 4) seems to give a contrary view point, in that rice crop at the Aframso may suffer water stress for the growing season. Nevertheless, the EPI results suggest sufficient river recharge for irrigation considering the mean annual runoff volume and daily discharge of the Afram river, which are estimated as 3.2×10^6 m^3 and 0.13 $m^3 s^{-1}$, respectively. It must be noted that the above contradiction is not unexpected (*see* Nathan, 1997). Whereas the irrigation water delivery (field modulus) deals with at least a 10-day time interval, the EPI calculation only considers monthly rainfall (due to data capture limitations).

What needs to be further investigated is the adequacy of soil moisture and deep percolation losses. Again, the potential for groundwater utilization is high (up to 10 $m^3 h^{-1}$ in the shales of the Obosum rock beds) and could be further investi-

TABLE 4
Irrigation water requirements of rice at Aframso

	May	June	July	August	Sep (i)	Sep (ii)	Oct
Crop coefficient (kc)	1.1	1.2	1.3	1.3	1.2	1.1	1.0
Water requirement (mm)	364	285.2	260.7	287.8	84.7	26.9	-
Rainfall (mm)	92.1	192.8	128.2	70.6	68.0	22.7	-
Irrigation requirement (mm)	271.9	92.4	132.5	217.2	16.7	4.2	-
Depletion rate (mm per day)	3.7	1.9	3.4	6.0	1.5	1.1	-
Field modulus (1 s^{-1} ha^{-1})	2.04	0.72	0.78	1.62	0.26	0.06	-

gated as a complement to rainfall and river water for small-scale irrigation.

Quality of water for irrigation

Table 5 presents a statistical summary of the physico-chemical analysis of the Afram river wa-

TABLE 5
Summary of water quality data of Afram river at Aframso

Parameter	*Mean*	*Minimum*	*Maximum*	*SD*	*FAO rating values*
*p*H	6.50	6.30	6.90`	0.34	6.5-8.4
Alkalinity ($CaCO_3$)*	1.31	0.87	1.53	0.15	8.5
Turbidity (NTU)	26.46	11.30	49.00	6.00	1000
Conductivity (dS cm^{-1})	0.094	0.078	0.105	0.08	> 300
Total dissolved solids (TDS)	73.00	56.00	80.00	4.78	> 2000
Calcium (Ca^{2+})*	0.39	0.25	0.41	0.02	5.0
Sodium (Na^{+})*	7.25	4.70	8.00	0.49	9.0
Potassium (K^{2+})**	0.16	0.10	0.27	0.03	4.0
Magnesium (Mg^{2+})*	0.29	0.06	0.40	0.04	4.0
Iron (Fe)*	0.04	0.002	0.09	0.01	5.0
Chloride ($C1^{-}$)*	0.25	0.19	0.36	0.04	> 50
Sulphate (SO_4^{2-})*	0.03	0.02	0.09	0.01	10.0
Bicarbornate (HCO_3)*	0.60	0.43	0.76	0.07	> 8.5
Silica (SiO_3)*	18.71	13.41	27.00	2.84	100
Nitrate (NO_3-N)**	1.06	0.01	3.30	0.46	> 30.0
Phosphate (PO_3-P)**	0.18	0.07	0.36	0.45	10.0
Adj. SAR	0.323	0.052	0.463	0.05	> 24.0

Note: Except *p*H, ASAR, conductivity and turbidity, other parameters have units in meq l^{-1} (*) or mg l^{-1} (**). (Value are each computed from 48 parametric samples.)

ter (at Aframso). The mean TDS of Afram river water (73.0 mg l^{-1}) is by far lower than the FAO threshold value of 2000 mg l^{-1} (FAO, 1987). This is comparable with observations made by Opoku-Duah, Kankam-Yeboah & Mensah (1999) in respect of water from the Oda River in Ghana (i.e. 118 mg l^{-1}).

The mean EC_w of the Afram river water (~ 0.09 dS cm^{-1}) is considered far too insignificant to cause salinity problems at the Aframso site. The EC_w threshold likely to cause moderate to severe salinity problems has been determined by Ayers & Westcot (1985) as 70 -300 dS cm^{-1}, respectively.

Even though the mean ASAR (0.32) was slightly higher than what was observed for the Oda River water (0.12) at Besease, the above level was again far below the threshold value of 6.0 to cause salinity and infiltration problems. Besides, the mean ASAR falls below the minimum level of 3.0 likely to cause ion toxicity problems.

Similarly, the mean $N\text{-}NO_3$ level (1.06 mg l^{-1}) is less than the FAO threshold value of 30 mg l^{-1}, likely to promote excess growth of leafy shoots at the expense of rice grain filling. Many scientist, including Driessen & Dudal (1991), Doorenbos & Pruitt (1997), Doorenbos & Kassam (1979) and Roscher (1989) have reported that increased soil $N\text{-}NO_3$ often promotes residual mineralization of organic matter which leads to unproductive tillering of rice, delayed or uneven maturity, or reduced crop quality. In the present study, the level of nitrogen in soil water is considered rather beneficial (natural fertilizer) for the rice crop throughout the growing period.

From Table 5, the *p*H of the river water (~ 6.5) and the HCO_3^- (0.060 meq l^{-1}) are comparable with similar humid agricultural catchments (e.g. the Oda river basin). Here, the biochemical activity over soil litter leads to low soil redox potential which may be consequential to the generally low *p*H and HCO_3 levels. The above results illustrate the suitability of the Afram River water for irrigated rice-based cropping at Aframso.

Conclusion

Rice farming at the Aframso project site is primarily rainfed. The Nathan's effective precipitation index (EPI) as well as flow characteristics of the Afram river suggest sufficient amounts of water for small-scale rice irrigation at the Aframso project site in the major growing season.

Again, the study has shown that, in terms of surface water quality, the Afram river water is very suitable for small-scale irrigation. The levels of TDS, Na^+, Cl^-, *p*H and conductivity are far below threshold values that irrigation water will not cause salinity, permeability or crop toxicity problems, except under extremely poor drainage and/or water management practices.

Furthermore, the level of $N\text{-}NO_3$ could provide substantial benefit as natural fertilizer throughout the rice-growing season in the Aframso area.

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