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# Assessing crop water productivity at Nyanyadzi smallholder irrigation scheme in Zimbabwe

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**Abstract**
This study determines the effects of variations in relative water supply (RWS) on bean and wheat crop water productivity (WP) under irrigation in Block C at Nyanyadzi irrigation scheme in Zimbabwe. Water supply, bean and wheat crop yield data spanning 17 cropping seasons from 1970 to 2003 were obtained from the irrigation scheme files. Research findings show a weak and significant ($R^2$=0.448, p = 0.006) quadratic relationshipbetween bean WP and RWS. Whereas, for the wheat crop, the relationship WP and RWS is a linear and significant ($R^2$ = 0.438, p = 0.004). Based on the research findings, the study recommends the measures to improve water supply and therefore, crop production. These include among others, switching to more drought tolerant crop varieties that require less water, rainfall harvesting, water conservation measures to retain soil water and, use of more efficient water application methods.

**Keywords:** Crop Water; Irrigation Performance; Nyanyadzi Irrigation Scheme; Relative Water Supply; Water Productivity

## INTRODUCTION

Global food production is increasing at a rate of 1.3% per year while the annual population growth stands at 33%. This imbalance is resulting in chronic food shortages felt by a quarter of the world's population or a third of those living in developing countries (FAO, 2002; Gilland, 2002). With rising incomes and urbanisation, the nature of food demand and preferences is also changing. As the rate of urbanisation is increasing by 61% between 2000 and 2030, human food demand is shifting from coarse grains to rice and wheat. At the same time, there is rising demand for coarse grains as animal feed (FAO, 2002). To meet these potential increases in food and nutrition demands, the Food and Agriculture Organisation of the United Nations (FAO) has projected that global food production needs to increase by 70% by 2050, thus adding 120 million hectares of cropland in the developing world. Nevertheless, there is a potential associated loss of 50 million hectares of cropland from the current 1.873 billion ha in developed countries to yield the current (FAO, 2002).

Under conditions of changing food preferences and increasing population, food production can be improved by diversification, extensification and intensification. However, it is widely accepted that the expansion of croplands and increased allocations of water for growing more food involve very heavy

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*Corresponding author: nemuj@yahoo.co.uk ecological and economic costs. Further, any expansion likely leads to an increase of greenhouse gases, primarily from clearing remaining tropical forests, savannas and/or wetlands vital for the health of the planet (Foley *et al*., 2020).

The world requires growth in crop production by 75% is required to feed 8 billion people by 2030 (FAO, 2002). This is expected to be achieved through increasing crop yields by 62%, cropping intensities by 13% and expanding arable land by 25% (Gilland, 2002). Accordingly, irrigated agriculture plays a critical role to improve the food availability and security. On a global scale crop yields from irrigation are estimated to triple or even quadruple from the 2000 figures by the year 2030 as a result of increasing crop output per unit land or per unit of water supplied. In developing countries, irrigated land area is expected to increase by 27% between 1996 and 2030 (Gilland, 2002; FAO, 2003).

Irrigation is practised to avert the food shortages, a situation which most developing states have become endemic. Almost 20% of the world's 1,500 million hectares under irrigation provides 40% of the food and 70% of cereal production (FAO, 2003). Irrigation also helps modernising peasant agriculture, reducing drought relief from the government, providing economic growth and employment opportunities, export earnings, more varied diets and better health standards (Kemerink-Seyoum *et al*., 2019; Scoones *et al*., 2019). Despite the considerable potential of smallholder irrigation projects, they are sub-optimally performing due to poor water supply, sustainability, market access and low productivity (Seckler, 1999; FAO, 2000). Inadequate water resources are increasingly becoming a major threat to food production and food security in arid and semi-arid areas. For example, in Zimbabwe more than 550,000 ha are suitable for irrigation, but only 331,000 ha are irrigated due limited water supply. Also, from 1982 to 1985, the irrigated area dropped from 165,000 ha to 136,000 ha as a result of droughts experienced in the country (Scoones *et al*., 2019).

The performance of irrigation projects, measured in terms of its water delivery, efficiency of water resource use, productivity, gross margins or return on investment, is largely dependent on available water resources (Seckler, 1999; Benavides *et al*., 2021). Water delivery performance measures include adequacy, equity, reliability and timeliness of water supply. Agricultural productivity at relates input to output and is assessed using quantifiable indicators of mass or economic value of crops produce per unit of irrigated area or volume of water supplied, that is water productivity (Sivakumar, 2021).

Water productivity (WP) is the amount of production from an area of land relative to water drawn, applied or consumed (Zoebl, 2006; Foley *et al*., 2020). It is an important index that takes into account of agricultural production and water use efficiency. Considering the amount of water consumed, agricultural water productivity is expressed as a ratio of evapotranspiration to crop yield or income. If output prices are used, water productivity is expressed in economic terms (Li *et al*., 2016). Economic water productivity considers the monetary value of the benefits produced per unit of water used or consumed. Physical water productivity refers to the produced amount of crop per unit volume of consumed water or supplied (Yokwe, 2009).

The growing physical water scarcity is hampering the food security. Over the past years, the concept of water productivity in agriculture has gained ground with a shift from land productivity to water productivity due to increasing shortage of irrigation water productivity. Besides agriculturalists, water productivity is relevant to economists and engineers who are interested in evaluate the sustainability and efficiency of agricultural water management in terms of produced yields per unit of water used. Strategies to increase the crop WP or produced yields per unit of water used, often referred to as ‘more crop per drop’ include increasing the yield of crop without using more water and reducing water use while maintaining or increasing yields (Yokwe, 2009).

To increase the crop WP, a clear understanding of how much water is used, where it is used, and its variability to produce a certain amount of crop is crucial. This helps us establish cropland areas where the crop WP is high, moderate, or low, establish causes for variability, and develop strategies for increasing it to achieve optimal production levels (Clemens and Molden, 2007; Carr *et al*., 2016). Identifying areas of disproportionate water use or water limited yield gaps is critical for supporting improvements in agricultural water management. Plant genetics, climate conditions, crops, soil properties and agronomic practices significantly cause variaions in the crop WP within and between farms (Zoebl, 2006; Bennet and Harms, 2011; Sivakumar, 2021).

Several studies have dealt with variations of crop water productivity with respect to evapotranspiration, rainfed and irrigated conditions in the global north (Carr *et al*., 2016). Regardless of the importance of crop water productivity in evaluating the efficiency and sustainability of agricultural systems, very few studies have been conducted in smallholder irrigation schemes in arid and semi-arid countries of the global south. This study therefore, determines how variations in relative water supply (RWS) affects crop WP at Nyanyadzi smallholder irrigation in Zimbabwe.

## MATERIALS AND METHODS

### *Study area*

Nyanyadzi irrigation scheme is located within semi-arid communal lands in Chimanimani District to the east of Zimbabwe (Figure 1). The scheme covering 440 ha, is state owned and, is administered and managed by the Department of Agricultural Rural Extension (AGRITEX) services under the Ministry of Agriculture (Mujere, 2011). Nyanyadzi irrigation scheme was opened in 1934 as part of the colonial government to disposess the native Zimbabwean population from their fertile lands upstream and to resettle them in smaller pieces of marginal land downstream. It also acted as a drought relief project to; provide food in an area of recurring droughts where peasants were only able to produce a meaningful harvest once in five years; reduce government cost in providing famine relief; and to reduce the peasants' method of shifting cultivation and consequential destruction of natural resources by setting them permanently on good soil where proper agricultural practices would occur and encourage peasant movement from subsistence to a cash economy to practise proper agricultural practices (Kemerink-Seyoum *et al*., 2017; UNDP, 2019).

Nyanyadzi irrigation scheme lies at an altitude of 530 m in a down-faulted valley of the Save and Odzi Rivers. Its soils of alluvial origin comprising deep, well-draining sand loams and sand clays of high fertility underlain by coarse river sand. Considerable N-S and E-W faulting has resulted in a complexity of geological horizons outcropping in the area. Rocks comprise basement complex granites, limestones and quartzites of the Umkondo system to pre-Karoo dolerites intruding into the Umkondo system rocks (Mujere, 2011).

### *Hydro-climatic conditions*

The scheme lies within the dry agro-ecological zone of the country on the rain shadow side of Eastern Highlands. Its mean monthly temperature range is 10°C. The highest mean monthly temperatures of 25°C is experienced in October, the hottest month. Whereas, July as the coldest experience a lowest mean monthly temperature of 15°C (Figure 2).

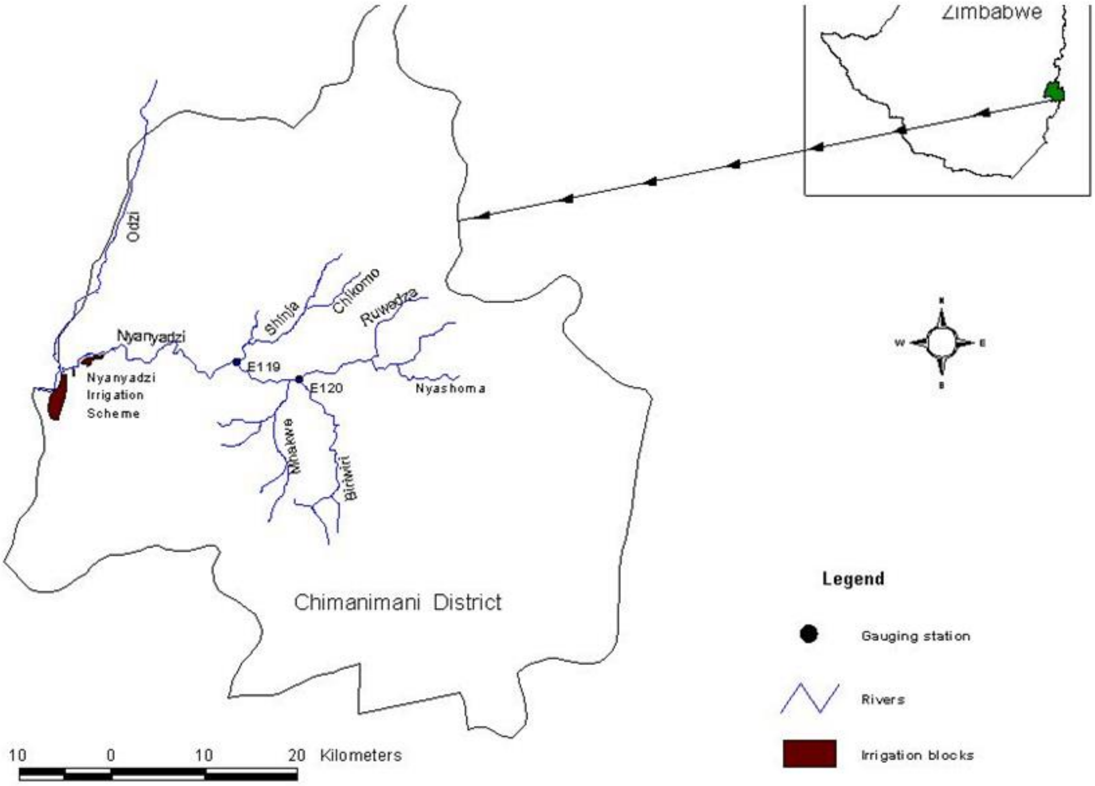

**Fig. 1.** Location of Nyanyadzi irrigation scheme in Chimanimani district

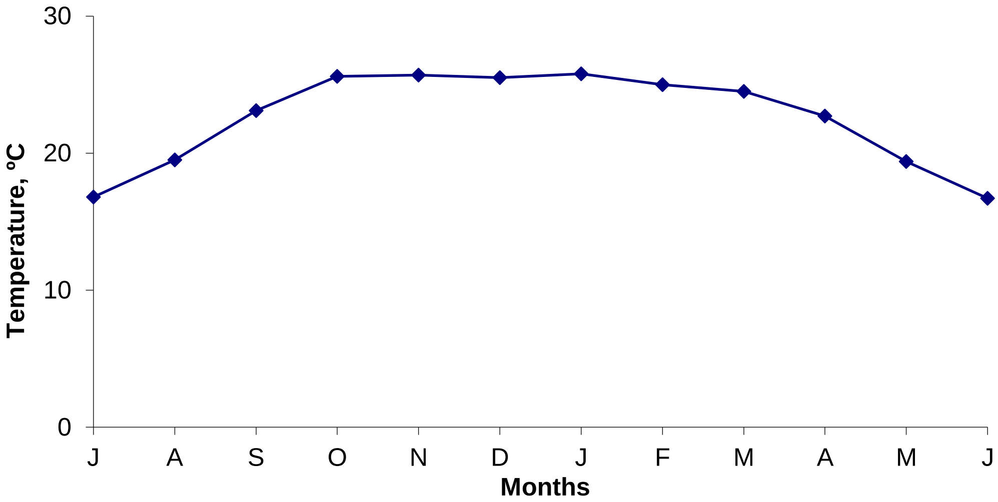

**Fig. 2.** Distribution of mean monthly temperature from 1970 to 2003

The scheme receives less than 400 mm of rainfall annually (Figure 3). The rainfall is unreliable since it comprises erratic and isolated rainstorms (Kemerink-Seyoum *et al*., 2019). The rain season occurs between October and March, but the onset of the rains may be delayed until late December and terminate at the beginning of February. In such a dry region of the country, irrigation water is crucial to satisfy crop water demand.

The total annual pan evaporation can rise to about 1900 mm while a daily maximum of 11 mm between September and February is often experienced. Annual evapotranspiration rates exceed rainfall even during the rainy season. The area's mean annual evapotranspiration is about

123 mm while the aridity index (mean annual evaporation divided by mean annual precipitation) is 3.0 (Figure 4).

***Irrigation water supply***

Nyanyadzi irrigation scheme obtains its water from both Nyanyadzi River and Odzi River. An open canal which was lined in 1996, diverts water from Nyanyadzi River by means of a weir and a gated off-take to Block C (65 ha) and the night storage dam. Three separate gates along the canal divert water into Block C. Water lifted from Odzi River is pumped and conveyed to the night storage dam through a concrete pipe (Mujere, 2011). From the night storage dam (Figure 5), water is distributed to Blocks A (137 ha), B (147 ha) and D (69 ha).

A block system of irrigation is practised. Flood irrigation is used in all the blocks. Farmers take water from the field canals using at each irrigation turn. Water movement to individual plots is controlled by sluice gates operated by water bailiffs assisted by supervisors along field canals. The irrigation schedule proceeds plot by plot along field canals and each farmer is notified about the time of receiving water. The blocks receive their water supply from 6 am to 4 pm on rotational basis according to a pre-designed schedule. The scheme has a design irrigation efficiency of 70% below the field gate (Mujere, 2011). This indicates that 70% of water transferred from the field gate reaches the crop root zone. Thus conveyance, distribution, field application and percolation losses constitute 30% of irrigation water supply.

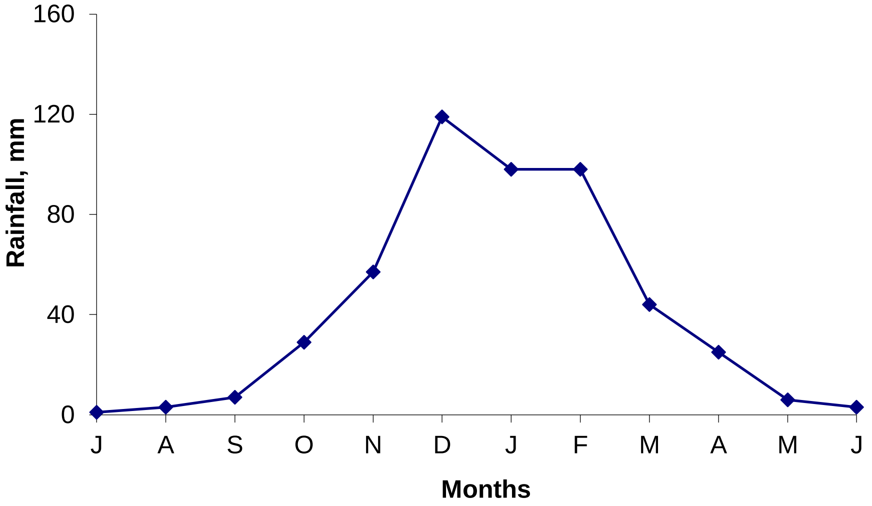

**Fig. 3.** Unimodal distribution of mean monthly rainfall from 1970 to 2003

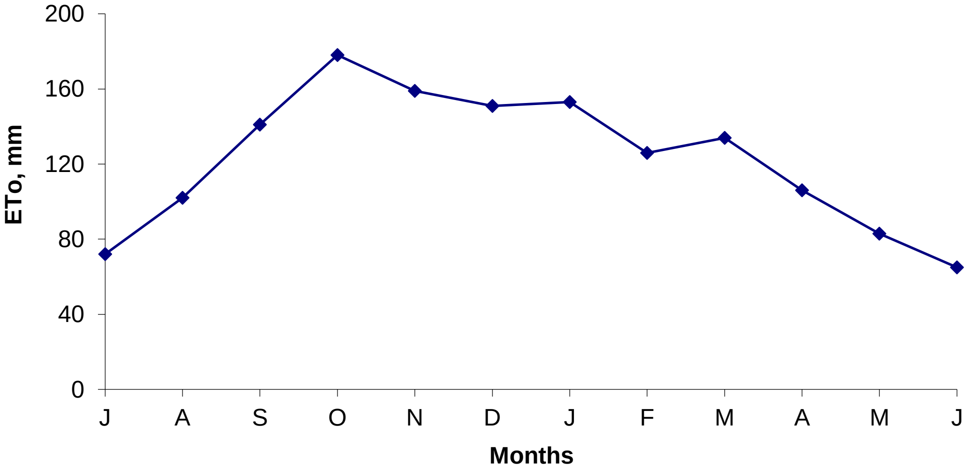

**Fig. 4.** Mean monthly reference evapotranspiration from 1970 to 2003

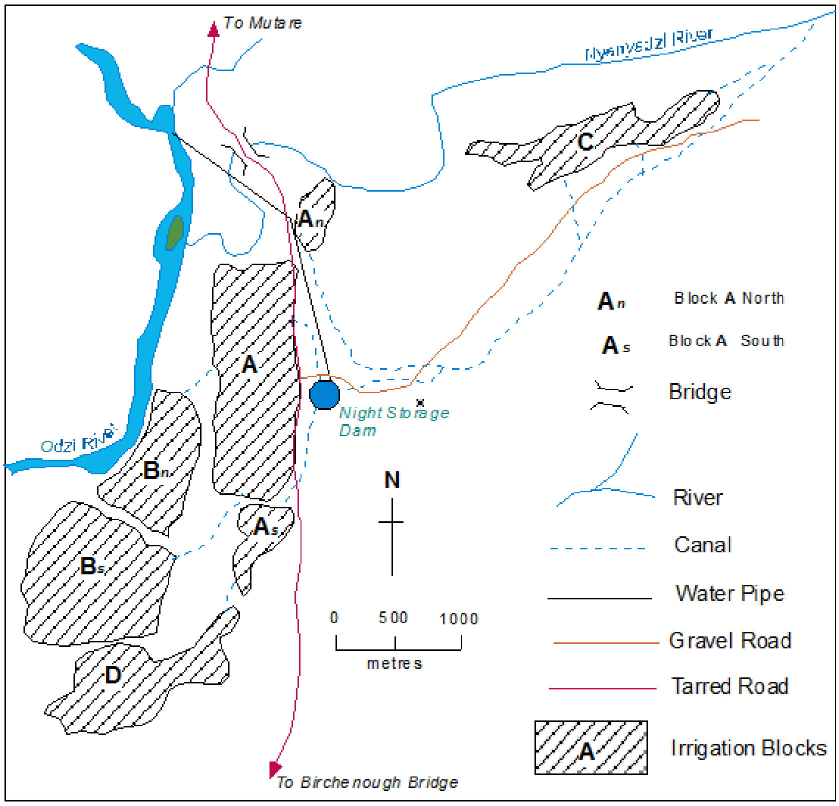

**Fig. 5.** Layout of Nyanyadzi irrigation and its water supply infrastructure

### *Cropping patterns*

The project manager and agricultural extension workers are responsible for irrigation scheme water supply. They make sure farmers adhere to uniform cropping patterns in each block and monitor the application of inputs in the fields. Crops are almost planted and harvested at the same time during each cropping season. On average, three crops are planted in each plot annually. The general pattern is maize and groundnuts during summer (October-February), beans, wheat and tomatoes in winter (March-September). Winter season cropping calendar commences in March when tomatoes and beans are planted. In June, beans are harvested while the wheat cropping season starts. Wheat is harvested in September. In Block C, contract farming of beans and tomatoes between irrigators and private companies was put in place in the early 1990s. The companies offer loans and train farmers basic agronomy skills. More than 50% of the cropland is put under tomatoes in winter because the soils are sandy (Mujere, 2011).

### *Data collection and analysis*

A case study approach was opted for, to facilitate in-depth insights into the subject under investigation since the scheme is too large to study within the given time period and available resources. Thus, among the scheme’s four blocks, Block C was selected to give an in-depth snapshot view of scheme water productivity. Since the block depends directly on irrigation water supply from Nyanyadzi River, it was easy and straight forward to estimating irrigation water supply. Also, long term winter season river flow, rainfall and crop yields data were readily available from responsible agencies.

Permission to conduct the research was granted by scheme AGRITEX officials at the scheme. After the permission was granted, primary data gathering commenced. Data collected included cropping programmes, landholding, land tenure, number of plot holders, problems, water supply and productivity of block.

*Estimating irrigation water supply and water productivity*

The volume (V, $m^3$) of water abstracted from Nyanyadzi River was expressed as irrigation depth (I, mm) using the equation (Zhang *et al*., 2016):

$$I = \frac{V}{A} \qquad (1)$$

where: *I* is the irrigation depth in mm, *V* is the volume in $m^3$ and *A* is the irrigated area in $km^2$

Crop water productivity (WP, t/mm) was estimated from crop output (C, t) and amount of water received in the field, irrigation depth plus rainfall (Y, mm) using the equation (Clemens and Molden, 2007):

$$\mathrm{WP} = \mathrm{C}/\mathrm{Y} \qquad (2)$$

WP indicates plot, block or farm level performance based on choices farmers make using available of factors of production. It is a robust measure of the ability of agricultural systems to convert water into food (Zoebl, 2006).

***Determining adequacy of water supply***

The variation of bean crop yields was analysed by comparing water supply (irrigation supply and rainfall) with crop water demand (crop water requirements and losses). To determine whether there were significant differences in WP during periods of adequate and inadequate water supply, comparisons were made between water supply and demand in each cropping season using the relative water supply (RWS) index. The index shows the relative abundance or scarcity of water in the fields by matching water available to the farmers with that which is actually needed. RWS was estimated from amount of water received (S) in the irrigation block and the overall irrigation water demand (D) using the equation (Benavides *et al*., 2021):

$$RWS = \frac{S}{D} \qquad (3)$$

where *RWS* is relative water supply (%), *S* is water received (irrigation depth, I in mm and effective rainfall, P, in mm), and *D* is irrigation water demand (crop water requirements and seepage losses, mm).

A RWS of 80%, denotes the minimum requirements below which significant yield reduction occurs (Bennet and Harms, 2011). Bean CWRs were estimated as 293.6 mm while wheat CWRs were estimated as 344.1 mm using the FAO CROPWAT model version 5.7. Seepage losses along the unlined canal from Nyanyadzi River to Block C were estimated to be 25% of flow at the intake as observed by Pearce and Armstrong (1990). However, since canal was lined in 1996, its seepage losses were estimated to, be negligible since then.

## RESULTS AND DISCUSSION

### *Temporal variations of bean crop water productivity and relative water supply*

Figure 6 shows the variations of bean crop WP and RWS. On average 13.876 t were produced from 511.03 mm of water. The average WP was 0.036 t/mm with a standard deviation of 0.046 t/mm. Crop WP ranged from 0.137 t/mm (1971) to 0.001 t/mm (2000) with a high coefficient of variability of 128%.

The RWS figures vary from 184.41% (1988) to 35.90% (1971) with an average of 109.16%. The pattern of RWS during the bean cropping season depict low variability with a standard deviation of 44.84% and coefficient of variation of 41% (Figure 7).

Figure 7 shows the variations of wheat crop WP and RWS. On average, 5.96 t were harvested using 12.28 mm of water was received. The average WP was 0.455 t/mm with a standard deviation of 0.117 t/mm. Crop WP varied from 0.66 t/mm (1974) to 0.26 t/mm (1971) and show a low coefficient of variability of 21.61%.

The RWS of wheat crop WP ranged from 139.12% (1986) to 23.98% (1987) with an average of 87.16% over the 17 seasons studied. The pattern of relative water supply shows low variability with a standard deviation of 34.28% and a coefficient of variation of 39.33%. Water supply was adequate during 11 cropping seasons (Figure 8).

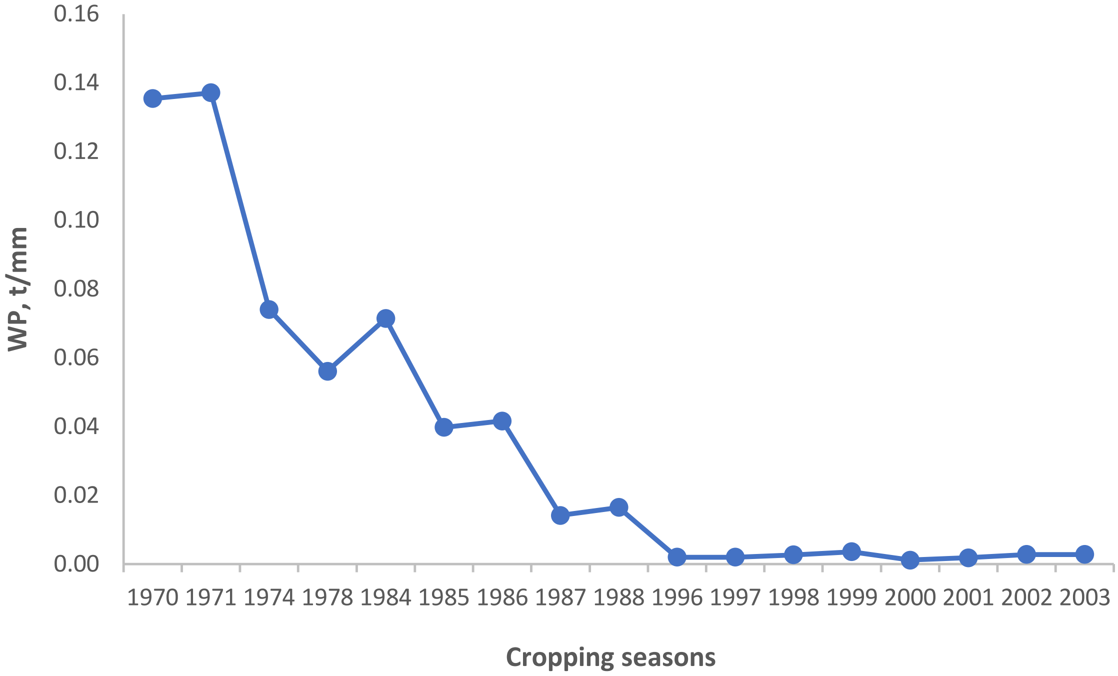

**Fig. 6.** Temporal variations of (bean production per unit water)

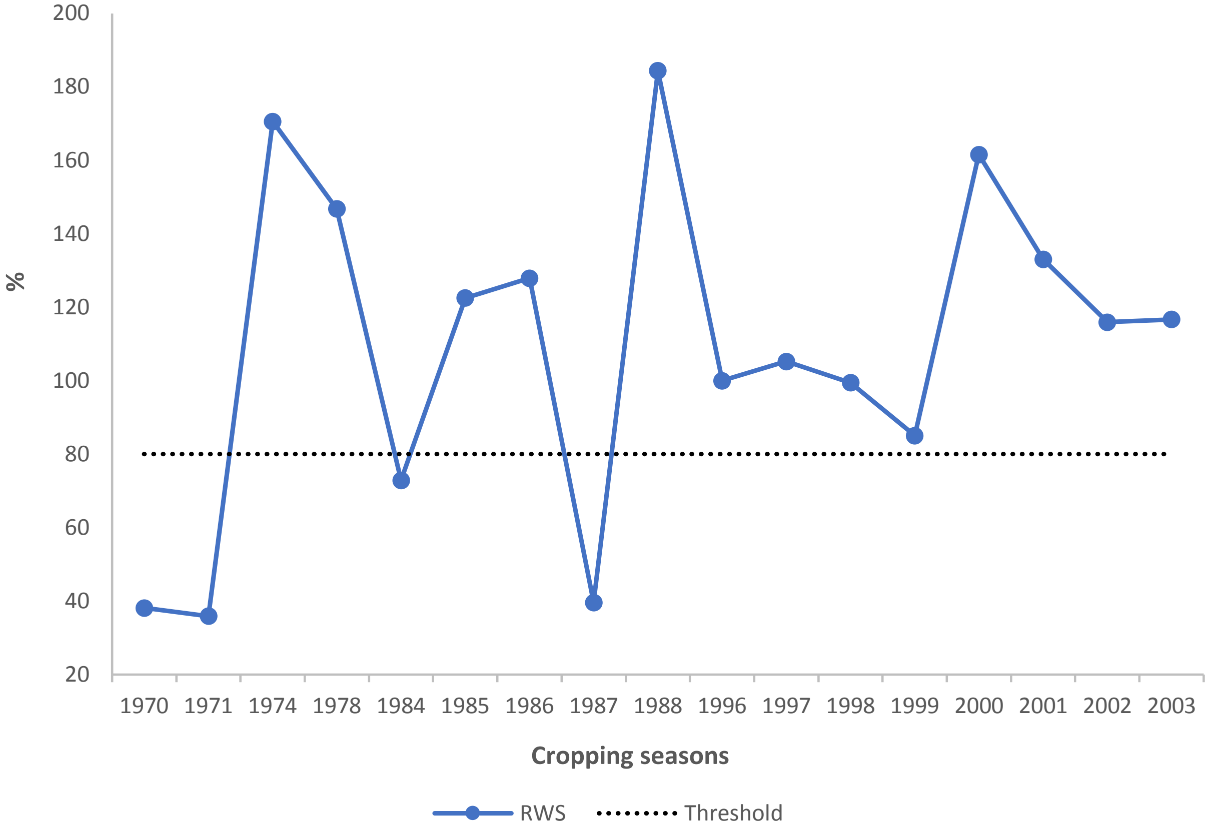

**Fig. 7.** Temporal variations of RWS during bean cropping seasons

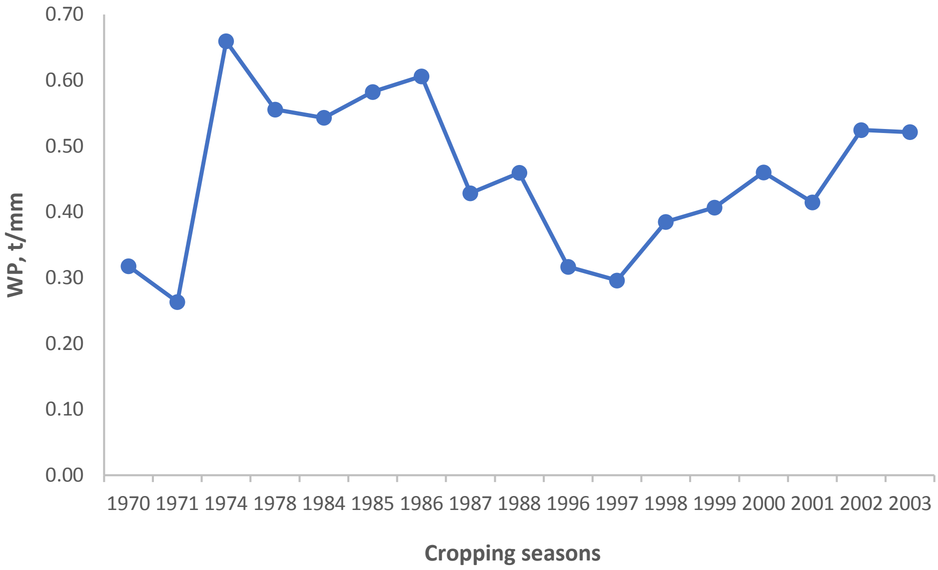

**Fig. 8.** Variations in wheat production per unit water

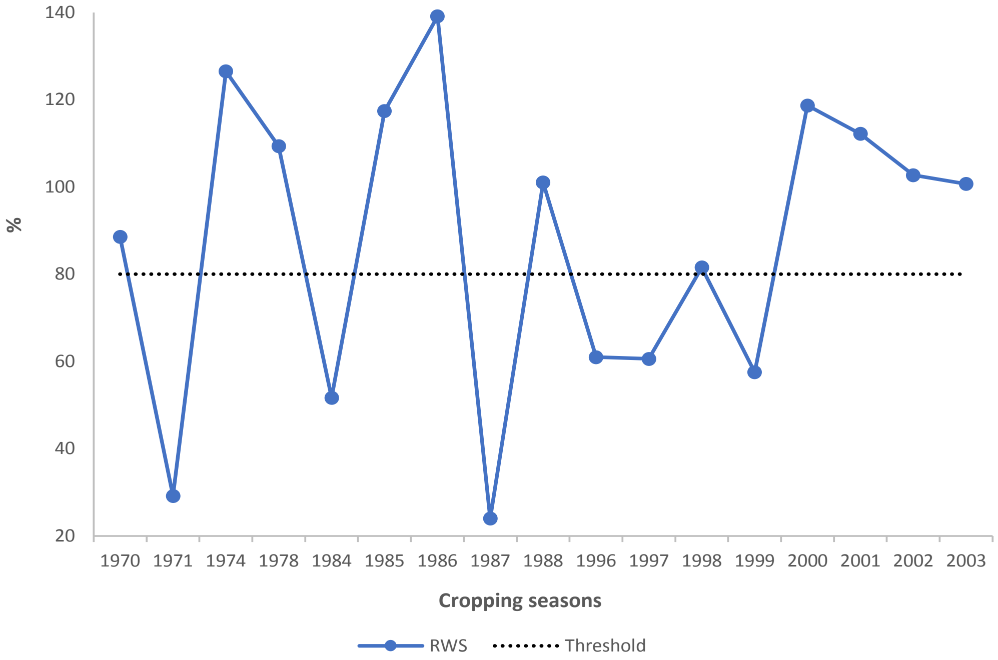

**Fig. 9.** Variations of RWS during wheat cropping seasons

***Relationships between crop WP with RWS***

Figure 9 shows a significant ($F_{2,14}$ = 5.680, $p < .05$, R = 0.669, n = 17) quadratic relationship between bean water WP and RWS. The model shows that WP decreases with RWS during periods on inadequate water supply. Whereas, as water supply becomes adequate, WP increases with RWS.

Figure 10 shows a weak and significant ($F_{2,15}$ = 11.771, $p < .005$, R = 0.663, n = 17) linear relationship between wheat crop WP and RWS. Thus, almost 44% of the variation in WP can be explained by variation in RWS.

Bean crop WP declined during the 17 cropping seasons studied while RWS increased during the same period (Figure 6). Adequate supply (RWS > 80%) was experienced in 13 seasons with an average yield of 0.019 t/mm. During four seasons of inadequate water supply (RWS < 80%), farmers harvested an average of 0.09 t/mm.

Wheat crop WP and RWS show general increasing trends (Figure 7). Adequate supply (RWS > 80%) was experienced in 11 seasons with an average WP of 0.499 t/mm. During six seasons which experience inadequate water supply (RWS < 80%) farmers harvested 0.376 t/mm of wheat on average.

A weak significant quadratic relationship ($p = 0.006$, $R^2 = 0.448$) exist between bean crop WP and RWS (Figure 8). Thus, 55% of the variations in WP can be explained by other factors besides RWS. These confounding factors are not accounted for in the model. Low values of WP during periods of adequate supply can be ascribed to water wastage in the fields. It has been noted that farmers in the scheme tend over-irrigated their fields leading to water logging of soils. In addition, under-irrigation commonly occurs due to water leakage along the distribution canals (UNDP, 2019). Also, farmers have a tendency under-estimate their crop yield data in anticipation to receive food aid from the state and donor agencies. Contrary to the second order polynomial *model* observed *between relative water supply and crop productivity* in this study, a linear relationship was

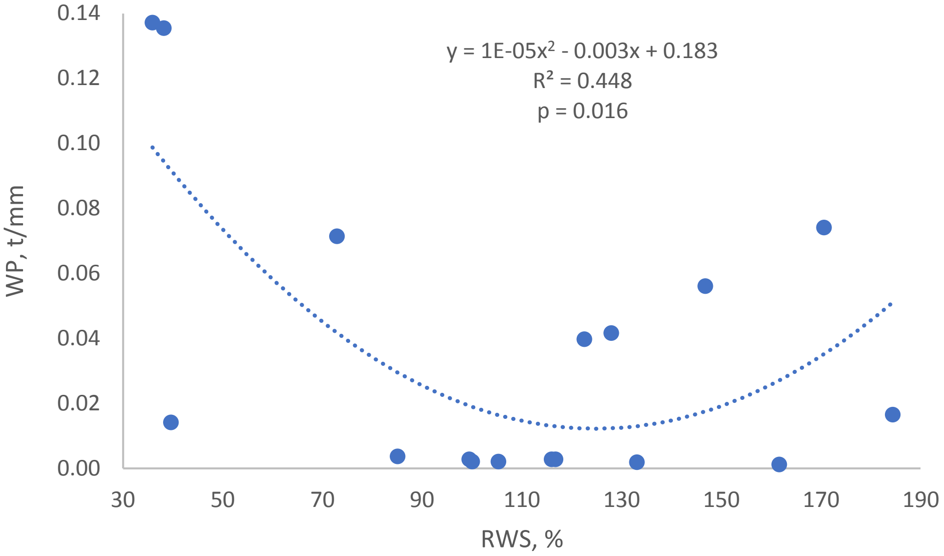

**Fig. 10.** Relationship between bean WP and RWS

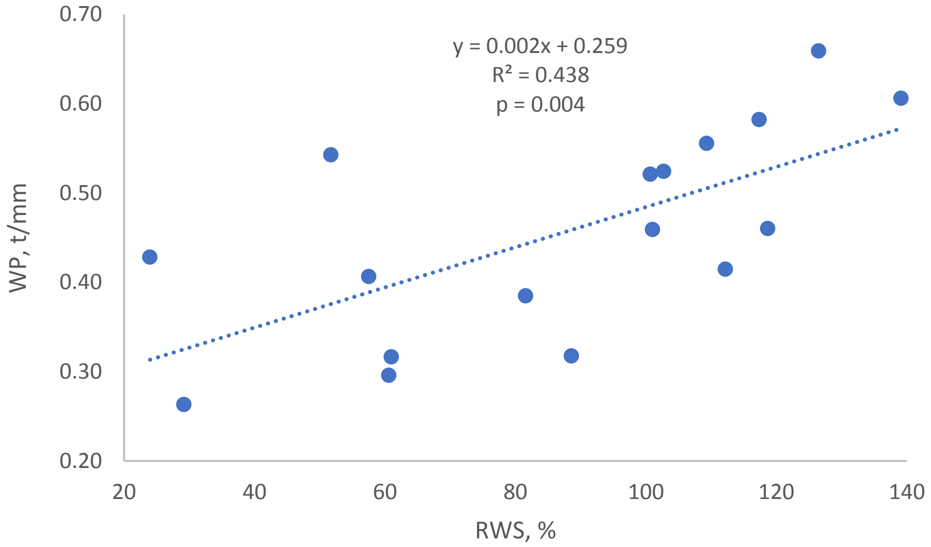

**Fig. 11.** Relationship between wheat crop WP and RWS

assumed in Southern Alberta by Bennet and Harms (2011).

The positive linear relationship (Figure 9) between wheat crop WP and RWS is weak and significant ($p = 0.004$, $R^2 = 0.438$). This means there are other significant factors which explain 56% of variations of crop water productivity. Also, the high degree of data scatter implies they inherent challenges. Studies by Bennett and Harms (2011), Faramarzi *et al*. (2010) and Kumari *et al.* (2017) also found a linear relationship between wheat productivity and water supply in Southern Alberta, Iran and India respectively. Any increase in water supply resulted in large improvement in crop WP. To improve wheat production in Iran, Faramarzi *et al*. (2010) recommended increasing the quantity of cereal production through more efficient use of land and water resources, improving activities related to soil moisture conservation and retention, and optimizing fertilizer application.

Several research gaps can be identified from this study. Using agricultural WP is useful to benchmark the performance of irrigated agriculture has sometimes been questionable because of the overemphasis on performance of just one production factor. It depends on a number of inputs, and each farmer will strive to use the proper mix of these inputs to obtain. It is defined as crop yield produced per unit of irrigation water used.

In estimation of seepage losses, it was assumed that irrigation efficiency below the field gate was 30% of irrigation water supply. This figure was based on the design scheme irrigation efficiency is 70%. Multiplying irrigation water supply by 0.3 when estimating losses does not enable a more realistic comparison between water supply and demand to be made. Such an optimistic figure corresponds to conditions of tight irrigation management of which the present situation at Nyanyadzi may not the case. Hence the resultant figure tended to under- and over-estimate losses and RWS value respectively.

Matching crop water requirements and local water supply was problematic since many factors made it difficult to arrive at values that are 100% correct. Due to shortage of resources, the effects of other confounding factors like field water utilisation and fertiliser input levels were not considered. Research on such factors, can help to explain variability of crop water productivity.

## CONCLUSION

Water scarcity has been intensifying and posing a threat to the sustainability of agricultural production in arid and semi-arid regions. Hence, understanding of the crop yield-water relations is essential for a sustainable production. This work evaluates water productivity of Nyanyadzi smallholder irrigation scheme's Block C in Zimbabwe. The findings of this study show that bean crop water productivity has been decreasing over the 17 cropping seasons studied. However, RWS was increasing. For wheat, both WP and RWS were generally increasing.

Based on the research findings, there is need to introduce water harvesting and water conservation systems in the scheme to supply sustainability of water supply. This can be realised by drilling boreholes along the Odzi, Nyanyadzi riverbeds and in the scheme. In addition to the boreholes, the construction of dams across Nyanyadzi River and/or Odzi River could offer an alternative solution to seasonal water shortage.

Significant water savings can be realised by retrofitting the less efficient flood irrigation with more efficient irrigation methods.

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## CONFLICT OF INTEREST

The authors declare no competing financial interests associated with this manuscript.

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