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Optimising the grey water footprint of crops to enhance the environmental integrity in the Gaza Strip, Palestine

Amjad Mizyed*[1)], Yunes Mogheir[1)], Mazen Hamada[2)]

[1)] Islamic University of Gaza, Faculty of Engineering, Civil Engineering Department, Gaza, Occupied Palestinian Territories

[2)] Al-Azhar University, Faculty of Science, Chemistry Department, Occupied Palestinian Territories

* Corresponding author

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Abstract: Water pollution and scarcity are amongst the most pressing challenges affecting the water environment in the Gaza Strip. Agricultural activities play an important role in this issue, consuming more than 50% of the extracted water, while contributing to environmental degradation through the excessive use of pesticides and fertilisers. The grey water footprint (*GWF*) was quantified to evaluate pollution from crops using the Hoekstra methodology. The grey water totalled 30.63 mln m^3, with 51% attributed to vegetables, 44.5% to horticultural trees, and 4.5% to field crops between 2018 and 2022. An evaluation of the sustainability of the water footprint revealed that the assimilation capacity of water resources has been completely consumed. As a result, the Gaza Strip is classified as an unsustainable area, which is a serious violation of globally approved water quality standards. To optimise the grey water footprint, the nitrogen balance, N-leakage rate, and associated uncertainties were analysed using fractional programming, leading to the development of a model aimed at achieving optimal results. The findings show the importance of implementing this approach in the Gaza Strip, enabling policymakers and local authorities to develop a promising strategy for agricultural practices. This would promote sustainable and effective management of water resources and a safe and productive agricultural environment.

Keywords: agriculture sector, Gaza Strip, grey water, interval programming, sustainability, water footprint, water pollution

INTRODUCTION

The water footprint (*WF*) is one of key concepts used to quantify human impacts on quantity and quality of water resources. Introduced by Hoekstra (2003), it serves as a consumption-based indicator that measures all direct and indirect freshwater consumption within the supply chain of a product, service, or production process. *WF* is a volumetric measure of water use and pollution (Hoekstra and Chapagain, 2011). It comprises three distinct categories: blue, green, and grey. The blue *WF* refers to the consumption of surface and groundwater resources, while the green *WF* relates to the consumption of rainwater preserved in soil as moisture. Green water is utilised through evaporation and transmission during the production process, as well as rainwater harvested for use (Mizyed, Mogheir and Hamada, 2024). The grey *WF* refers to the volume of freshwater required to assimilate pollutant loads, taking into account regional water quality standards and natural background concentrations (Hoekstra *et al.*, 2011; Herath, 2013).

The grey water footprint (*GWF*) offers a novel approach by evaluating water quality from the perspective of water quantity. Unlike traditional methods such as the comprehensive pollution index method or the artificial neural network analysis, the *GWF* considers the impact of pollution discharge on water bodies (Fu *et al.*, 2022). The *GWF* is a versatile indicator for water resource management. As an indicator of water resource appropriation through pollution, it serves as a valuable tool for evaluating the sustainable, efficient, and equitable use of water resources (Franke, Hoekstra and Boyacioglu, 2013). The *GWF* has been assessed at different spatial levels: Indonesia (Bulsink, Hoekstra and Booij, 2010), Beijing (Wang *et al*., 2013), Milan, Italy (Vanham and Bidoglio, 2014) and California, U.S. (Fulton, Cooley and Gleick, 2014), as well as at global level (Hoekstra and Mekonnen, 2012). Globally, agriculture is the primary driver of land-use change, with the agricultural sector accounting for about 70% of freshwater withdrawals for irrigation. This has led to the rapid depletion of groundwater and surface water resources in some areas (Dalin *et al*., 2017). Therefore, one of the greatest challenges in the coming decades will be to sustainably increase global crop production while reducing negative impacts on global societies and ecosystems (Mekonnen and Hoekstra, 2020).

Planning and management of water resource systems has used simulation models for decades as a fundamental approach to assessing the impacts of changes in water supply and demand. These water resource management models are primarily used to complement our existing qualitative understanding with additional quantitative insights. Simulation models can be classified based on their approach to resource allocation. The simulation models can be categorised into two main types: those that use a rule-based or ad hoc approach for resource allocation, and those that use mathematical programming (optimisation) to simulate water allocation across a resource network at each time step (Tomlinson, Arnott and Harou, 2020). Optimisation models have been widely used to address problems in multiple fields, including water resource management and agriculture. Initially, optimisation approaches focused solely on achieving individual objectives of ecological systems. The complexity of environmental impacts was often ignored, with single-objective optimisation of agricultural systems prioritising the maximisation of financial gains (Singh, 2014). More recently, studies have incorporated multi-objective methods; however, these approaches face many difficulties in their application to water management systems. Challenges arise in identifying appropriate weighting factors or economic indicators, and selecting solutions from the Pareto front. Additionally, traditional methods fail to effectively measure system competence, which is represented as output-to-input ratios (Liang, 2013). An effective tool for optimising agricultural systems is fractional programming. It can directly compare the objectives across different components through innovative magnitudes and provide a balanced assessment of system competence. However, fractional programming has limitations in addressing uncertainties and negative eco-environmental impacts of crop production simultaneously (Cui, Guo and Li, 2013). Moreover, previous studies has rarely focused on incorporating the *GWF* into the decision-making process and dealt with uncertainties in the optimisation of agricultural crop production.

Assessment of the *GWF* requires careful consideration of key factors, including the leaching runoff coefficient, fertiliser application rates, acceptable level of nitrogen in freshwater, and the natural baseline nitrogen levels within water bodies (Hoekstra *et al*., 2011). To ensure sustainable water resource management, it is important to take into account both current conditions and future demand and supply while preventing harm to the ecosystem. Recent studies have evaluated the sustainability of the *GWF* (D'Ambrosio, Girolamo de and Rulli, 2018; Lathuillière *et al*., 2018; Novoa *et al*., 2019). Signs of unsustainability include disruptions in the supply and demand of water, continuous declines in groundwater resources, and insufficient environmental flow (Raeisi *et al*., 2019). Liu *et al*. (2020) stated that the *GWF* contributes to policymaking regarding sustainable water resource management.

This article quantifies the *GWF* of all crops in the Gaza Strip, Palestine, for the period 2018–2022. Crops were divided into horticultural trees, field crops, and vegetables according to the Ministry of Agriculture's classification. Additionally, the sustainability index of the *GWF* was evaluated to introduce innovative methods and present the first analysis of the environmental sustainability of the *GWF* across the Gaza Strip. This research develops an agricultural water management model based on the *GWF*, fractional programming, and interval programming. To address the complexities of pollution leaching associated with crop production, the study evaluates the negative effects of crop production through the *GWF* framework. The model uses interval fractional programming to maximise economic returns per unit of *GWF* while also formulating a comprehensive and sustainable planting strategy. Additionally, it takes into consideration various levels of uncertainties in key factors, including hydrology, technology, and economic conditions. The model provides a theoretical foundation and assists as a decision-support tool for optimising crop planting strategies. It also contributes to decision-making processes aimed at promoting sustainable water resource management while enhanceing the agricultural environment.

MATERIALS AND METHODS

STUDY AREA

Gaza Strip is a semi-arid region located on the South-eastern coast of the Mediterranean Sea between Egypt and occupied Palestine. Exactly, it is located between longitudes 34°2' and 34°25' East, and latitudes 31°16' and 31°45' North (Aish, 2014). It is part of the Palestinian coastal plain and covers a coastal area of about 365 km^2: its length along the coast is approximately 40 km and its width ranges from 6 to 12 km. There are five governorates and 25 municipalities in the Gaza Strip. The annual rainfall in the northern regions of the Gaza Strip is 474 mm, while in the southern areas, it is around 250 mm (JICA, 2017). The average temperature is 26.5°C in summer and 13.4°C in winter. The relative humidity is 62–78%. The location map of the Gaza Strip is shown in Figure 1. Population was estimated to be 2.22 mln in Dec 2022 and the natural population growth rate is 3.37% per year. By 2035, the population is expected to reach a total number of about 3.7 mln (PCBS, 2022). The main rainy season in the Gaza Strip extends from October to March, while the dry season, lasting from June to August, experiences very little rainfall. Relative humidity in the region is 62–78% (Al-Najjar *et al*., 2021). Agricultural areas occupy about half of the Gaza Strip, with remaining land comprising built-up areas and sand dunes (EMCC (2014).

DATA SOURCES

To estimate the grey agricultural water footprint, it is essential to collect appropriate data for the studied crops. Information on the main crops grown domestically, total agricultural production, and cultivated areas was obtained from the Ministry of Agriculture, as outlined in the 2021 Agriculture Census. Data on agricultural

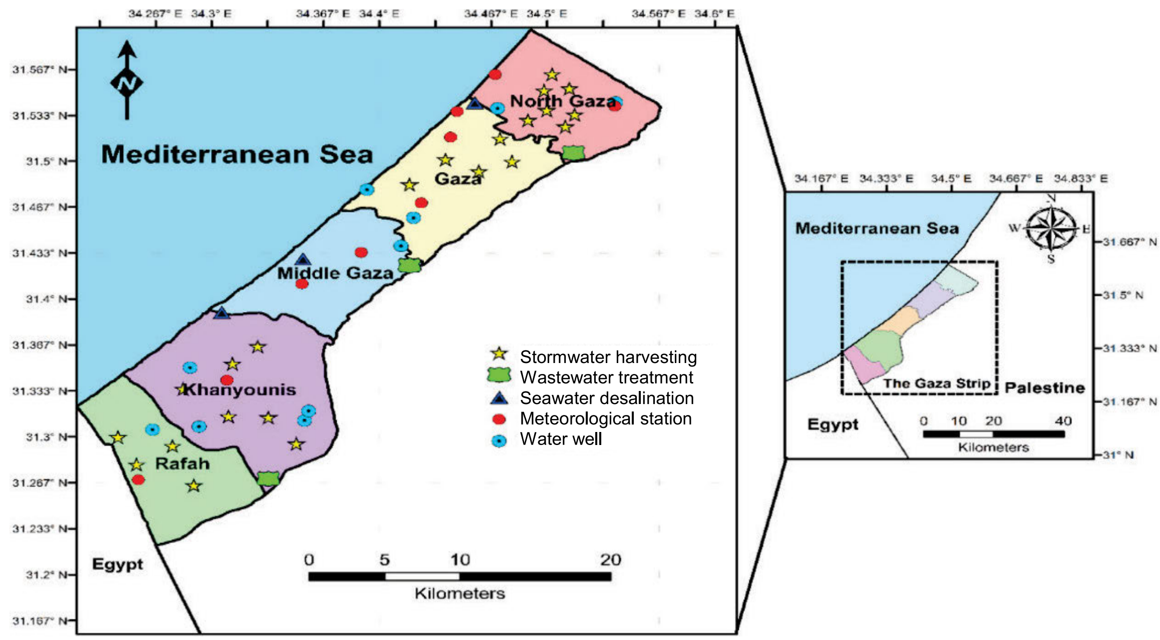

Fig. 1. Location map of the Gaza Strip; source: Al-Najjar, Ceribasi and Ceyhunlu (2021)

land use cover in the Gaza Strip and its governorates were obtained from the Palestinian Central Bureau of Statistics (PCBS, 2023).

Parameters such as leaching runoff coefficient, acceptable nitrogen levels in freshwater, and the natural nitrogen concentration in water bodies were obtained from the FAOSTAT for Palestine. Runoff quantity and pollution rates were estimated based on the Water and Environmental Authority standards. The approach suggested by Hoekstra and Chapagain (2011) and Franke, Hoekstra and Boyacioglu (2013) was employed for this analysis. Three sources of fertiliser data were used to calculate the fertiliser application rate per crop: FAO (2012), Heffer *et al.* (2013), and the International Fertilizer Industry Association (IFA, 2002). The IFA data was further supplemented with information for crops and countries that were not covered by original datasets.

CALCULATION OF GREY WATER FOOTPRINT OF CROPS

The water footprint assessment manual (Hoekstra *et al.*, 2011) was the source of the grey water footprint (*GWF*) computation, which is represented by Eq. (1):

$$GWF = \frac{\frac{\alpha Appl}{C_{\max} - C_{\text{nat}}}}{Y} \tag{1}$$

where: α = leaching runoff coefficient (%) which assumes 10% of nitrogen is lost through the application process, *Appl* = application rate of fertiliser per crop type (kg·ha^{-1}) (data on fertiliser application rates have been taken from for crop types in the FAO fertiliser and plant nutrition guide or region-specific authorities), $C_{\max}$ = maximum permissible concentration of the pollutant per unit volume of water (mg·dm^{-3}) following the World Health Organization guideline, C_{nat} = natural concentration of the pollutant per unit volume of water (kg·m^{-3}), C_{nat} should be taken as 0 for human-made chemical substances that naturally do not occur in water, Y = crop yield (Mg·ha^{-1}).

The sustainability of grey water footprint (*WFS* grey), established as the consumed waste assimilation capacity, was calculated according to the Equation (2):

$$WFS \text{ blue } (x, t) = \frac{\sum WF\text{blue } (x, t)}{R_{\text{act}}} \tag{2}$$

where *WF* grey (m^3 per period) corresponds to the sum of the *WF* grey of the crops grown in the basin (x) assessed according to nitrogen input, R_{act} the actual run-off from that catchment (R_{act}) in a time (t) (m^3·y^{-1}). The *WFS* grey was classified according to two levels $1 < WFS$ grey ≤ 2 when its assimilation capacity has been completely consumed and *WFS* grey >2 when limits set by environmental water quality standards are exceeded.

The World Health Organization and the European Union recommend a maximum nitrate concentration of 50 mg nitrate (NO_3) per dm^3 in surface and groundwater. In contrast, the US-EPA sets the maximum limit at 10 mg per dm^3, measured as nitrate-nitrogen (NO_3-N). The study adopted the nitrate-nitrogen (NO_3-N) standard of 10 mg per dm^3 as recommended by Franke, Hoekstra and Boyacioglu (2013).

MODEL OBJECTIVE FUNCTION AND CONSTRAINTS

To establish an agricultural water management model taking into account both the economic benefits and the grey water footprints, the objective function could maximise the economic benefits from a unit grey water footprint during crop production and reasonably determine the areas of crops in different regions. The objective function is denoted by Equation (3):

$$\text{Max } f = \max \frac{f_1}{f_2} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}[(Y_{ij} \cdot p_i - C_i) \cdot A_{ij} - \sum_{i=1}^{n}\sum_{j=1}^{m}(Q_{ij} \cdot A_{ij} \cdot T) - \sum_{i=1}^{n}\sum_{j=1}^{m}(Q_{ij} \cdot A_{ij} \cdot B)]}{\sum_{i=1}^{n}\sum_{j=1}^{m}\frac{Q_{ij} \cdot A_{ij}}{C_m - C_i}} \tag{3}$$

where: f = economic benefits obtained from the unit grey water footprint (GWF) value of crop production (USD·m^{-3}), f_1 = sum of the economic benefits obtained from the production of various crops in different regions (USD), f_2 = grey water footprint caused by agrochemical leaching (m^3), i = main crops in agricultural system, j = different area in agricultural systems, Y_{ij} = productivity of the i-th crop in the j-th region (Mg·ha^{-1}), P_i = unit price of the i-th crop (USD·Mg^{-1}), C_i = cost of planting the i-th crop per unit area (USD·ha^{-1}), (Y_{ij}·p_j – Cj) = profit value obtained from the planting area of the i-th crop unit in the j-th region (USD·ha^{-1}), A_{ij} = planting area of different crops (ha), Q_{ij} = amount of agrochemical leaching from different types of soil in different regions during period (kg·ha^{-1}), T = unit price of nitrogen supplemented to the soil after nitrogen leaching (USD·kg^{-1}), B = cost of processing the unit input of nitrogen discharged into the water body (USD·kg^{-1}), C_m = maximum concentration of pollutants allowed in the environment (kg·m^{-3}), C_i = original concentration of agrochemical in groundwater in different regions (kg·m^{-3}).

The objective function of the model clearly highlights its ability to balance economic profitability against harmful effects on the environment. The profit returns from crops are represented in the numerator, while the GWF, a measure of water pollution, constitutes a denominator. This balance helps achieve the best agricultural structures for crops in the Gaza Strip.

The horticultural crops included in this model are olives, citrus, and grapes. Vegetables include tomatoes, potatoes, aubergine, squash, and cucumbers, along with wheat from crop fields. These crops account for 65% (19.75 mln m^3) of the total grey footprint in the Gaza Strip.

The model consists of multi constraints to address real-world problems such as water availability constraints, food safety constraints, cultivated area constraints, grey water footprint constraints, and non-negativity constraints. Below is a detailed explanation of each model constraint.

Water availability constraints: it is essential to ensure that the water demand for crop production does not exceed the amount of water available in each region. Water availability constraints are represented by Equation (4):

$$\sum_{i=1}^{n} W_{di} \cdot A_{ij} \leq W_{aj} \cdot \rho \tag{4}$$

where: W_{di} = irrigation demand of the i-th crop (m^3·ha^{-1}), W_a = agricultural available water in the j-th region (m^3), ρ = irrigation water utilisation coefficient.

Food safety constraints: it is essential to limit the productivities of several crops are no less than the lowest social demands in order to confirm that the demand for food production is met. Food safety constraints are represented by Equation (5):

$$\sum_{j=1}^{I} A_{ij} \cdot Y_{ij} \geq T_{Di} \tag{5}$$

where: T_{Di} = minimum social demand for the i-th crop (Mg).

Cultivated area constraints: it should be to ensure the ideal crop cultivated area does not exceed the total available area. The constraints are represented by Equation (6):

$$\sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} \leq A_a = \sum_{i=1}^{n}\sum_{j=1}^{m} A_{Oij} \tag{6}$$

where: A_a = available area equals the sum of the original cultivated crop areas (A_{Oij}); it is different from (A_{ij}).

The area allocated for a crop depends on the currently existing cultivated area. Changes in the production area of a crop must fall within a specific range (maximum and minimum values) to ensure diversity of crop production. These constraints ensure that the optimised area is suitable for crop growth, aligning with the soil and climatic conditions required for successful crop cultivation.

Grey water footprint (*GWF*) constraints: GWF generated by crop production ought to be no further than the current footprints preceding optimisation (GWF_0) to avoid the overly critical influence of the optimised results on the environment. The constraints are represented by Equation (7):

$$\begin{aligned} GWF &= \sum_{i=1}^{n}\sum_{j=1}^{m} \frac{Q_{ij} \cdot A_{ij}}{C_m - C_i} \leq GWF_0 \\ &= \sum_{i=1}^{n}\sum_{j=1}^{m} \frac{Q_{ij} \cdot A_{Oij}}{C_m - C_i} \end{aligned} \tag{7}$$

Non-negative constraints: crop cultivating areas cannot take negative values, which can be denoted as follows in Equation (8):

$$A_{ij} \geq 0 \tag{8}$$

INTERVAL PROGRAMMING METHOD

The interval mathematical approach effectively manages input uncertainty by using interval parameters. An interval parameter $x^{\pm}$ does not require distributional information and is expressed as $x^{\pm} = [x^{-}, x^{+}]$, where x^{-} and x^{+} represent the lower and upper bounds, respectively. This method addresses the optimisation of ratios and uncertainties related to pollutant migration and transformation. Therefore, an interval-based GWF assessment method was developed in this study. The GWF calculation under uncertainty is presented by Equation (9).

$$GWF_j^{\pm} = \frac{\frac{\alpha^{\pm} \cdot Appl^{\pm}}{C^{\pm}\mathrm{max}j - C^{\pm}\mathrm{ini}j}}{Y_j^{\pm}} \tag{9}$$

where: $\alpha^{\pm}$ = interval of leaching runoff coefficient expressed as a percentage (%) which assumes in the standard approach as 10% of nitrogen lost through the application process, $Appl^{\pm}$ = application rate of fertiliser per crop type (kg·ha^{-1}), $C^{\pm}\mathrm{max}_j$ and $C^{\pm}\mathrm{ini}_j$ = maximum and initial concentration of the pollutant in the water body as intervals respectively.

RESULTS AND DISCUSSION

GREY WATER FOOTPRINT (*GWF*) OF AGRICULTURAL CROPS

Table S1 shows the total value of the GWF of agricultural crops in the Gaza Strip amounted to 30.63 mln m^3. It varied from 1.3 mln m^3 for field crops (4.5%), to 13.65 mln m^3 (44.5%) for horticultural trees and 15.68 mln m^3 for vegetables (51.0%).

For horticultural trees, the olive and citrus crops accounted for the highest crops in the GWF, with a total of 8.63 mln m^3, which represents 63% of the total GWF for horticultural trees in the Gaza Strip. However, the results varied when analysing the GWF per Mg.

In this case, dates and grapes was the highest crop, while almonds and mangoes recorded the lowest quantities. These differences are largely influenced by the extent of the cultivated area and the intensive application of fertilisers. Field crops have minimal impact on the *GWF* in the Gaza Strip. This is because they do not heavily depend on the use of nitrogen fertilisers and are known for their high nitrogen absorption, resulting in less nitrogen leakage into groundwater. The vast majority of field crops in the region consist of wheat, which accounts for over 86% of all field crops in the Gaza Strip. On the other hand, vegetables contribute significantly to the *GWF* due to the large cultivated area and the widespread use of intensive agricultural systems in the Gaza Strip. The potato crop has the largest *GWF* value of 4.03 mln m^3, followed by tomatoes. When considering the impact by mass expressed in Mg, strawberries and green beans show increased values. Additionally, tomatoes and cucumbers, which were planted in greenhouses, were factored into the calculation for the assessment.

GREY WATER FOOTPRINT (*GWF*) SUSTAINABILITY ASSESSMENT

The average actual run-off (R_{act}) in the Gaza Strip, according to AQUSTAT and recent updates, is 25.5 mln ($m^3 \cdot y^{-1}$). The annual *GWF* in the Gaza Strip amounts to 30.63 mln m^3, significantly greater than 1.2. The grey water footprint sustainability classifies the Gaza Strip as unsustainable. The value of 1.2 exceeds 100%, which reflects unsustainable conditions and indicates the presence of an environmental hotspot. Both the *GWF* and the run-off levels vary throughout the year, causing seasonal fluctuations in water pollution levels. However, no studies have yet evaluated the sustainability of the water footprint in the region. A previous study by Novoa *et al.* (2019) and another study by Miguel de, Kallache and García-Calvo (2015) used the same methodology to evaluate water sustainability. No previous studies have estimated the grey water footprint in the Gaza Strip. However, Mekonnen and Hoekstra (2011) provide *GWF* values for crop-growing processes in various countries. Therefore, this study's estimates have been compared with those reported by Mekonnen and Hoekstra for neighbouring countries globally. For food crops, the global average water footprint per Mg of vegetables is lower than observed in the Gaza Strip. It is important to note that while the global average water footprint of one product may exceed average, the comparison can differ significantly for specific regions. Water footprints for crops vary across countries and regions due to differences in crop yields. In addition to the massive soil pollution in the Gaza Strip, the elevated *GWF* can also be attributed to the excessive use of pesticides.

GREY WATER FOOTPRINT (*GWF*) MODEL RESULTS

Effect of N-fertilisers application rate

The fertiliser application rate and its impact on the *GWF* for targeted crops during N balance is presented in Table 1.

The results stipulated in Table 1 show a significant impact of N-application fertilisers based on the analysis of the nitrogen balance for the Gaza Strip. This indicates that the *GWF* increased to 46.4 mln m^3 in comparison to reference indicators (19.75 mln m^3) as shown in Figure 2.

These results were consistent with the rates used in the Recanati's (2013) study of tomatoes and cucumbers, as well as to some extent in aubergine yield with 860 kg·ha^{-1}, while in this study it was 597 kg·ha^{-1}. It is because the Recanati's study was limited to

Table 1. The effect of N-application rate of grey water footprint (*GWF*) for studied crops

Crop	Area (ha)	Average fertiliser application rate (kg·ha^{-1})	Total fertiliser applied (Mg·y^{-1})	Nitrogen leaching 10% (Mg·y^{-1})	Total *GWF* per year (10^6 m^3)	Total production (Mg)	*GWF* (m^3·Mg^{-1})
Olive	3,860	248	957.28	95.73	9.57	24.000	398.87
Citrus	2,000	555	1,110	111.00	11.10	35.000	317.14
Grape	700	189	132.3	13.23	1.32	3.800	348.16
Wheat	1,250	107	133.75	13.38	1.34	4.300	311.05
Tomato	800	1,050	840	84.00	8.40	79.415	105.77
Potato	1,150	583	670.45	67.05	6.70	49.400	135.72
Squash	448	569	254.91	25.49	2.55	16.330	156.10
Aubergine	338	597	201.786	20.18	2.02	33.972	59.40
Cucumber	301	1,135	341.635	34.16	3.42	28.774	118.73
Total			**4,642.113**	**464.21**	**46.42**	**274.991**	**168.8**

Source: own study.

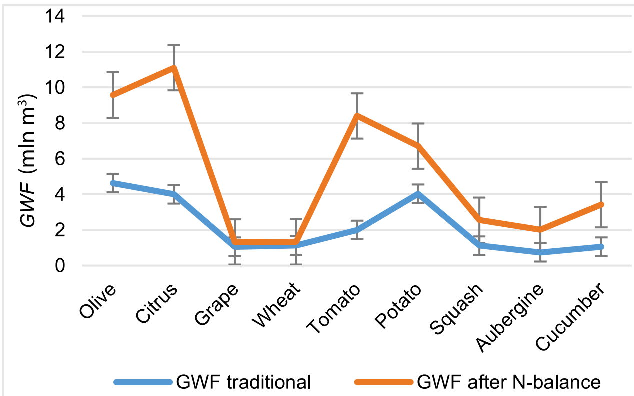

Fig. 2. The effect of N-fertilisers application rate of grey water footprint (*GWF*) before and after N-balance for studied crop; source: own study

a small farm and did not involve a comprehensive survey to cover a number of diversities in practices as in this study.

The efficiency of nitrogen intake in crops is relatively low compared to nitrogen input. As a result, excess nitrogen is often leached into groundwater, leading to pollution and unnecessary financial burdens for farmers without producing any additional benefits. While reducing fertiliser application should be carefully studied to monitor the input of nitrogen into soil and groundwater (as supported by Al-Najar *et al.*, 2014), increasing plant uptake to decrease nitrogen leaching into groundwater is not considered practicable.

Effect of nitrogen leaching

Nitrogen leaching can be an important outflow and is calculated using the regression model proposed by Willegen de (2000). This model is based on an extensive literature search and is valid for a wide range of soil types and climates. Nitrogen leaching is calculated based on Equation (9):

$$\text{N leaching }(\alpha) = (0.0463 + 0.0037\frac{P}{C \cdot L}(F + D \cdot NOM - U) \quad (10)$$

where: N leaching = amount of nitrogen leaching from the soil (kg N·ha^{-1}), P = annual precipitation (mm) plus the irrigation crop required, C = average clay soil content (%) obtained from the (Ubeid and Ramadan, 2020) study, L = crop root depth (m) derived from FAO (Allen *et al.*, 1998), F = nitrogen rate application (kg·ha^{-1}) mineral and organic fertiliser nitrogen, D = annual decomposition rate, established as 1.6% as recommended by the FAO (Roy *et al.*, 2003), NOM = amount of nitrogen in soil organic matter (kg·ha^{-1}) 1.9 g·kg^{-1} according to FAO (Nachtergaele *et al.*, 2023), U = nitrogen uptake by crops (kg·ha^{-1}). The N leaching for the studied crop, percentage of leaching, and the new *GWF* are explained in Table 2.

According to Table 2, there is a large difference in the extent of groundwater pollution caused by agricultural practices due to the increase in the percentage of leached nitrogen. This percentage reached 45%, compared to the global average of 10% used in estimating the *GWF*. The rate of nitrogen leakage was very high in crops like cucumbers, tomatoes, and squash, which are widely grown in the Gaza Strip. These crops play a pivotal role in food security and serve as a primary source of income for many farmers. Additionally, large amounts of fertilisers are applied to maximise productivity. This is linked to many factors, including significant increase in irrigation practices, the nature of the soil, and the excessive use of nitrogen fertilisers. Moreover, the intensive agricultural system in the Gaza Strip aims to maximise financial profits without taking into account soil safety and environmental dimensions. Figure 3 shows the water needed to assimilate *GWF* by crops (in m^3·Mg^{-1}).

These results exceed those reported in Al-Najjar's study (2014) regarding the amount of nitrogen leakage into the soil and groundwater. It is worth noting that Al-Najjar's study relied on an estimated percentage (30%) rather than a mathematically derived figure based on methodological foundations.

While the results of this study were lower than those reported in the study by Nassar *et al.* (2009), which involved much larger amounts of nitrogen, they highlighted the total amount of fertilisers applied in agricultural fields. This underscores the need for critical intervention and the implementation of procedures to determine the amount of the fertiliser used during irrigation and fertilisation process.

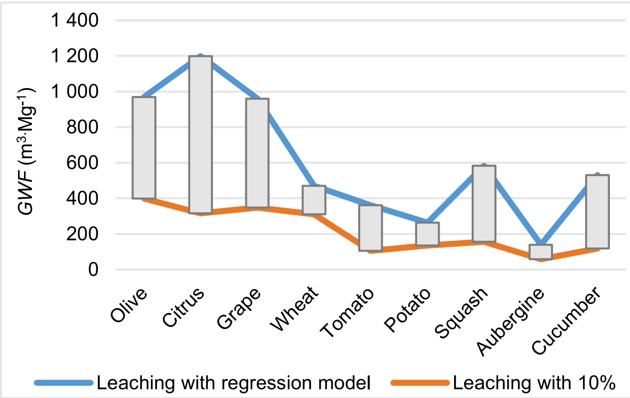

Fig. 3. Effect of N leaching with α = 10% and regression model at *GWF*; source: own study

Table 2. The effect of N leaching on the grey water footprint (*GWF*)

Crop	Area (ha)	Total applied of N (Mg·y^{-1})	N leaching		*GWF*	
			(Mg N)·ha^{-1}	%	mln m^3	m^3·Mg^{-1}
Olive	3860	1,652.08	232.44	14	23.24	968
Citrus	2000	1,516.00	419.31	28	41.93	1,198
Grape	700	342.30	36.47	11	3.65	961
Wheat	1250	421.25	20.22	5	2.02	470
Tomato	800	840.00	287.07	34	28.71	362
Potato	1150	670.45	129.87	19	12.99	263
Squash	448	295.23	95.32	32	9.53	584
Aubergine	338	201.79	47.62	24	4.76	140
Cucumber	301	341.6	152.46	45	15.25	530

Source: own study.

Employing interval programming method

The optimisation function to address uncertainty was modified, as presented in Equation (11). The interval data outlined in Table 3 can be achieved by improving each objective function separately, or by adjusting the range by a specific percentage. This data encompasses information on cultivated areas, production, costs, and selling prices, as well as the amount of fertiliser applied, fertiliser price fluctuations, and the cost of treating their impacts.

compared to the pre-optimisation scenario. The optimisation process accomplished an increase in economic benefits, raising the total evaluation for all crops from an average of USD132 mln to USD194 mln. Furthermore, the average objective function value increased from USD 2.58·m^{-3} to USD 4.07·m^{-3} after optimisation. It is worth noting that the optimisation process for vegetables showed better results compared to olives and citrus fruits. These results are considered advantageous as the agricultural structure of vegetables can be better controlled compared to horticultural trees. It is also possible to change planting locations, enabling the application of these results in real-world agricultural practices. Furthermore, vegetables cultivated in greenhouses, such as tomatoes and cucumbers, offer better control over their productivity levels compared to fruits and horticultural trees. The latter are typically grown in open fields and are therefore more heavily affected by climatic conditions and fluctuations in irrigation operations.

$$\text{Max } f = \max \frac{f_1}{f_2} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(Y_{ij}^{\pm}\cdot P_j^{\pm} - C_j^{\pm}\right)\cdot A_{ij}^{\pm} - \sum_{i=1}^{n}\sum_{j=1}^{m}\left(Q_{ij}^{\pm}\cdot A_{ij}^{\pm}\cdot T^{\pm}\right) - \sum_{i=1}^{n}\sum_{j=1}^{m}\left(Q_{ij}^{\pm}\cdot A_{ij}^{\pm}\cdot B^{\pm}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{m}\frac{Q_{ij}^{\pm}\cdot A_{ij}^{\pm}}{C_m - C_i^{\pm}}} \tag{11}$$

Table 3. Intervals data for the elements of optimisation function

Crop	Area ± (ha)	Yield ± Mg·ha^{-1}	Price ± USD·Mg^{-1}	Cost ± USD·ha^{-1}	Agrochemical leaching ± Mg·ha^{-1}	Price of nitrogen ±	Cost of N-processing ±
						USD·Mg^{-1}	
Olive	[3,474; 4,439]	[4.67; 7.78]	[1,088; 1,632]	[2,856; 4,284]	[0.186; 0.31]	[178; 240]	[86.7; 117.40]
Citrus	[1,800; 2,300]	[13.13; 21.90]	[544; 816]	[3,200; 4,800]	[0.416; 0.693]	[99; 134]	[36.4; 49.20]
Grape	[630; 805]	[4.07; 6.8]	[576; 864]	[2,400; 3,600]	[0.141; 0.236]	[181; 245]	[74.35; 100.50]
Wheat	[1,125; 1,438]	[2.58; 4.3]	[296; 444]	[1,664; 2,496]	[0.08; 0.133]	[86; 117]	[46.9,63.50]
Tomato	[720; 920]	[74.4; 124]	[488; 732]	[4,112; 6,168]	[0.787; 1.312]	[14; 19]	[5.95; 8.05]
Potato	[1,035; 1,323]	[32.2; 53.7]	[416; 624]	[3,097; 4,646]	[0.437; 0.728]	[23; 31]	[4.66; 6.31]
Squash	[403; 515]	[27.3; 45.5]	[400; 600]	[2,896; 4,344]	[0.426; 0.711]	[28; 38]	[10.72; 14.51]
Aubergine	[304; 389]	[75.4; 125.6]	[512; 768]	[2,640; 3,960]	[0.447; 0.746]	[7; 10]	[2.74; 3.71]
Cucumber	[271; 346]	[71.7; 119]	[496; 744]	[3,366; 5,049]	[0.851; 1.418]	[9; 13]	[6.7; 9.07]

Source: own study.

The interval fractional models were applied to derive solutions. Accordingly, the objective function was divided into two sub-models (f^{+}) and (f^{-}). The sub-model (f^{+}) incorporates interactions between the two sub-models and is defined in Equation (12) to find the optimum solution S^{-} ($j = r + 1, \ldots, n$) and S^{+} ($j = 1, 2, \ldots, r$).

The sub-model (f^{-}) is obtainable by Equation (13) to find the optimal solutions as S^{-} ($j = 1, \ldots, r$) and S^{+} ($j = r + 1, \ldots, n$).

$$\max f^{+} = \frac{\sum_{d=1}^{r}\left[\left(Y_d^{+}\cdot P_d^{+} - C_d^{-}\right) - Q_d^{-}\cdot\left(T^{-}+B^{-}\right)\right]\cdot A_d^{+} + \sum_{d=r+1}^{n}\left[\left(Y_d^{+}\cdot P_d^{+} - C_d^{-}\right) - Q_d^{-}\cdot\left(T^{-}+B^{-}\right)\right]\cdot A_d^{-}}{\sum_{d=1}^{r}\frac{Q_d^{-}}{C_m - CI_d^{-}}\cdot A_d^{+} + \sum_{d=r+1}^{n}\frac{Q_d^{-}}{C_m - CI_d^{-}}\cdot A_d^{+}} \tag{12}$$

$$\max f^{-} = \frac{\sum_{d=1}^{r}\left[\left(Y_d^{-}\cdot P_d^{-} - C_d^{+}\right) - Q_d^{+}\cdot\left(T^{+}+B^{+}\right)\right]\cdot A_d^{-} + \sum_{d=r+1}^{n}\left[\left(Y_d^{-}\cdot P_d^{-} - C_d^{+}\right) - Q_d^{+}\cdot\left(T^{\mp}+B^{\mp}\right)\right]\cdot A_d^{+}}{\sum_{d=1}^{r}\frac{Q_d^{+}}{C_m - CI_d^{+}}\cdot A_d^{-} + \sum_{d=r+1}^{n}\frac{Q_d^{+}}{C_m - CI_d^{+}}\cdot A_d^{+}} \tag{13}$$

By combing the results from sub-model (f^{-}) and sub-model (f^{+}), the entire solution $S = [S^{-}; S^{+}]$ for the model can be determined. The results of the optimisation process can then be evaluated in terms of economic benefits, objective function, and grey water footprint. These results can also be compared with the initial scenario by solving the model. The findings are detailed in Table 4.

Figure 4 illustrates the adjusted *GWF* for the studied crops. The average values of the upper and lower limits for all intervals show a 15% reduction in the *GWF,* amounting to 7.58 mln m^{3},

In the Gaza Strip, characterised by a dry climate, fluctuating rainfall, and the spread of pollutants from non-point sources such as fertilisers, it is possible to enhance agricultural structure and change crop composition to achieve higher profits and improve environmental conditions. However, this solution may not be acceptable from a practical perspective due to the nature of the study area. For instance, it would not be feasible to cultivate the entire Gaza Strip solely with cucumber crops, which are highly profitable and have a relatively low environmental impact.

Table 4. Grey water footprint (*GWF*), economic benefit, and objective function before and after optimisation process

Crop	*GWF* before optimisation	*GWF* after optimisation	Benefit before	Benefit after	Objectives function before	Objectives function after
	mln m^3		mln USD		USD·m^{-3}	
Olive	[9.1; 11.5]	[8.26; 10.77]	[11.14; 23.2]	[5.4; 36.8]	[1.23; 2.02]	[0.65; 3.41]
Citrus	[10.5; 13.3]	[9.57; 12.49]	[9.37; 19.53]	[9.07; 29.7]	[0.89; 1.47]	[0.95; 2.38]
Grape	[1.25; 1.58]	[1.14; 1.49]	[0.36; 0.75]	[0; 1.76]	[0.28; 0.47]	[0; 1.18]
Wheat	[1.25; 1.6]	[1.15; 1.5]	[–0.62;–1.29]	[0; 0.6]	[–0.49; –0.8]	[0; 0.4]
Tomato	[8; 10]	[7.25; 9.45]	[26.59; 55.39]	[49.4; 77.8]	[3.33; 5.49]	[6.82; 8.23]
Potato	[6.4; 8]	[5.78; 7.54]	[12.37; 26.52]	[20.6; 38.1]	[2; 3.3]	[3.56; 5.05]
Squash	[2.42; 3.06]	[2.2; 2.87]	[3.92; 8.16]	[6.02; 11.8]	[1.62; 2.67]	[2.74; 4.12]
Aubergine	[1.91; 2.42]	[1.74; 2.27]	[12.37; 25.78]	[24; 35.9]	[6.46; 10.65]	[13.79; 15.84]
Cucumber	[3.25; 4.1]	[2.95; 3.84]	[9.94; 20.71]	[18.8; 29]	[3.06; 5.05]	[6.38; 7.54]
Total	**[44.1; 55.7]**	**[40; 52.22]**	**[85.81; 178.7]**	**[127; 261.7]**	**[1.95; 3.21]**	**[3.17; 4.98]**

Source: own study.

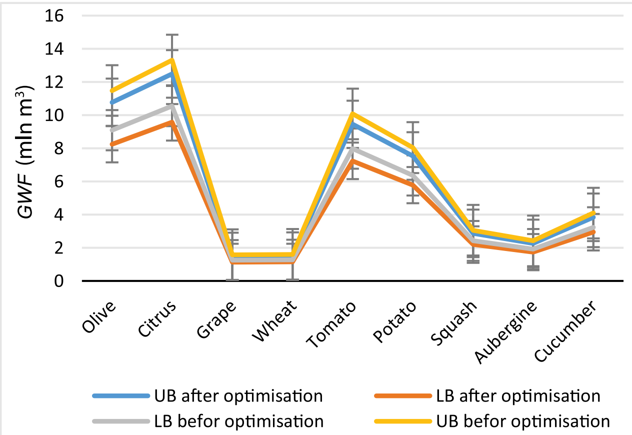

Fig. 4. Upper and lower bound of grey water footprint (*GWF*) before and after optimisation; LB = lower bound, UB = upper bound; source: own

Therefore, a more balanced approach was adopted, relying on fractional models to strike an equilibrium between economic profitability, environmental safety, and the existing agricultural structure. This approach successfully achieves the desired goal. Additionally, this model can be developed and improved by increasing the scope of constraints to better align with the specific nature of pollution in the region. Improvements can also be made by refining the quality of input data and targeting additional pollutants beyond those considered in this study.

CONCLUSIONS

This study assessed the water footprint of agricultural crops in the Gaza Strip, focusing on its grey water components. The Hoekstra methodology was adopted to evaluate the grey water footprint (*GWF*) for nitrogen fertiliser used in the Gaza Strip. The total *GWF* for the Gaza Strip was about 31 mln m^3, with vegetables accounting for 51% of the total. The grey component was calculated for each crop, revealing a diversity of values influenced by several factors. These factors include the crop's area and morphology, length of growth period, irrigation efficiency, and N-application rate.

The sustainability of the *GWF* in the Gaza Strip was also evaluated. The evaluation revealed that the sustainability index is at a critical level based on the classification used, as the grey footprint index exceeds the approved standards for water quality, with a value greater than 1.2. This alarming indicator calls for immediate action by environmental decision-makers and water resource managers to implement necessary measures to prevent further deterioration.

Optimisation factors were also investigated, including nitrogen application rates, leakage rates, and interval programming to deal with uncertainty. This opens the way for future studies to determine leakage percentages using more accurate models. This estimation of *GWF* for the Gaza Strip highlighted important indicators of environmental integrity. It underscored the importance of determining appropriate fertiliser quantities, guiding farmers on optimal fertilisation practices, ensuring the efficient use of irrigation water, and aligning soil characteristics with cultivated crops. These findings position the water footprint index as a valuable tool for effective and sustainable management of water resources in the Gaza Strip.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Mizyed.pdf.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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