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Prospects for treated wastewater reuse in agriculture in low- and middle-income countries: Systematic analysis and decision-making trees for diverse management approaches

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ABSTRACT

The Middle East and North Africa (MENA) region is suffering from severe water scarcity. Decision-makers in MENA are tackling this challenge by tapping the potential of reusing treated wastewater in agriculture so that large volumes of freshwater sources can be released for priority domestic needs. This aligns with the global efforts to make wastewater reuse mainstream in developing countries by overcoming the technological, infrastructural, health, and socio-cultural barriers that are limiting the expansion of wastewater reuse in agriculture. In this regard, this paper analyses the management modalities of wastewater reuse practices in agriculture in MENA by studying two case studies from Egypt and Jordan. The result of this analysis is a proposed decision-tree tool to help decision-makers in making optimal wastewater reuse decisions based on contextual factors including agricultural field demands, location, freshwater resources, sanitation coverage, and infrastructure, as well as regulations, policies, and restrictions for wastewater reuse. The decision-tree framework was operationalized and validated using the two case studies. The decision tree proved to be an effective framework in assisting decision-makers in making the optimum choice for wastewater reuse in agriculture. It aided the decision maker in evaluating potential reuse options and selecting between several courses of action.

1. Introduction

In most countries in the Middle East and North Africa (MENA) region, agriculture dominates freshwater withdrawals (FAO, 2022). However, the agricultural sector is facing challenges in safeguarding its water supply, now and in the future (Allan, 2008). Water scarcity is adversely impacting agrarian communities and national economies, including causing internal and external human displacement (Haddadin, 2001). These challenges have triggered global and national efforts to substitute freshwater with non-conventional water sources in the agricultural sector (Dobbin et al., 2007).

The reuse of treated wastewater and agricultural drainage water offers an alternative source of water that can curtail the supply-

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demand gap in agriculture (ARD-USAID, 2001). The application of treated wastewater in agriculture is expected to grow in the coming decades in the MENA region. Advanced treatment technologies and changing perceptions about the urgency and safety offer opportunities for governments to strengthen institutional frameworks for the expansion of direct and indirect wastewater reuse (Ait-Mouheeb et al., 2020).

Currently, the global intentional reuse of treated wastewater in agriculture is 41 billion m³/year, while the wastewater generated globally is 360 billion m³/year, of which 188 billion m³/year is treated (Qadir et al., 2020; Jones et al., 2021). However, sanitation coverage and treatment technologies are impacting the extent to which treated wastewater can be used safely (Hernández-Chover et al., 2018; Jones et al., 2021). Moreover, in several low- and middle-income countries, unregulated reuse, often untreated, exceeds the levels of regulated reuse (Scott et al., 2009; Kesari et al., 2021).

The reuse of treated wastewater in agriculture can be classified as direct reuse or indirect reuse (Jeong et al., 2016). **Direct reuse** means irrigating agricultural lands and crops with treated wastewater without mixing or diluting it with any other water resource. Where advanced wastewater treatment technologies are present, health and production risks can be minimised, which contributes to a safe water supply for alternative purposes (Zekić et al., 2018). However, direct reuse has a proven risk to public health and to soil and groundwater quality if wastewater is only treated through primary or secondary treatment or where advanced treatment is unreliable (Shakir et al., 2017). In these cases, with lower treatment standards, irrigation methods and crop choice can mitigate the associated risks, for example through the production of non-food crops such as timber, biofuels or fodder (El Moussaoui et al., 2019; Ungureanu et al., 2018; Kesari et al., 2021). Also, growing non-food crops is a feasible approach for direct reuse as it gains public acceptance in these countries relatively safe (Kesari et al., 2021). Thus, effluent quality, crop type, and soil characteristics require consideration prior to the direct supply of effluent as irrigation water (Akpan et al., 2020). Direct reuse can be adopted when conventional water sources are far from or inaccessible to farms, and/or when farms are in the vicinity of wastewater treatment plants (Tawfik et al., 2021).

Indirect reuse means using wastewater that was discharged to other water bodies where it has been diluted with freshwater (Tawfik et al., 2021). Indirect reuse receives high public acceptance rates and is widely used for edible and inedible food crops, often unrestricted (Akpan et al., 2020). In the MENA region, indirect reuse is common, for example through pumping of diluted treated wastewater downstream from an effluent disposal point (Abu-Madi and Al-Sa'ed, 2009). However, the quality of the mixed water is highly variable and depends on the treatment levels, effluent characteristics, and informal or illegal discharges of untreated wastewater (Jeong et al., 2016; Helmecke et al., 2020).

In the MENA region, the reuse of treated wastewater in agriculture is expected to increase. Therefore, taking stock of current diverse approaches in making use of its potential, while at the same time mitigating the environmental and health risks, can inform the future acceleration of wastewater reuse. Hence, this article investigates the prospects of wastewater reuse in Egypt and Jordan as representatives of low- and middle-income countries in the MENA region. The economies of these two countries depend on the agricultural sector in various ways. In Egypt, agriculture is one of the top employers for the mostly young population (USAID, 2022), while in Jordan, the agricultural sector supports a large number of foreign labourers, particularly from Egypt and Syria (Hussein, 2018). In both countries, diverse approaches to direct and indirect wastewater reuse have emerged, which differ in terms of scale, economic feasibility, institutional frameworks, and costs of implementation, operation, and maintenance (Tawfik et al., 2022). Based on these different experiences, this research aims to develop a framework for wastewater reuse and planning, which builds on two central research questions.

RQ (1). What are the current management approaches and scales for wastewater reuse in agriculture in Egypt and Jordan?

RQ (2). How is it possible to plan for wastewater reuse based on: the existing scale of sanitation coverage service, agricultural determinants, and management/governance structure for reuse?

An analysis of the wastewater reuse practices and management approaches in Egypt and Jordan informs us about the opportunities and challenges encountered. Based on an enhanced understanding of these existing practices and regulations, a decision-tree tool for wastewater reuse planning and management is developed. This decision tree aims to support policymakers in low- and middle-income countries in identifying suitable and context-specific reuse approaches to accelerate the safe expansion of treated wastewater reuse in agriculture. Two case studies from Egypt and Jordan will be used to operationalize and validate the decision-tree tool.

2. Methodology

2.1. A framework for managing wastewater reuse

Management of treated wastewater reuse in agriculture is a cross-sectoral process where treated wastewater flow and allocation to agricultural users is mediated through various technologies/infrastructures, institutional arrangements (formal/informal organizations control the water allocation), standards and regulations. Analysing the flow of treated wastewater to agriculture highlights the complexity of treated wastewater reallocation from the water sector to the agricultural sector, where the two sectors are often working in silos or even competing with each other. To recognize this complexity, this manuscript will develop an analytical framework that addresses wastewater management, the reallocation of treated wastewater to agriculture, and management of treated wastewater reuse in agriculture.

2.2. Description of the case studies in Egypt and Jordan

The data for the two case studies (Sarapeum in Egypt and the Middle Jordan Valley) were collected through several visits to both locations and interviews with stakeholders representing the different aspects of wastewater management and reuse in agriculture. The stakeholders and their institutions were identified based on their role in the management activities of wastewater management (i.e. treatment and discharge); treated wastewater reallocation to agriculture (i.e. institutional arrangements); and treated wastewater reuse arrangements in agriculture (i.e. irrigation, crops, and land management) according to the analytical framework. This is in addition to reviewing the existing literature and official reports. In many instances, there were overlapping roles and responsibilities between the different stakeholders as shown in [Table 1](#).

The site visits and the interviews were facilitated and arranged as part of the ReWater MENA project that was led by the International Water Management Institute – MENA regional office (IWMI-MENA) that took place from 2018 to 2022. Stakeholders were interviewed through focus group discussions that took place at the Sarapeum site, and farm-to-farm interviews that were conducted with farmers in the Jordan Valley in 2021. Besides the main institutions that were listed in [Table 1](#), data validation and further clarifications were obtained by discussions with local consultants, experts from the Royal Scientific Society (RSS) in Jordan and experts from the International Center for Agricultural Research in the Dry Areas (ICARDA), Egypt.

2.3. The decision tree

The development of the decision-making procedure tree begins with identifying a root of the tree that represents the target or dependent variables, which are the decisions of wastewater reuse in agriculture. The independent variables are the availability of freshwater resources, accessibility, reliability, affordability, vulnerability, agricultural field location, sanitation services coverage, wastewater reuse standards, institutional arrangements, governmental subsidies for reuse, public acceptance, restrictions, infrastructure to transfer treated wastewater to agricultural fields, and irrigation techniques that could utilize the treated wastewater.

3. Results

3.1. Framework of wastewater reuse management

The analytical framework shown in [Table 2](#) reflects the complexity of reusing the treated wastewater in agriculture by addressing: wastewater management, the reallocation between the water and agricultural sectors, and treated wastewater management approaches in agriculture, in terms of management approach (es) and institutional arrangement(s).

- Treated wastewater generation (i.e. the status of wastewater management prior to reuse, particularly wastewater treatment and discharge or mixing with freshwater).
- The reuse and reallocation of treated wastewater from the water sector to the agricultural sector. This reallocation considers the scale of reuse, available infrastructure, standards and regulations.
- Management of treated wastewater reuse in agriculture, which includes irrigation technologies, irrigation patterns, crop selection, and land allocation.

This framework addresses wastewater reuse management in agriculture in terms of.

- I. Wastewater flow that describes the stages prior to treated wastewater reuse including wastewater treatment technologies (i.e. primary, secondary, tertiary or advanced treatment) and the discharge of treated wastewater as treated effluent complying with the national standards for discharge and/or reuse (either direct discharge into agricultural plots or mixing with freshwater sources), where the latter is the starting point for treated wastewater reallocation across the different sectors, institutional arrangements and users.
- II. Reallocation of treated wastewater to the agricultural sector, which addresses the associated effect of the shift of this reallocation on the various stakeholders' roles and responsibilities. This reallocation differs according to the scale of reuse, available infrastructure/technological advancement, and reuse institutional arrangements (i.e. policy, standards and regulations).

Table 1

Stakeholders/institutions responsible for treated wastewater management and reuse in the two case studies.

Aspects of the analytical framework	Stakeholders/institutions at the Sarapeum site (Egypt)	Stakeholders/institutions in the Middle Jordan Valley (Jordan)
Wastewater management (collection, treatment and discharge)	The Holding Company for Water and Wastewater (HCWW) belongs to the Ministry of Housing Utilities and Urban Communities (MoHUUC)	Water Authority of Jordan (WAJ)
Treated wastewater reallocation to agriculture (institutional arrangements)	Treated wastewater direct reuse code (501/2015) set by MoHUUC	Jordan Valley Authority (JVA)
Treated wastewater management in agriculture	Ministry of Agriculture	JVA Ministry of Agriculture

Table 2

Framework to understand wastewater management and reuse in agriculture.

Wastewater generation		Treated wastewater reallocation to agriculture			Treated wastewater management in agriculture			
Treatment	Discharge arrangement(s)	Institutional arrangements Policy	Reuse standard(s)	Reuse regulation(s)	Irrigation infrastructure	Irrigation pattern	Crop selection	Land allocation/selection

III. Treated wastewater management in agriculture; this component addresses the irrigation modalities (i.e. irrigation techniques and patterns), crop selection and land allocation for reuse purposes.

3.2. Wastewater reuse in Egypt and Jordan according to the analytical framework

3.2.1. Egypt

3.2.1.1. Wastewater generation and flow. Egypt is facing major challenges to meet its population's needs of water and sanitation services. Despite reaching an impressive 98% of water supply coverage of the population, this has not been matched by a similar expansion in sanitation services, particularly in rural areas, where only 12% of the rural population has access to conventional sanitation services (HCWW, 2019). Nevertheless, this percentage is increasing steadily with the implementation of large-scale wastewater management projects (e.g. the Mahsama and Bahr El Baqar treatment plants) as shown in Fig. 1.

There were 446 wastewater treatment plants operating in Egypt in 2021 that generated a total number of 12.6 million cubic meters (MCM) of treated wastewater per day, 79% of which had secondary treatment, 18.8% had primary treatment, while only 1.6% had tertiary treatment (Raslan, 2022).

Wastewater treatment plants located in the Nile Valley and the Nile Delta discharge their treated wastewater directly to the agricultural drainage network according to Law 48/1982 (Annex 1) where agricultural drainage water and treated domestic water are mixed. However, wastewater treatment plants in new cities (outside the delta and valley) do not have access to the drainage network, thus here direct reuse of treated water takes place according to the Egyptian reuse code 501/2015 (Annex 2). Direct water reuse is practised mainly by the Holding Company for Water and Wastewater (HCWW) for afforestation purposes on land plots adjacent to wastewater treatment plants in order to reduce the cost of water transfer (Tawfik et al., 2021).

Currently, out of the total generated treated wastewater (approximately 4.6 BCM/year), more than 70% of the treated wastewater is discharged into agricultural drains and mixed with agricultural drainage water prior to its reuse in agriculture (i.e. indirect reuse in agriculture); around 10% is reused directly in agriculture (i.e. without mixing with freshwater); and the rest are discharged into the sea (HCWW presentation, July 2022).

3.2.1.2. Treated wastewater reallocation and reuse in agriculture. Treated wastewater is transferred from the water sector institutional arrangements to those that belong to the agricultural sector through various mechanisms based on the scale of reuse and its purposes. This is mediated by infrastructure/technology, policy, regulations, and standards. Collectively, these processes enable the reallocation of water across sectors and users/uses.

Indirect reuse in agriculture is formally carried out through water mixing stations allocated across the delta and operated by the Ministry of Water Resources and Irrigation, as shown in Fig. 2. These mixing stations pump drainage water to supply agricultural

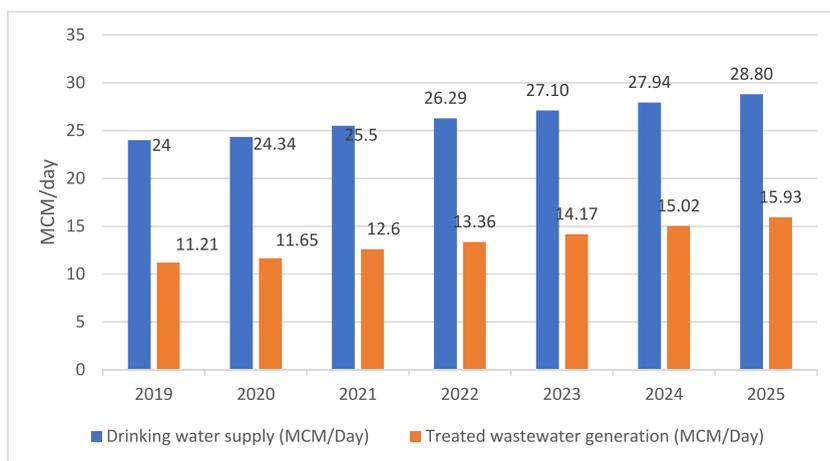


Fig. 1. Annual volume of drinking water supply and treated wastewater generation in Egypt (adapted from the HCWW chairman presentation, the Second Science-Policy Dialogue, July 2022).

2020 (CAPMAS, 2022). Fig. 3, adopted from Tawfik et al. (2021), depicts the interconnectedness between the drainage and irrigation networks in Egypt.

Successive Egyptian governments have exerted considerable efforts to maximize the irrigation water use efficiency by modifying and upgrading the distribution, which was expected to improve agricultural productivity and prompt land reclamation to cope with the food security challenges. Most of the effort has been on the expansion of drainage water reuse in Egypt, which is projected to increase by 50% compared to 2015 and is planned to reach 16.26 BCM by 2037 where 37% of it will be treated domestic wastewater (Molle et al., 2019). Fig. 4 depicts the expansion in the agricultural drainage water reuse in the period between 1996 and 2037.

The crop types, patterns of growth, maturity periods, and cultivation percentage in the agro-ecological zone are presented in Table 3.

Irrigation infrastructure and patterns vary according to the location, available irrigation water resource and crops. In the Nile Delta and the Nile Valley, traditional farrow irrigation is the dominant irrigation pattern which requires minimum irrigation infrastructure, except for irrigation water pumps that transfer water from canals to the irrigation ditches that distribute irrigation water among clusters of farmers as shown in Figs. 5 and 6. Irrigation frequency varies based on the season (summer and winter) and crops; according to farmers in Fayoum, the average irrigation frequency is once every seven days in summer and once every 14 days in winter, which is representative for most of the farmers in the delta and valley including the Fayoum depression. In the reclaimed lands outside the delta and valley, surface/farrow irrigation is prohibited, and farmers must use drip irrigation to reduce water consumption in the sandy soil which has a low water-holding capacity, as shown in Fig. 7.

3.2.2. Jordan

3.2.2.1. Wastewater generation and flow. In order to combat water scarcity, successive Jordanian governments have worked to increase the share of treated wastewater as an important component of the water budget, thus enabling more freshwater to be saved for domestic use. In 2018, 67% of the population in Jordan were covered by conventional sanitation/sewerage systems through 33 wastewater treatment plants. This is expected to generate 240 million cubic meters of treated wastewater per year by 2025, or approximately 16% of Jordan's water budget (Breulmann et al., 2019). According to Halalsheh and Kassab (2018), 70% of the collected wastewater receives tertiary treatment, and thus can be used as an irrigation source for a wide variety of crops.

Treated wastewater discharge into water bodies and reuse in agriculture is regulated according to the 2006 standards (JS 893) (Annex 3); additionally, treated wastewater is collected in dammed reservoirs for mixing with freshwater prior to its transfer to the agricultural sector for irrigation. This arrangement allows the reuse of treated wastewater (mixed water) for unrestricted agricultural purposes (particularly in the Jordan Valley), where all types of crops can be grown using this 'blended' water source; in other words, indirect reuse of wastewater in agriculture. The blended water is a mixture of two or more sources of water and in this case the treated wastewater is mixed with freshwater resources.

3.2.2.2. Treated wastewater reallocation and reuse in agriculture. The transition of treated wastewater to agriculture in Jordan takes place mainly in the Middle Jordan Valley (MJV), where farmers receive treated wastewater from the As-Samra wastewater treatment plant mixed with freshwater, with plans to expand this reallocation to the Northern Jordan Valley (NJV). The reallocation process is regulated through multiple layers of infrastructural and institutional arrangements that are controlled/mediated by various stakeholders, most notably the Jordan Valley Authority that claims a centralized role in the Jordan Valley, as shown in Fig. 8 (Tawfik et al., 2022 forthcoming).

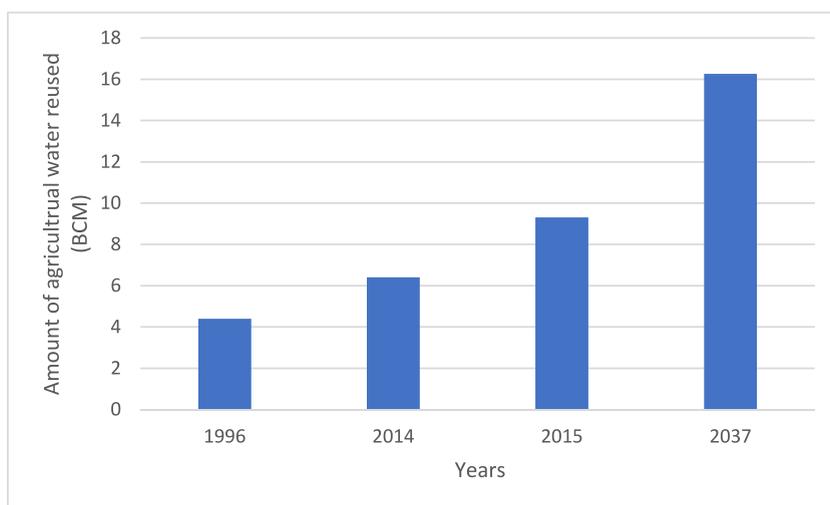


Fig. 4. Egyptian government expansion strategy of the reuse of drainage wastewater from 1996 to 2037.

Table 3
Cropping patterns and agro-ecological zones in Egypt.

Agricultural crops	Agro-ecological zones share %			Cultivation period	Maturity period
	Upper Egypt	Middle Egypt	Lower Egypt		
Winter crops (e.g. wheat, barley, onions, beans, lentils, fenugreek, chickpeas, alfalfa)	23.3	33.7	33.4	September–November	During winter season
Summer crops (e.g. cotton, sugarcane)	69.1	54.1	55.7	February–May	During summer season
Nili crops (e.g. rice, maize)	10.5	3.6	0.6	July–August	
Fruits	7.2	8.6	10.3	Spaces standing throughout the year	
Deciduous fruit (e.g. grapes, pears, apricots, peaches, apples)					
Permanent foliage (e.g. mandarins, oranges, salty lemons, rough limes, bananas, guavas)					



Fig. 5. (left) Irrigation water pumps in the Nile Delta.



Fig. 6. (right) Irrigation ditch that distributes water among a cluster of farmers.

3.2.2.3. Management of treated wastewater in agriculture. The cultivated area in Jordan was approximately 10,218 km² in 2018, which represents about 11% of the total area of Jordan, according to Jordanian official statistics on the Aquastat database (FAO, 2022). Nevertheless, the cultivated area in Jordan could increase to 11,650 km² (maximum value recorded in 1988) or decrease to 9633 km² (minimum value recorded in 2007), based on the rainfall rates (TheGlobalEconomy, 2022). Agricultural activities in Jordan are centralized in three climatic areas, which are the Jordan Valley, the desert, and the highlands. These areas are heterogeneous in terms of biophysical characteristics (water resources availability, micro climate, soil types, crop patterns, irrigation techniques, and irrigation patterns), and socio-economic contexts (Sixt et al., 2018). However, despite this heterogeneity, there has been a continuous



Fig. 7. Drip irrigation on reclaimed land outside the Nile Delta and Nile Valley.

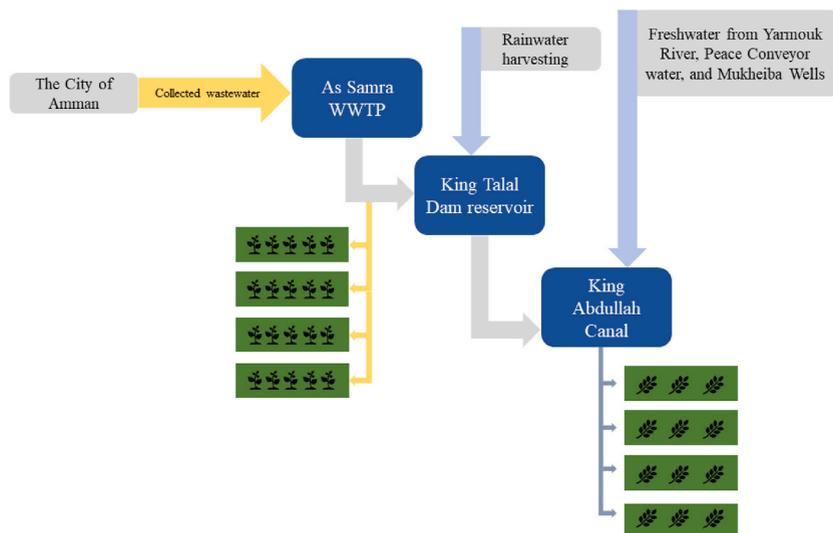


Fig. 8. Mixed TWW flow in the Jordan Valley.

increase in the reuse of treated wastewater irrigation water in Jordan across the different cultivated areas in various ratios between 1985 and 2020, as shown in Fig. 9 (MWI, 2000–2020).

Amongst the three climatic areas, the Jordan Valley is the largest agricultural area which consumes around 25% of the available water resources and is considered the ‘market garden’ of Jordan. The Jordan Valley is sub-divided mainly into three micro-climatic zones: the Northern Jordan Valley (NJV), the Middle Jordan Valley (MJV), and the Southern Jordan Valley (SJV) (Sixt et al., 2018). These three sub-zones allow for year-round agricultural activities that support a large number of (mainly) foreign and local labour (Kattaa et al., 2018). All the social and economic development aspects in the Jordan Valley are managed by the Jordan Valley Authority (JVA), which is in charge of the operation and maintenance of the irrigation systems (Al-Karablieh, 2014). The irrigation water varies in the three sections of the Jordan Valley: the NJV receives freshwater from the King Abdullah Canal (KAC), which is mostly diverted for municipal use in Amman before reaching the MJV and supplemented with mixed treated wastewater from the King Talal Dam (KTD). The Southern Jordan Valley (SJV) relies mainly on groundwater sources. The irrigated crops in the north are predominantly citrus trees with open field vegetable farms, while the crops in the MJV and SJV are vegetable crops in greenhouses and open lands with palm trees. The southern part of the Jordan Valley (SJV) relies on irrigation water resources from the Kafrein Dam, Shuib Dam, the KAC, the Hisban Wadi, and brackish groundwater (Qtaishat, 2020). More details about crop type and irrigation water sources are provided in Table 4.

In contrast, Jordan’s highlands are dominated by family-based agriculture with small and medium-sized agricultural fields and the most commercial farming lands in Jordan (Mustafa and Tillotson, 2019). The cultivated crops include olives, grapes, stone-fruit trees, and alfalfa. The main water source for irrigation in this area was previously rainfall but due to the climate challenges, the resources have shifted to groundwater which is in short supply and to reuse of treated wastewater which is being developed within the increased

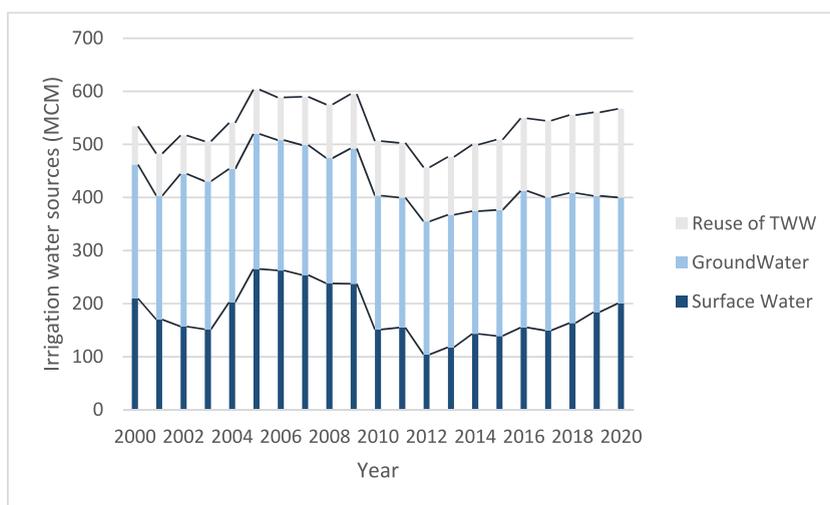


Fig. 9. Historical trends in irrigation water consumption rates in agriculture between 2000 and 2020, Jordan.

Table 4

Summary of agricultural activities in Jordan.

Agricultural zone	Crop types	Quota per crop m ³ /ha. year (Molle et al., 2008)	Irrigation water source
Jordan Valley	<ul style="list-style-type: none"> • Citrus trees • Bananas • Vegetables (open-field) 	• 1010	<ul style="list-style-type: none"> • Surface water from the King Abdullah Canal and Yarmouk River • Limited use of freshwater mixed with treated wastewater from the King Talal Dam • Rainfall
		• 15,000	
		• 5050	
	MJV	• 5050	<ul style="list-style-type: none"> • Treated wastewater from the King Talal Dam • Surface water from the King Abdullah Canal • Limited rainfall • King Talal Reservoir
	SJV	• 5050	<ul style="list-style-type: none"> • Treated wastewater from the King Talal Dam • Limited rainfall • King Talal Reservoir • Surface water from the King Abdulla Canal
Highlands	<ul style="list-style-type: none"> • Olives • Grapes • Stone-fruit trees • Alfalfa 	• 5050	<ul style="list-style-type: none"> • Surface water from the King Abdulla Canal • Groundwater • Springs • Reuse of treated wastewater • Limited rainfall
Desert area	<ul style="list-style-type: none"> • Vegetables • Field crops • Fruit trees 	• 5050	<ul style="list-style-type: none"> • Groundwater

urbanization population rates in this area (Mustafa and Tillotson, 2019). It is well-known that the highland farmers over-abstract the groundwater, which is why the government is attempting to remove the direct and indirect subsidies for irrigated agriculture in this area in order to promote the use of treated wastewater. However, these policies have been resisted by local farmers and not ultimately fully implemented (Liptrot and Hussein, 2020). Fig. 10 depicts the wastewater reuse rates in the Jordan valley and the highlands (MWI, 2000–2020). As shown in Fig. 10, there has been a dramatic increase in the reuse in the Jordan Valley and a slight increase in the highlands. In contrast to the highlands, the Jordan Valley uses most of the reused wastewater. This is due to the size of the agricultural fields and its strategic location, which allows mixed TWW flow by gravity from the King Talal Dam that collects TWW from the As-Samra wastewater treatment plant (Sixt et al., 2018).

In the desert area, which is near Jordan's borders with Saudi Arabia, Iraq and Syria, there is no more than 25 cm (10 inches) of precipitation per year. Here the agricultural practices rely on groundwater from renewable and non-renewable resources. This area is mainly used for cultivating vegetables and field crops with some fruit trees in particular locations. It is clear that the energy consumption for irrigation/agriculture in the desert area is relatively high compared with other areas in Jordan due to the over-abstraction of groundwater and the subsequent decrease in groundwater tables that require higher intensity pumps to recover the irrigation water from the aquifers (Talozi et al., 2015). Nevertheless, a re-allocation strategy to control the groundwater abstraction is not favoured by the government since it will impact small-scale farmers and increase the unemployment rates (Liptrot and Hussein, 2020).

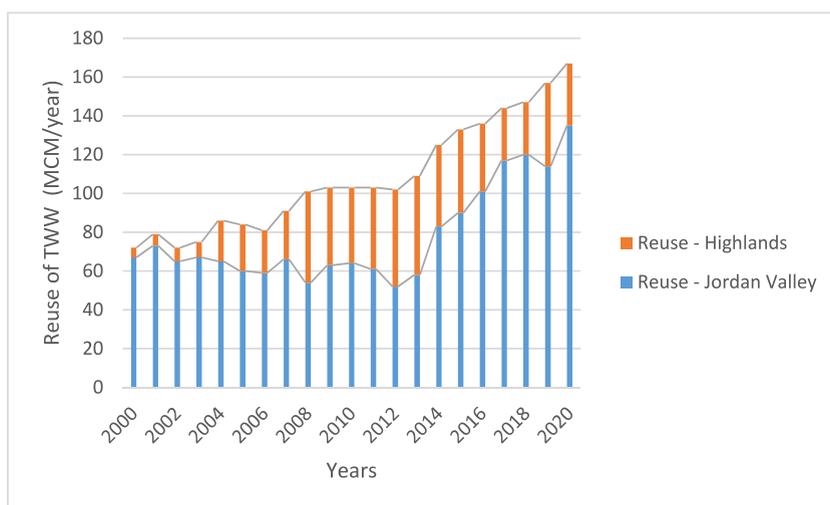


Fig. 10. Historical development of the reuse of treated wastewater in agriculture in the Jordan Valley and the highlands, Jordan (2000–2020) (MWI, 2000–2020).

Each area of these agricultural zones has distinct characteristics regarding the farm sizes, crop types, crop-based water quota allocation, and sources of water for irrigation, as summarized in Table 4. Currently, irrigation water quota allocation for farmers, particularly those in the NJV, has seen a significant reduction and a corresponding increase in water tariffs. This has been carried out in parallel with the promotion of water-efficient irrigation techniques and treated wastewater reuse.

In terms of irrigation infrastructure, severe water scarcity in Jordan means a more conservative pattern in the irrigation infrastructure and irrigation pattern. In the Jordan Valley – the focus of this paper – farmers receive their weekly water quotas via the Farm Turnout Assembly (FTA) units at the head of each farm unit; FTAs are set at a fixed flow rate based on the crop type registered at each farm (Mustafa et al., 2016). Each FTA unit is either connected to irrigation line hoses to irrigate the crops directly, or to a water collection pond, where irrigation water quotas are collected and further distributed through a drip irrigation network. The latter method is increasingly spreading among farmers in order to mitigate the reduction in water availability (Tawfik et al., 2022 forthcoming). Fig. 11 shows a neglected FTA and Fig. 12 shows a water collection pond in the Jordan Valley.

3.3. The decision tree

The decision tree is a new approach to addressing and facilitating decision-making regarding treated wastewater management in irrigated agriculture; it is intended to map the potential outcomes of a set of related options for reusing treated wastewater in irrigated agriculture, as shown in Fig. 13. The decision to reuse wastewater in agriculture is driven by countries' quest to achieve food security under freshwater scarcity, which is causing competition for the available water resources between various sectors. In response to this competition, decision-makers frequently reallocate the agricultural sector's designated freshwater share, which exceeds 50% of water withdrawals in most of the MENA countries, to other priority uses and users, particularly municipal water users. Since the reuse decision is site-specific, the decision tree has been developed by assessing four site-specific determinants, which are the (un)



Fig. 11. (right) A neglected FTA at the entrance to a farm in the Jordan Valley.



Fig. 12. (left) An irrigation water collection pond in the Jordan Valley.

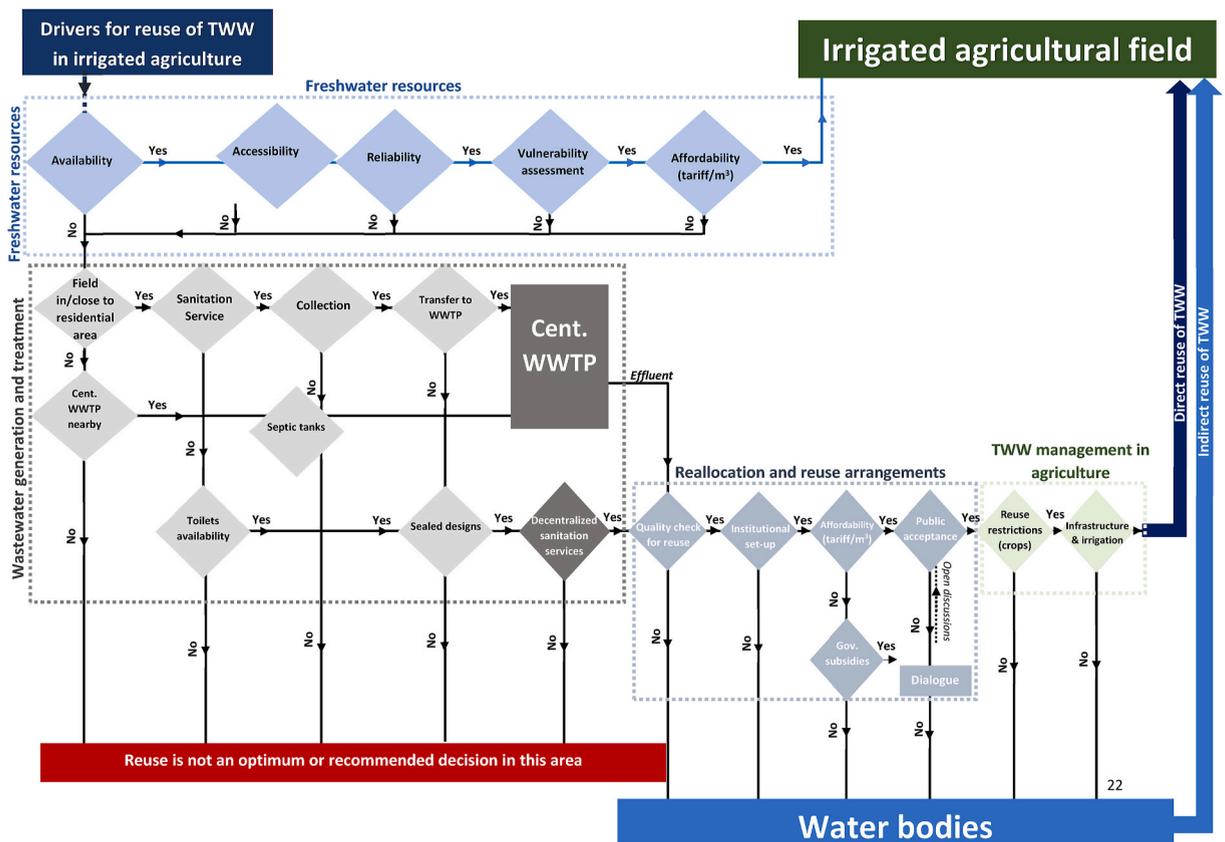


Fig. 13. Decision-tree framework.

availability of reliable freshwater resources; wastewater collection and treatment infrastructure (including treatment technology); treated wastewater reallocation and reuse arrangements; and management mechanisms for TWW in irrigated agriculture.

The decision to reuse treated wastewater, either directly, indirectly, or not optimally, begins with the drivers for the reuse; these could be water scarcity issues, the country’s national strategy, agricultural water demands, and/or valorisation for TWW. If freshwater resources for irrigation are available, accessible, and reliable, have passed the vulnerability assessment (evaluation of water resources in terms of quality, sensitivity to the surrounding environment, and sustainability), and are affordable, then relying on freshwater resources for irrigation is the recommended decision. However, if this is not the case, the next question in the decision tree investigates whether the agricultural field is in or nearby residential areas (i.e. in a semi-rural area). If so, the following questions (in the diamond shapes) investigate wastewater treatment and generation, beginning by determining whether there are sanitation services (i.e.

wastewater collection, transfer, and treatment plants at centralized wastewater treatment plants (hereafter referred to as Cent. WWTPs). This is followed by checking the reallocation and reuse arrangements that include the following: the compatibility of the treated effluent with the national reuse standards; if there is an institutional set-up for the reuse; and if the reuse is affordable and accepted by local communities. Additionally, the management of TWW in irrigated agriculture is investigated by checking if there are reuse restrictions in place for particular crops (i.e. non-edible crops), and if there is an infrastructure or irrigation techniques to transfer and efficiently utilize the treated effluent to the agricultural fields. Under these circumstances, direct treated wastewater reuse would be recommended.

For agricultural fields in remote or rural areas, the questions on the wastewater generation and treatment will explore whether there is a Cent. WWTP nearby or not; if not, the reuse option would not be feasible. However, if there is a Cent. WWTP nearby the field, the effluent quality will be investigated under the quality check and reuse regulations. The institutional set-up for reuse, affordability, public acceptance, reuse restriction, and the availability of infrastructure and irrigation techniques for the transfer and utilizing the TWW in irrigation are as in the previous effluent assessment scenario. If these conditions are met, the decision to be made will also be direct reuse. However, if the effluent quality is inadequate for reuse purposes, there is no institutional set-up or tariff for reuse, reuse is not publicly accepted, unrestricted irrigation is practiced, there is no infrastructure to transfer treated wastewater, or there are no irrigation techniques suitable for utilizing the TWW as irrigation water, then the effluent will be discharged to water bodies or used to recharge groundwater aquifers. In these circumstances, indirect reuse from water bodies or groundwater aquifers will be recommended. In addition, especially when there is no public acceptance, there will be an open discussion with the local community about the reuse decisions; there can also be governmental subsidies for reuse when the costs of TWW are high and cannot be afforded by the local community.

In the case of a lack of sanitation services in a residential area near an agricultural field, it is necessary to assess the existing on-site sanitation facilities, such as the availability of toilets and septic tanks with sealed designs; if these exist, then the recommended decision is to establish a decentralized wastewater treatment unit. If the effluent from this unit meets the quality check, reuse and reallocation arrangements, is affordable and accepted by the public, and the TWW can be managed in the agricultural field, then direct reuse for irrigation will be recommended once the required infrastructure is available.

In a nutshell, direct reuse is usually possible when the effluent quality is monitored, the reuse standards, institutional set-up, subsidies and public acceptance are met, restricted irrigation is practiced (non-edible crops), and the effluent infrastructure and irrigation techniques are available. In addition, it is worth mentioning that some countries in the MENA region practise direct reuse for unrestricted irrigation if the wastewater has been advanced treated. However, reuse is not optimal or recommended when sanitation services, toilets, septic tanks with sealed designs, and reuse standards are not available/fulfilled. Furthermore, when the effluent is not monitored, is inadequate to standards and policy, cannot be transferred to the field, and the irrigation technique is not suitable, indirect reuse is recommended so that it is blended with other freshwater sources.

4. Discussion

Egypt and Jordan have witnessed rapid population growth and an associated reduction in the *per capita* water share over the years. This means that the competition for available water resources could curb the agricultural – overall economic – development of the two countries. However, unless the existing agricultural land and irrigation schemes can be expanded, the national strategies that aim to achieve food self-sufficiency and secure more job opportunities for their populations, the majority of whom are young, will be jeopardized. Donor organizations are playing a crucial role in promoting wastewater reuse in water-scarce countries in the MENA region, either through bilateral agreements or global commitment under a unified umbrella (e.g. SDGs, MDGs, and the European-Mediterranean Agreement). This shift towards reuse is often linked to a request by donors for institutional reforms (e.g. increasing water tariffs, implementing water allocation plans, and adoption of reuse codes) in order to agree to allocate financial assistance to a country (ARD-USAID, 2001). Additionally, many countries are responding to external threats such as climate change impacts and conflict over transboundary water resources (e.g. Egypt, Jordan, and Iraq) by improving the efficiency of water use in agriculture and substituting freshwater with treated wastewater (e.g. the water substitution and allocation policy in Jordan) according to national codes.

4.1. Analysis of reuse management for two case studies in Egypt and Jordan

Treated wastewater reuse management modality (i.e. scale, regulation, organization etc.) differs considerably between countries and within countries, due to the heterogenic nature of the agricultural and reuse practices/arrangements; this hinders any attempt to provide a universal management approach that can be generalized to the various local contexts. Thus, there is a need for a framework to enable decision-makers to understand the possible outcomes of their contextual challenges and opportunities for enabling or prohibiting wastewater reuse adoption in agriculture in order to be able to design a tailor-made management approach that fits these constraints. Accordingly, the following subsection starts by introducing the decision-tree framework that aims to serve this purpose. This is followed by two treated wastewater reuse case studies from Egypt and Jordan that represent the direct and indirect reuse modalities, respectively, in terms of location specificities, reuse rationale, and the governance approach (i.e. who owns and who operates them, allocation management, targeted crops), and challenges of wastewater reuse in agriculture. The two case studies will be used to apply the decision-tree framework and to explore the various local reuse management alternatives.

4.1.1. Direct wastewater reuse – Sarapeum in Egypt

4.1.1.1. Location specificities. The Sarapeum WTT is in an area located in the Ismailia Governorate bordering the western fringes of the Nile Delta and Suez Canal; Ismailia is a desert-front governorate (i.e. the predominant terrain is desert) where direct wastewater reuse is centrally managed by the state institutions (i.e. the Ministry of Housing, Ministry of Agriculture and Land Reclamation, and their affiliated institutions such as the Holding Company for Water and Wastewater, as well as various agricultural research institutes and directorates). Sarapeum is one of various sites where formal direct reuse of treated wastewater is taking place on land owned by the Ministry of Agriculture (500 feddans) that lies adjacent to the Sarapeum wastewater treatment plant, as shown in Fig. 15. Treated wastewater is pumped directly from the treatment plant to the forest at a rate of 30,000 cubic meters per week, according to the operators; various timber trees are grown for commercial/industrial purposes (i.e. timber production) such as mahogany, acacia and lemon acacia, as shown in Figs. 14 and 15.

4.1.1.2. Reuse rationale. The Sarapeum forest is one of several sites where direct wastewater reuse is practised, particularly in desert-front governorates.

During the last few decades, desert-front governorates have seen increasing rates of wastewater generation due to increasing urbanization rates. However, the generated wastewater – unlike the delta mixing strategy of fresh and treated wastewater for irrigation – has not had a clear reuse approach/modality that would have minimum health and environmental impacts. Accordingly, Egypt has adopted a wastewater reuse for afforestation strategy that would enable safe direct reuse while creating a new source of income through timber production, as shown in Fig. 16.

4.1.1.3. Governance approach & challenges. In the mid-1990s, Egypt started the National Program for Safe Use of Treated Sewage Water for Afforestation, which was followed later in 2005 by the development of the Egyptian treated wastewater reuse code 501 with the support of the USAID mission in Cairo. At the same time (2004–2005), the Ministry of Housing, Utilities, and Urban Communities allocated 84,000 ha of desert land to the newly established Holding Company for Water and Wastewater (HCWW) for irrigation with treated wastewater (Zalesny et al., 2011).

The program is implemented by three main governmental institutions: the Ministry of Housing, Utilities and Urban Communities (MoHUUC), the Ministry of Agriculture and Land Reclamation (MALR), and the Ministry of Environment (MoE). It is also in collaboration with the Ministry of Local Development, the Ministry of Water Resources and Irrigation, and the Ministry of Health, governorates, research institutes (e.g. *Desert Research Institute*) and NGOs, as well as donor organizations such as USAID, DAAD and JICA.

This program was seen by many experts as a promising economic solution to enable the utilization of one of Egypt's most underused resources i.e. the desert land and treated wastewater, particularly when the rate of tree growth is around one fifth that of tree growth in Germany (El Kateb, 2014). However, the program (and similar reuse initiatives) did not have the required legal, financial, regulatory, or monitoring framework to sustain its implementation and progress. In addition, the consortium of ministries that carried out the project has no clear organizational set-up to clarify how the different ministries collaborate with each other.

4.1.2. Indirect (mixed) wastewater reuse – middle Jordan valley (MJV)

4.1.2.1. Location specificities. The Jordan Valley (JV) runs adjacent to the Jordan River and it is considered the market garden of Jordan. The microclimatic variations between the North, Middle and South regions of the JV allow diverse crops throughout the year. Citrus trees are traditionally grown in the Northern Jordan Valley (NJV) as well as the Middle Jordan Valley (MJV). According to personal communication with a representative from a local NGO in the Jordan Valley, during the 1980–1990s MJV farmers shifted to other crops, mainly vegetables, and dates after the introduction of treated wastewater (mixed with freshwater at the King Talal Dam reservoir) for irrigation purposes.

The King Abdullah Canal (KAC) is the main King Talal Dam (KTD); source of freshwater for irrigation in the Jordan Valley. It runs southwards, starting at the Northern Jordan Valley. However, freshwater from the KAC is diverted upon reaching the MJV to provide freshwater for domestic use in Amman. After the diversion point, the KAC receives water from the this has previously been treated at the As-Samra wastewater treatment plant which collects and treats Amman's wastewater (Almanaseer et al., 2020). See Figs. 17 and 18.

4.1.2.2. Reuse rationale. Jordan's water resources policy in 2016 was developed to respond to the increasing water scarcity in the country, which places Jordan as one of the most water-scarce countries in the world. In this context, the agricultural sector consumes around 60% of Jordan's water budget, while making a minor contribution to the national GDP (Hussein, 2018). Accordingly, the government's water reallocation policy has de-prioritized the agricultural sector in order to fulfil its domestic water needs, particularly in Amman and other large cities such as Irbid. Thus, the agricultural sector in Jordan must shift to treated wastewater reuse, particularly in large agricultural schemes such as the MJV and NJV.

4.1.2.3. Governance approach and challenges. Wastewater reuse and allocation in the Jordan Valley (including the MJV) is the responsibility of the Jordan Valley Authority (JVA), which is a regional organization that oversees the development aspects in the Jordan Valley including water, agriculture and other services. Farmers in the MJV receive irrigation water based on a weekly quota that is organized either by the JVA directly or through the Water Users Association (WUA) that operates under the supervision of the JVA. The



Fig. 14. (right) Lemon acacia trees irrigated with treated wastewater in the Sarapeum forest.



Fig. 15. (left) Map of the Sarapeum site (green indicates the forest area, blue the WWTP, and yellow the adjacent land of the local community). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

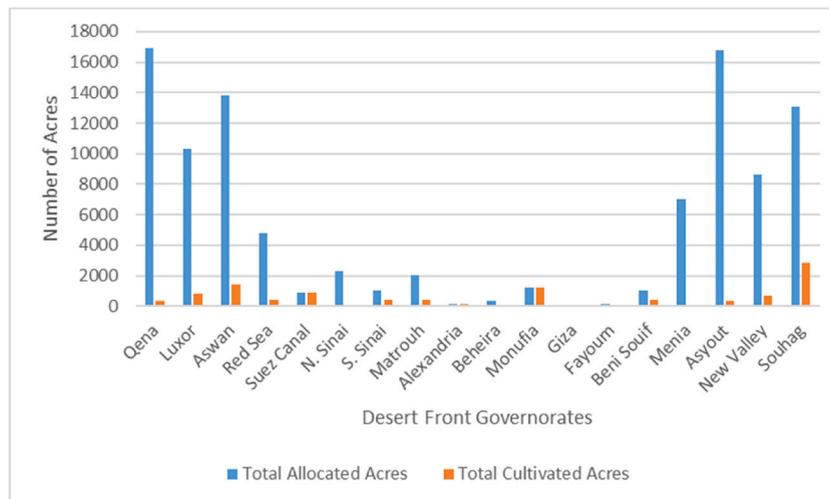


Fig. 16. Total land allocated and total land irrigated through direct reuse of treated wastewater in Egypt (source: HCWW website).

weekly irrigation water quota is deigned based on the crop type, where farmers who grow crops such as citrus fruit or bananas receive a larger water quota than farmers growing vegetables (see Table 5).

The main challenge for indirect (mixed) wastewater reuse in the MJV was at the beginning of the implementation of the reuse scheme when farmers' citrus fruit plantations were damaged and eventually farmers had to replace them with different crops. This coincided with the low quality of the effluent from the As-Samra wastewater treatment plant. Accordingly, farmers in the MJV saw a direct link between wastewater reuse in irrigation and the loss of their traditional agricultural practices. The loss of citrus fruit



Fig. 17. (left) Water diversion point in the Middle Jordan Valley, where freshwater is substituted by treated wastewater.



Fig. 18. (right) Map showing the flow of freshwater and treated wastewater in the Jordan Valley.

Table 5
Water allocation per crop in the Jordan Valley (Tawfik et al. forthcoming).

Season	Citrus tree water allocation (average m ³ /ha/day)	Vegetable water allocation (average m ³ /ha/day)
Summer (April–October)	30	15
Winter	20	15

plantations meant that farmers shifting towards vegetables crops will also be deprived of the larger water quota allocated by the JVA (see Table 5). Therefore, although the As-Samra plant has been upgraded and its effluent quality has improved considerably, the negative perspective on wastewater reuse across the Jordan Valley has persisted among farmers (Tawfik et al., 2022).

4.2. Operation and validation of the decision tree

4.2.1. Validation of case study#1: Sarapeum, Egypt

The decision on wastewater reuse (either direct or indirect) will be made using the decision-tree diagram that was shown in Fig. 13 and the case of Sarapeum in Egypt. According to this case, a forest that grows timber trees for commercial and industrial purposes uses 30,000 m³/week of irrigation water. The driver of the decision to reuse treated wastewater begins with the country’s national strategy to reuse TWW for agricultural and land reclamation purposes. Thus, for this case, the decision tree starts with the first investigation of the freshwater resources for irrigation. In this case, the answer is that no freshwater resources are available, which also implies no accessibility, reliability or application for the vulnerability assessment to freshwater resources. This leads to the second question in the decision tree, which is whether the forest is in a residential area or nearby. This means whether it is in a rural or semi-rural area, to which the answer is no. This leads to the third decision-tree question, which is whether the field is close to the Cent. WWTP, to which the answer is yes, there is a wastewater treatment plant at Sarapeum.

So now there is a demand for irrigation water where there are no available water resources and the field is close to a Cent. WWTP which produces sufficient effluent that passes the quality check for the reuse and also fulfils the timber agricultural demand. The fourth question is whether there is an institutional set-up for reuse. According to the Egyptian reuse code 501/2015, the answer is yes because timber falls under category D. The next question is whether a reuse is affordable in terms of tariff/m³ of TWW; again the answer is yes, Egypt has an affordable tariff that is supported by governmental subsidies which applies to this governorate and this agricultural crop.

The question is then if the reuse is accepted by the public in this agricultural area; in this particular case the land belongs to the Ministry of Agriculture, accordingly public acceptance is not a challenge (since the land is not privately owned). The question then becomes whether timber agriculture is considered under restricted or unrestricted reuse practices. With timber, it falls into the restricted reuse category. The final question is whether there is an infrastructure and irrigation technique suitable to transfer and utilize the effluent to the agricultural field, and the answer is yes.

By following these questions, the developed framework establishes that the direct reuse of treated wastewater for irrigating the timber field is the best option. This decision is consistent with on-the-ground practice. Fig. 19 depicts the decision pathway through the decision-tree framework for the case of Sarapeum, Egypt.

4.2.2. Validation of case Study#2: middle Jordan valley (MJV), Jordan

The decision tree will be used to determine whether direct or indirect wastewater reuse is preferable in Jordan’s Middle Jordan Valley (MJV). According to the decision tree, the driver for the decision is made based on the agricultural demand that exists in this case in the MJV. The first set of questions investigates the freshwater resources, and begins with the question whether freshwater is available, which it is in this case. Moving on to the second question of the accessibility of fresh resources, Jordan’s government has transferred freshwater resources away from agriculture in the MJV for priority users in Amman, limiting accessibility. This brings the decision maker to the third question: is agriculture practised in a residential area or nearby? The answer is yes as it is a semi-rural area. The following questions concern sanitation service in this area, wastewater collection, and wastewater transfer to a Cent. WWTP, to which the answers for all three questions is yes.

In this case, As Samra is the centralized wastewater treatment plant that produces effluent. The next two questions are whether the effluent quality meets the reuse standards and whether there is an institutional set-up in place: yes, the produced effluent from the Cent. WWTP is of high quality and meets Jordan’s wastewater reuse code, and a reuse institutional set-up is in place. This prompts the decision-maker to think about the affordability of TWW, public acceptance, and reuse restrictions. The Jordanian government is supporting the TWW tariff with subsidies and there is a public acceptance and official contracts between farmers in this area and water authorities in Jordan. However, because of the crop types cultivated in this agricultural area (MJV), there are unrestricted irrigation practices in place, so the answer to the question of reuse restrictions is no. Therefore, the treated wastewater will be discharged to water bodies.

Therefore, according to the previous answers and decision-tree framework, the advice is to select indirect reuse in the MJV in

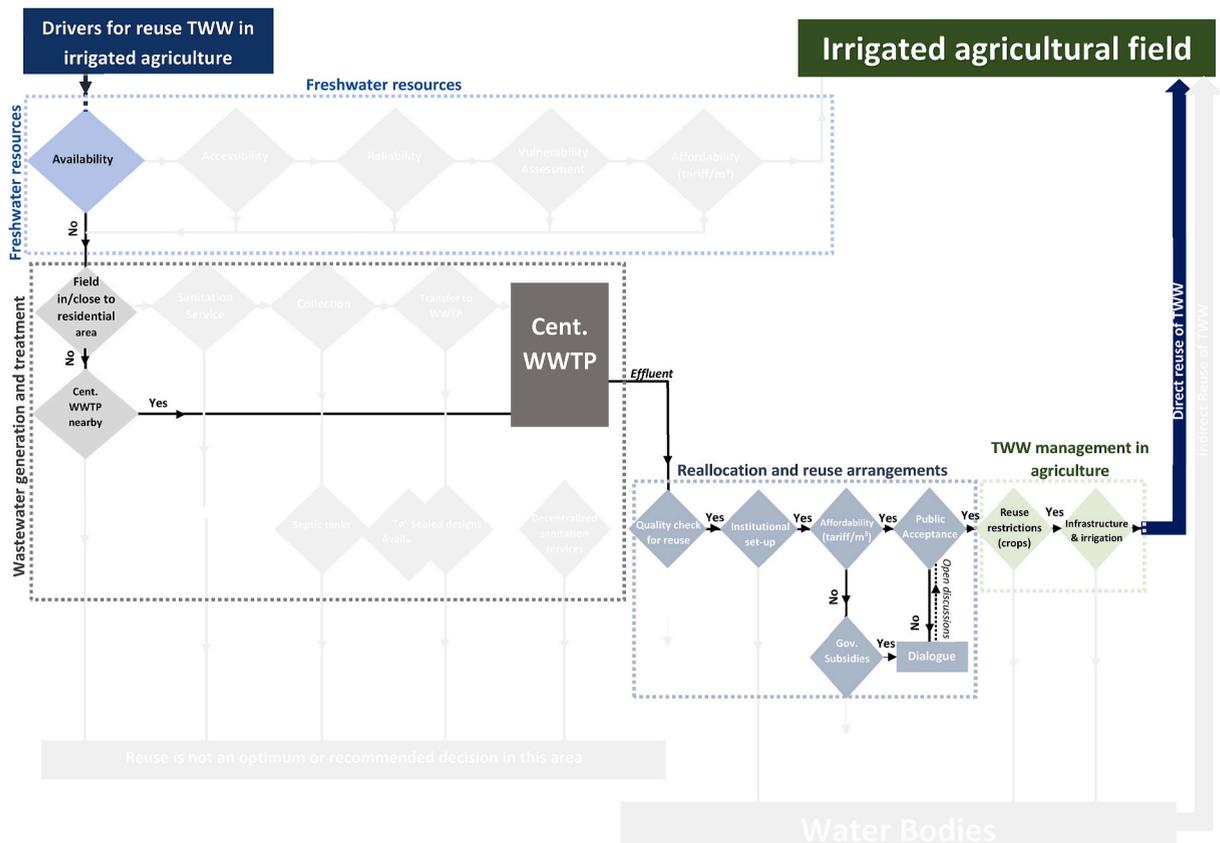


Fig. 19. Decision-tree pathway for treated wastewater reuse in Sarapeum, Egypt.

- Often illegal practices without authorities controlling water quality. Farmers might measure water quality for basic water quality parameters (salinity, nitrogen content) but lack awareness and financial resources to sample and analyse to satisfy formal reuse guidelines and regulations. This is a factor that increases health risks.
- Potential source of tensions between farming communities and government authorities or urban communities, especially after disease outbreaks.

However, the public health risks could be balanced by increased food production and the subsistence of poor communities. Authorities might choose an approach to reduce the risk of the practice or try to forbid the practice altogether. However, a 'zero risk' approach is not possible particularly when severe water scarcity leads to an increased supply-demand gap. Thus, a realistic risk management approach based on risk reduction should be adopted by 1) farmer awareness and agricultural practices, 2) crop restrictions imposed by authorities, 3) on-farm water treatment, and 4) a multiple barrier approach: food preparation practices of consumers should be further investigated and integrated in a more comprehensive decision-making support system that enables the adoption of safer treated wastewater management approaches for agricultural purposes.

Author statement

- **Hadeel Hosney:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration, Funding acquisition.
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- **Peter van der Steen:** Conceptualization, Resources, Validation, Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared all the data mentioned in the manuscript

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Annexes.

Annex 1

Law 48/1982 that regulates treated wastewater discharge into water bodies.

Parameters	Standards (mg/l)
Temperature	Maximum 35 °C
pH	6–9
BOD	60
COD	80
Dissolved oxygen	Not less than 4
Oils and greases	10
Dissolved solids	2000
Suspended solids	50
Sulphides	1
Nitrate	50
Total of heavy metals	1
Most probable number of coliforms in 100 cm ³	5000

Annex 2

Egyptian reuse code 501/2015 issued by the National Housing and Building Research Center (HBRC).

Parameters	Crop category			
	Category A	Category B	Category C	Category D
Total suspended solids (mg/L)	15	30	50	300
Turbidity (NTU)	5	Not applicable	Not applicable	Not applicable
BOD5 (mg/l)	15	30	80	350
E. Coli (count per 100 ml)	20	100	1000	NA
Intestinal nematodes/litre	1	Not applicable	Not applicable	Not applicable

Annex 3

Treated wastewater reuse standards in Jordan (JS 893–2006).

Parameters	Unit	Maximum allowable limits				
		Class A (<i>cooked vegetables, parks, stadiums & side roads within cities</i>)	Class B (<i>fruit trees, roads outside cities & landscape</i>)	Class C (<i>field crops, industrial crops & forest trees</i>)	Cut flowers	Discharged into streams, wadies & water bodies
BOD	mg/l	30	200	300	15	60
COD		100	500	500	50	150
DO		≥2	–	–	≥2	≥1
TSS		50	200	300	15	60
pH	unit	6–9				
Turbidity	NTU	10	–	–	5	–
NO3	mg/l	30	45	70	45	80
TN		45	70	100	70	70
E. Coli	MPN/ 100 ml ³	100	1000	–	≤1.1	1000
Intestinal helminth eggs	egg/l	≤1				≤0.1
Fat, oil and grease	mg/l	8			2	8

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