Rev. Int. Contam. Ambie. 37, 513-525, 2021
https://doi.org/10.20937/RICA.53749

MULTI-CRITERIA ASSESSMENT MODEL TO IDENTIFY SUITABLE AREAS FOR TREATED WASTEWATER REUSE IN AGRICULTURE

Modelo de evaluación multicriterio para la identificación de áreas adecuadas para reúso de aguas residuales tratadas en agricultura

María Laura GATTO D'ANDREA[1], Martín Alejandro IRIBARNEGARAY[1]*, Walter Alfredo TEJERINA[2], Ariela Griselda Judith SALAS BARBOZA[1], Juan José CORREA[1], María Soledad RODRIGUEZ-ALVAREZ[1] and Lucas SEGHEZZO[1]

[1] Instituto de Investigaciones en Energía No Convencional (INENCO), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Salta (UNSa), Av. Bolivia 5150, A4408FVY Salta, Argentina.
[2] Facultad de Ingeniería, UNSa, Av. Bolivia 5150, A4408FVY Salta, Argentina.

*Corresponding author: miribarnegaray@conicet.gov.ar

(Received: October 2019; accepted: November 2020)

Key words: Geographical Information System, land suitability, wastewater reuse, Cafayate.

ABSTRACT

A model of land suitability analysis for irrigation with treated domestic wastewater is presented. The model integrates tools of Multi-Criteria Evaluation with Geographical Information Systems. Several criteria were selected to adapt the model to the conditions and characteristics of the case study. The adaptation process included field visits, a bibliographical review, and personal interviews with local actors and experts. Six constraints and 10 factors were selected and 3158 hectares suitable for the activity were identified. The areas were classified into three categories of aptitude, representing high fitness sites close to the current wastewater treatment plant. The developed tool allowed us to integrate different criteria to assess site suitability for wastewater reuse, with the advantage that the tool can be adapted to other regions and/or objectives.

Palabras clave: sistemas de información geográfica, idoneidad de las tierras, aguas residuales, Cafayate.

RESUMEN

Se presenta un modelo de análisis de viabilidad de áreas para riego con aguas residuales domésticas tratadas. El modelo integra herramientas de evaluación multi-criterios con sistemas de información geográfica. Se seleccionaron varios criterios para adaptar el modelo a las condiciones y características del estudio de caso. El proceso de adaptación incluyó visitas de campo, revisión bibliográfica y entrevistas personales con actores y expertos locales. Se seleccionaron seis limitantes y 10 factores y se identificaron 3158 hectáreas aptas para la actividad. Las áreas se clasificaron en tres categorías de aptitud, que representan sitios de alta viabilidad cerca de la planta de tratamiento de aguas residuales en funcionamiento. La herramienta desarrollada nos permitió integrar diferentes criterios para evaluar la viabilidad del sitio para la reutilización de aguas residuales, con la ventaja de que la herramienta se puede adaptar a otras regiones y objetivos.

INTRODUCTION

It is estimated that by 2025 almost a third of the population in developing countries will live in regions with severe water shortages (Urkiaga et al. 2008), and approximately half of the world population will face water access restrictions (Lazarova et al. 2001). Agriculture, the largest consumer of freshwater resources, will be the most affected economic sector due to increased competition with urban sectors. Considering this scenario, the utilization of treated domestic wastewater (TDW) constitutes an alternative water resource for growing agricultural demands for irrigation (Miller 2006).

Treated wastewater has been used in agriculture in different parts of the world, driven by the fact that agriculture represents the largest user of water worldwide, at around 70 % compared to industrial (20 %) and domestic use (10 %) (FAO 2003). Social and environmental impacts derived from the reutilization of TDW in agriculture are complex and multidimensional, involving multiple criteria and stakeholders (Gómez-López et al. 2009; Jaramillo and Restrepo 2017). The stakeholders can be defined as people with some degree of interest in the planning and decision-making process (Lahdelma et al. 2000). However, non-expert actors such as politicians and state officials frequently take land and urban planning decisions based on diffuse criteria (Brahim and Turki 2015). Decision-makers involved in site-selection processes for wastewater reuse must deal with complex problems (Chang et al. 2008). Despite the potential benefits of reuse in agriculture, diverse sectors of the population often oppose undesirable activities near their location (Duong and Saphores 2015). The selection of places with deficient conditions for wastewater reuse implies potential risks for human health, the environment, and high associated economic costs. The capacity to support wastewater reuse depends not only on environmental, economic, political, and legal criteria but also on socio-cultural ones.

The use of TDW for irrigation has the potential to increase development in many places in the world. The total area irrigated worldwide using raw or treated wastewater is approximately 20 million hectares in more than 50 countries (Jiménez and Asano 2008). In Latin America, where less than 14 % of the wastewater collected receives some kind of treatment, irrigation with untreated wastewater (direct or indirect) could exceed more than two million hectares. In Mexico, Peru, Colombia, Chile, Argentina, and Bolivia, treated wastewater is currently used for irrigation of pastures, crops, vegetables, and fruit. In general, informal practices predominate, without adequate control (Crook et al. 2005). However, the regional expansion of projects needs to comply with several conditions, including economic interests, health security, and environmental protection issues.

The process of site suitability analysis for treated wastewater irrigation is based on a simultaneous assessment of multiple factors (Kihila et al. 2014). The integration of Multi-Criteria Evaluation (MCE) and Geographical Information Systems (GIS) is a proven tool to assess site suitability (Malczewski 2000). This tool is also known as Spatial Analysis of Multi-Criteria Decision (Pasuello et al. 2012). The MCE allows one to combine several criteria and the importance values (weights) for an activity, assessing potential locations through GIS tools. The procedure requires data to be expressed in variables of comparable units (Malczewski 2004). De Prada et al. (2014) assessed agricultural alternatives for treated wastewater effluents in Cordoba (Argentina) using the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) method. Applying the Analytic Hierarchy Process (AHP) method, Hadipour et al. (2016) determined that the best alternative for the TDW in Iran was the aquifer recharge. For several years, GIS and MCE have been used for environmental studies of various kinds, such as the location of wastewater treatment systems (Gemitzi et al. 2007), aquifer recharge with wastewater (Kallali et al. 2007, Anane et al. 2008, Pedrero et al. 2011, Gdoura et al. 2015), and location of sanitary landfills (Chang et al. 2008), among other applications. Anane et al. (2012) assessed the site location for wastewater irrigation, and Pasuello et al. (2012) evaluated the use of biological sludges as fertilizer. Borrego-Marín et al. (2018) focused on technical bases and the criteria required for the allocation of reused water in agriculture in the Guadalquivir River Basin, Spain. Nassar et al. (2015) studied the most sustainable scenarios for using wastewater in Gaza by identifying environmental impacts using MCE and GIS. Despite consistent advances in technical aspects, most studies rarely include direct consultation and interaction with local actors. The identification, selection, and valuation of criteria should not be adapted exclusively from other regions. Local information and experiences also need to be gathered from local actors that have a direct or indirect relationship with the activity. A focus on participants facilitates a learning process in which experts and non-experts can connect local experience with systemic knowledge in order to generate, evaluate, and select sustainable solutions (van Buuren and Hendriksen 2010).

In this work, we present a case study in Cafayate (Salta province, Argentina), where technical criteria collected from international experiences were combined with the personal views and knowledge of local actors. Cafayate is a town with significant irrigation problems due to a dry and highly seasonal climate, where the reuse of domestic wastewater could become an important resource for irrigation in dry seasons. A replicable technical tool for the identification and evaluation of the most suitable areas for TDW irrigation could help to significantly improve water security and reach the sixth Sustainable Development Goal (SDG6) (UN-Water 2016). The main objective of the study was to integrate different tools, like MCE, GIS, and semi-structured interviews, with experts and local actors, in order to identify the most suitable sites for irrigation with urban treated wastewater.

MATERIALS AND METHODS

Study area

With an altitude of 1680 masl, Cafayate is a town situated in the center of Valles Calchaquies, a region in Salta province, Argentina. Its climate is characterized by dry weather (only 200 mm of rain per year) and a high temperature range. The scarce rainfall during summer does not cover the water needs of the area, so irrigation is essential for land use and water rights are crucial issues. The population growth of Cafayate has been significant in recent years, mainly driven by the revaluation of the wine industry and the increasing tourism in the region. According to the last National Census, the town has more than 14 000 inhabitants.

Currently, 90 % of the population is concentrated in urban sectors and the rest is distributed in nearby rural areas. The water and sanitation coverage is more than 80 %. According to data provided by the provincial water company, there are more than 4500 active water accounts, 90 % of which are also connected to the sewage network. The water supply is around 600 L per inhabitant per day, due to high consumption and leakages in the distribution network. This high consumption of drinking water is associated with ostensive urban growth and tourism-related population as well as the cultural practices of backyard vineyard irrigation and street cleaning. The amount of wastewater estimated for this study comes from the collection of sewage network data in urban areas, which includes home users, commercial activities (restaurants, warehouses, hotels), and four wineries in urban sectors that dump their effluents into the sewage system. The effluents from wineries have a high organic concentration with a biochemical oxygen demand (BOD) between 200 and 500 mg/L in the low season and up to 10000 mg/L during the harvest, as well as an acidic pH and abundant settleable and suspended solids. During the harvest, the effluent also contains plant residues such as leaves, grains of grape, skin, remains of stalks, seeds, and substances forming acids such as sugars and alcohols. Despite the existence of legislation to regulate maximum concentrations discharged to sewers, the level of compliance is low and institutional controls are scarce.

The existence of a wastewater treatment plant (WTP) near the farmland area is a requirement to evaluate the use of this resource. In the case study presented, Cafayate's

WTP is located on a private farm due to a particular agreement between the owner and the local water company, and the effluents are currently informally used for irrigation of vines, pastures, and pepper and fruit trees. The physicochemical and bacteriological analyses show that the microbiological quality of the effluents does not comply with the guidelines proposed by WHO (2006) for unrestricted irrigation (Gatto 2018). Unrestricted irrigation refers to the use of treated high-quality effluents for the irrigation of any type of crop, without causing risks to public health. Irrigated area is a function of two additional variables: (1) the available effluent from the WTP and (2) the water requirements of the selected crop. The effluent from the WTP was measured as a function of the number of sewer accounts, estimated inhabitants per account, and the water consumption per person. The water leaks in the system were estimated at 35 % according to data from the water company. A return coefficient of 0.8 % was used. Effluents from the WTP are not suitable for unrestricted irrigation of crops due to deficient quality.

The model

The model was configured using a simple objective MCE integrated into a GIS. MCE in the context of a GIS is focused on the allocation of land sectors to suit the specific objective of irrigation with treated wastewater based on a variety of criteria (or attributes) that selected areas should fulfill. The following steps were considered: (1) selection of criteria, aptitude ranges, and the identification of a hierarchical structure; (2) identification of constraints; (3) weighting of factors; (4) normalization of factors; (5) obtaining constraint maps; and (6) classification of the sites with the best aptitude.

Selection of criteria, factors and constraints

A criterion is used for choosing between measurable alternatives. Generally, two types of criteria can be distinguished: factors and constraints. The factors increase or decrease the capacity of a specific alternative for the activity, and they are usually measured on a continuous scale. The constraints restrict the available territory, indicating the areas where effluents cannot be reused for technical reasons. They are expressed in Boolean (binary) form, where the excluded areas have the value 0 and the rest of the area the value 1. Boolean variables can be usefully thought of as constraints, since they serve to delineate areas that are not suitable for consideration. **Figure 1** shows the hierarchical structure of the criteria used in the decision-making model. Factors and constraints were selected from international experiences according to their importance, aptitude, and simplicity for measuring and mapping (see Gemitzi et al. 2007, Kallali et al. 2007, Anane et al. 2008, 2012, Chang et al. 2008, Pedrero et al. 2011, Pasuello et al. 2012, Gdoura et al. 2015, Nassar et al. 2015, Borrego-Marín et al. 2018). Additionally, 27 complementary semi-structured interviews were conducted with local stakeholders in November 2017, in order to consider their valuable thoughts in the final selection of criteria (Bossel 1999, Kallali et al. 2007, Bell and Morse 2008). Particularly, we contacted local governmental agencies such as the Ministry of the Environment and Sustainable Development, the National Institute of Agricultural Technology (INTA), public health and public infrastructure departments, irrigation consortiums, a local water company, and other local stakeholders including farmers, winemakers, and residents near the WTP. Ten factors and six constraints were categorized into five classes: (*i*) legal, (*ii*) sanitation, (*iii*) economic, (*iv*) technical, and (*v*) environmental criteria.

Legal criteria

Land-use planning

This criterion is linked to current land planning in the area, which includes areas for agricultural production and native forests organized into three conservation categories defined by the National Forest Law (Law No. 26 331). The corresponding classes are: (1) White (current land under cultivation); (2) Green (forests of low conservation value, Category III); (3) Yellow (forests of medium conservation value, Category II); and (4) Red (forests of high conservation value, Category I).

Sanitation criteria

Distance to urban areas

Buffer zones around wastewater use sites are intended to control public access, avoid human exposure to pathogens and contaminants, and maintain aesthetic conditions. The most appropriate distance will be one that facilitates irrigation practices with wastewater, protecting the health of the population from contamination, minimizing environmental impacts, and maintaining the efficiency of adjacent land use (US-EPA 2012). Several studies on the application of wastewater for irrigation or aquifer recharge have adopted a safety distance of 200 m from residential areas (Kalalli et al. 2007, Anane et al. 2008, Pedrero et al. 2011, Anane et al. 2012, Silva et al. 2012).

Crops

The risk of human contamination is lower when irrigation is applied to crops that are not in direct

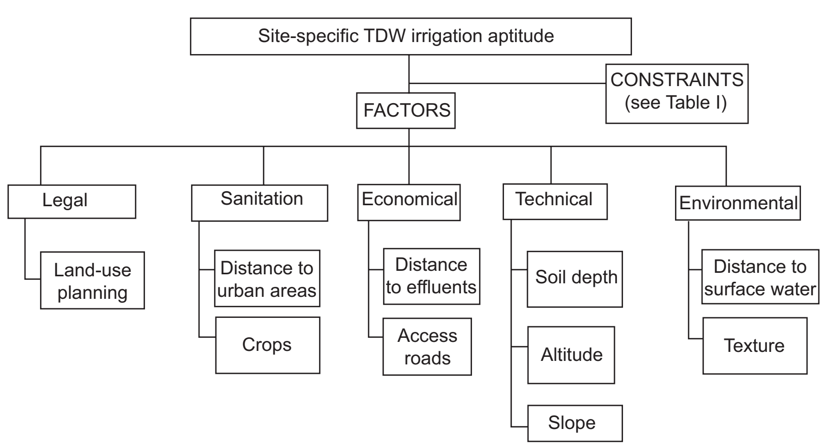

Fig. 1. Hierarchical structure of the site aptitude assessment model.

contact with effluents or ingested in the raw state (WHO 2006). Due to the deficient quality of effluents in the study area, restricted irrigation is recommended. The grapevine is the most important crop in Cafayate, with good profitability and belonging to a lower risk category than the raw consumption crops (WHO 2006). However, it was found that in many cases the grapevine could be combined with pepper production in the same lot. Vegetables are produced only in very smalls lots, which are irrelevant to the considered scale. Therefore, this criterion was not digitized into the spatial analysis but could be considered in more detailed studies.

Economic criteria
Distance to the effluents

It refers to the geographical proximity of the potential reuse site to the WTP. The distance reflects the necessary length of the pipe or transport channel, and therefore the necessary costs to transport the effluent to the production area. The transportation and distribution infrastructure represent the main cost of most water reuse projects (Declercq et al. 2017). The US-EPA (2006) considers that the distance of the treatment system from the area of potential utilization should not exceed 8 km. This value has been adopted as a threshold in previous studies (Kalalli et al. 2007, Silva et al. 2012).

Access roads

It refers to the infrastructure of roads and routes. Farmers should have good accessibility to agricultural parcels to facilitate the transport of their products.

Technical criteria
Altitude

This aspect involves the difference in altitude between the WTP and the potential irrigation site. When the cultivation area is located at a higher level than the WTP, pumping will be required. As recommended by the US-EPA (2006), a maximum value of 15 m was used to constrain altitude difference. A similar value was adopted by Kallali et al. (2007) and Pedrero et al. (2011).

Slope

Although the slope is closely linked to the irrigation method, an excessive slope is not recommended due to possible runoff and erosion. The US-EPA (2006) recommends slopes lower than 20 % for agriculture. However, other studies adopted slopes of less than 12 % (Kallali et al. 2007, Anane et al. 2008, Pedrero et al. 2011, Silva et al. 2012) and 15 % (Anane et al. 2008).

Soil depth

Soil provides support for the development of roots and influences the amount of water available for crops (Asawa 2008). The soil depth is also important for the natural purification process of remaining contamination in the effluent. Anane et al. (2008) adopted a minimum value of 25 cm of soil depth for the irrigation of crops with sewage liquids.

Environmental criteria
Distance to surface water

Buffer zones are intended to protect the quality of natural bodies of water (rivers, streams, and others). The US-EPA (2006) suggests a safety distance of 50 m.

Texture

Soil texture determines the characteristics of drainage, nutrient retention, microorganism removal rate, and water retention capacity (Poole et al. 2004). The content of fine material in soils is important for the removal of viruses and bacteria. The most suitable soils for recovery and drainage of WTP effluents will be those with intermediate textures, providing good storage capacity for water and nutrients, as well as microorganisms retention (van Cuyk and Siegrist 2007).

Identification of constraints

Constraints (exclusion criteria) were established according to Boolean logic (**Table I**). Because there is still no specific local legislation regulating the conditions for irrigation with effluents, exclusion values were carefully established. A threshold value of aptitude was assigned based on an extensive review of international guidelines, technical reports, and

TABLE I. CONSTRAINTS INCLUDED IN THE MODEL OF IRRIGATION APTITUDE WITH TDW.

Constraints	Threshold value
Land-use planning	Category I (red) and II (yellow)
Slope	> 5 %
Soil depth	Flat shallow soils (soil depth < 30 cm)
Distance to urban areas	< 200 m
Altitude	Sites at higher elevations to the treatment system
Distance to surface water	< 50 m

scientific articles. After the technical review, values were redefined with the opinions and considerations gathered from local stakeholders through the surveys. As we explained above, interviews were carried out with local actors and agricultural experts from INTA and the Salta National University. Areas outside the thresholds were considered unfeasible for irrigation with effluents. The constraint map was obtained by combining all Boolean maps by an intersection operator (AND).

Weighting

A weight was assigned to each factor in order to determine the degree of relevance to the criteria. The weight expresses the degree of relevance or preference of one factor with respect to others. Although there are several methods to assign these values, the Simple Multiple Attribute Rating Technique (SMART) was chosen due to its simplicity (Alinezhad and Khalili 2019). SMART is a multi-criteria method widely applied in the decision-making process (Belton and Stewart 2001, Mustajoki et al. 2005). The preference assignment of values was based on the literature review, participatory workshops with members of the research team, and information gathered from the interviews (**Table II**).

TABLE II. CRITERIA AND FACTORS WEIGHING.

Criteria	*p*	Factors	*p*	Final weighing
Legal	0.20	Land-use planning	1	0.20
Sanitation	0.20	Distance to urban areas	0.5	0.10
		Crops	0.5	0.10
Economical	0.15	Distance to effluents	0.8	0.12
		Access roads	0.2	0.03
Technical	0.20	Slope	0.35	0.07
		Soil depth	0.2	0.04
		Altitude	0.45	0.09
Environmental	0.25	Distance to surface water	0.50	0.125
		Texture	0.50	0.125

Normalization

The combination of factors must be done on comparable scales, so it was necessary to standardize them. Continuous factors, such as slope and distances, were normalized with the FUZZY function. Through this adjustment, the pixel values of the original raster layers were transformed into a scale between 0 (less suitable) and 255 (more suitable), by means of a sigmoid or linear function (incremental or decreasing). For the distances to urban areas and surface water, a variable minimal buffer was settled. From this point, the aptitude increased until it reached an optimal value. The distance to access roads and the treatment plant was settled as a maximum of 15 000 m, according to information from interviews with local actors (**Table III**).

For the discrete factors (soil depth, soil texture, and land-use planning), the categories were grouped according to their irrigation capacity with treated wastewater. Weights were assigned to each category through the SMART method. Finally, the weights obtained were linearly extended between 0 and 255. **Table IV** shows the weights corresponding to each category and **Table V** shows the inflection points for the discrete factors used.

Composite Decision Value (CDV)

Once the weight scores were determined, the final land suitability analysis map was obtained by means of a Composite Decision Value (R_i) for each pixel ($_i$), through the Weighted Linear Combination method. The CDV was obtained as follows:

$$R_i = \sum_{k}^{n} w_k \, r_{ik} \tag{1}$$

where w_k is the weight of the criteria, r_{ik} is the normalized pixel i in the factor map k, and n is the total

TABLE III. INFLECTION POINTS FOR THE NORMALIZATION OF CONTINUOUS FACTORS.

Sub-criterion	*a*	*b*	Function
Slope	5 %	0 %	Monotonically decreasing (linear)
Access roads	15 000 m	0 m	Monotonically decreasing (sigmoid)
Distance to urban areas	200 m	1000 m	Monotonically increasing (sigmoid)
Distance to effluents	15 000 m	0 m	Monotonically decreasing (linear)
Altitude	246 m	0 m	Monotonically decreasing (linear)
Distance to surface water	50 m	1000 m	Monotonically increasing (sigmoid)

TABLE IV. DISCRETE FACTORS AND WEIGHTS ACCORDING TO ITS IMPORTANCE FOR IRRIGATION WITH TDW.

Land-use planning		Soil depth (cm)		Texture	
White areas	0.65	> 100	0.48	Sandy loam	0.65
Green areas	0.35	80-100	0.38	Sandy	0.25
Yellow and red areas	E	30-80	0.14	Loamy sand	0.1
		< 30	E		

E: excluded

TABLE V. INFLECTION POINTS FOR THE NORMALIZATION OF DISCRETE FACTORS.

Factors	*a*	*b*
Land-use planning	0.35	0.65
Soil depth	0.14	0.48
Texture	0.1	0.65

number of criteria. The value R_i varies between 0 and 255, where 0 is the least suitable value for wastewater irrigation and 255 is the most appropriate value.

After the construction of the CDV map, different sites were classified into three levels of aptitude for irrigation with treated effluents. All information was used as cartographic data where each factor and constraint were represented through a thematic the layer. The combination of layer along with weighting produces the outcome map.

Scenarios

A small variation in weights can have a considerable influence on the ranges of site aptitude for irrigation. The scenario analysis constitutes a "final control" of the whole process, which contributes to evaluating how "robust" the site selection is. This helps to understand if a change in the assigned weights could affect the final ranking and lead to the selection of a different site. During this procedure, when the weight of each criterion is altered, all other weights in the same group are adjusted proportionally. In this way, the method requirement is fulfilled when all criteria weights total 1. The scenario analysis consists of varying the weight of the principal criteria according to the following steps:

- Scenario 1: The "economic" weight is 0. This case explores the importance of the environmental, technical, legal, and health criteria, assuming that the selection of areas suitable for irrigation does not consider the associated costs.
- Scenario 2: The "environmental" weight is 0. This case assumes that the impacts on the environment caused by reuse would be insignificant.
- Scenario 3: The "technical" weight is 0. It is assumed that there are no technical impediments to conduct the irrigation activity.
- Scenario 4: The "health" weight is 0. In this case, it is assumed that the effects of the health point of view of the activity are not considered.
- Scenario 5: All criteria have the same weight.

The process was applied to the suitable and most suitable areas in which the surface can absorb the current flow of effluent. In the suitable areas, R_i values were classified into three categories, then the results obtained in each of them were compared. In the most suitable areas, the area was obtained according to the irrigation potential with the highest R_i values in each case. Then, the overlap percentage of the original case and the proposed scenarios were obtained.

Digitalization

The maps were digitized using the software IDRISI Selva 17.0 and issued in QGIS 3.8.3. The general process consisted of two steps. First, different treatments were applied to the cartographic inputs to obtain the same format and size in order to produce a structured model with a resolution of 30 × 30 m of cell and representing the same geographic extension. The layers were represented in thematic layers with raster format. Second, all values were normalized to obtain scales and units of measure for comparisons between them.

RESULTS AND DISCUSSION

Figure 2 shows the maps obtained for each of the selected constraints. The total area available for irrigation with wastewater comprised 3158 ha, which represent 2.5 % of the total area of Cafayate. The most restrictive criteria were Altitude, Land-use planning,

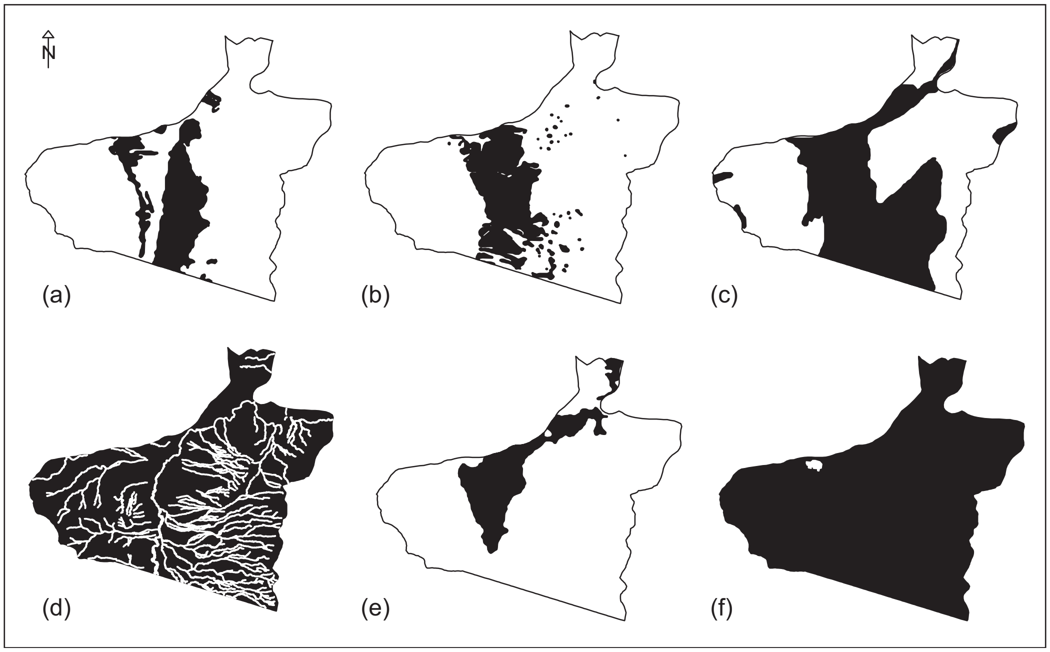

Fig. 2. Suitable areas for irrigation with treated wastewater (in black color) according to: (a) land-use planning, (b) slope, (c) soil depth, (d) distance to surface water, (e) altitude, (f) distance to urban areas.

and Slope, which represent only 13.6, 15.4, and 16.7 % of the total area, respectively. The criteria Distance to urban areas and Distance to surface water were the least restrictive (99.7 and 95.8 %). However, the areas showed substantial differences in their suitability for irrigation with effluents.

Wastewater irrigation aptitude

Once the area obtained by the constraints was discarded (**Fig. 3**), the study area was classified into different alternatives. The composite decision value (*Ri*), used to classify the 3158 ha, varied from 125 to 240. The final map was reclassified in three categories according to its suitability for effluent irrigation: Low aptitude (range 125-163), with 221 ha, Medium aptitude (range 164- 202), with 1990 ha, and High aptitude (range 203-240), with 947 ha (**Fig. 4**). The area obtained exceeds the area that can be irrigated with the current flow of effluent from the WTP.

Considering the current effluent flow, the proposed irrigation method and the storage capacity, around 150 ha of vine could be irrigated. Within the obtained suitable area, these hectares should be assigned, if it is economically and socially feasible, to sites of high aptitude. As noted, several areas with high aptitude for irrigation are close to the WTP.

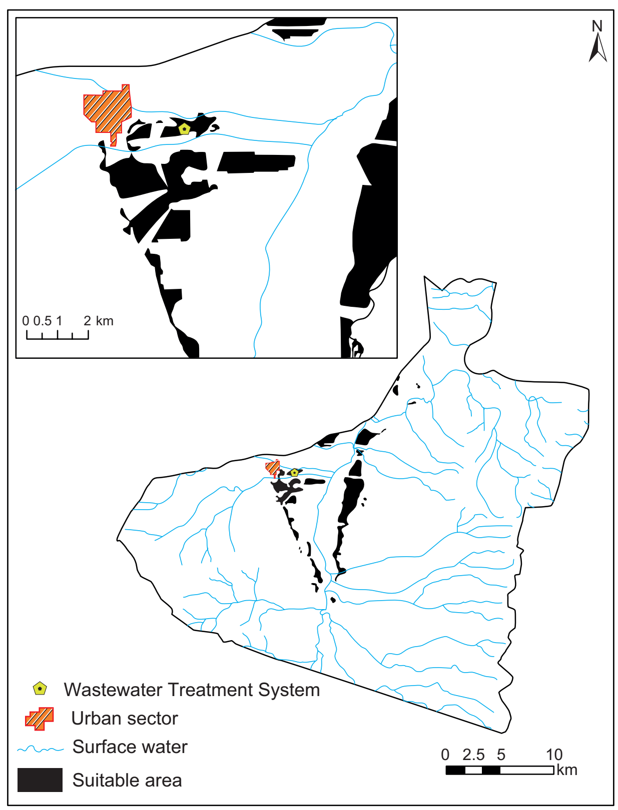

Fig. 3. Suitable area for irrigation with TDW obtained by a combination of constraints.

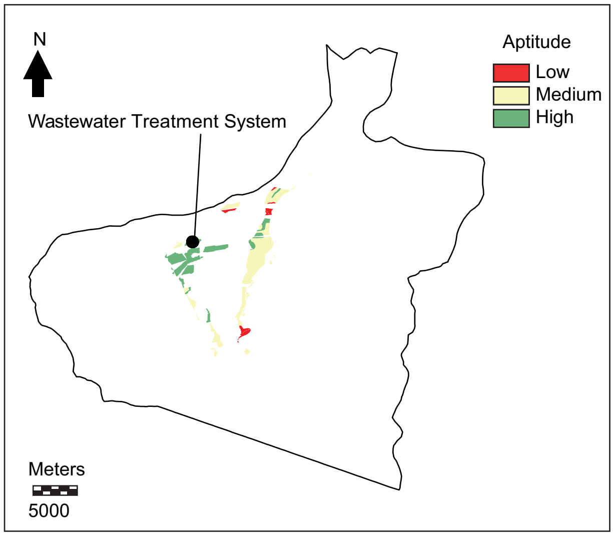

Fig. 4. Classification of sites suitability for irrigation with TDW in Cafayate.

Scenario analysis

Each selected criterion influenced the suitability evaluation of potential areas for irrigation with effluent. Greater differences were obtained when the E2 (Environmental) and E3 (Technical) criteria were discarded. **Figure 5** presents the original case and the resulting maps from the scenarios proposed for the most suitable areas. The digitized areas show only the 150 best hectares in each case. This area has the highest values of *Ri*. The original case (E0) is similar to E1 and E4 scenarios. In scenarios E2 and E5, a better location of the optimal area is obtained in relation to the location of the WTP. This is reasonable because E2 does not consider the environmental criteria, affected by the distance factor towards the water bodies, which are close to the treatment system. In comparison with the other cases, E3 is circumscribed to a specific area, while the rest of the scenarios have more dispersed areas, which can make it difficult to manage the allocation of areas for irrigation. It is observed that scenarios E2 and E5 present sites that coincide with the development of the current reuse activity, which in a way implies that if an unfair weighting of criteria is carried out, particularly if a high weight is assigned to the environmental criteria, the current location is not the most suitable for the irrigation activity.

The area overlapping between the best areas identified in each scenario and the original scenario showed

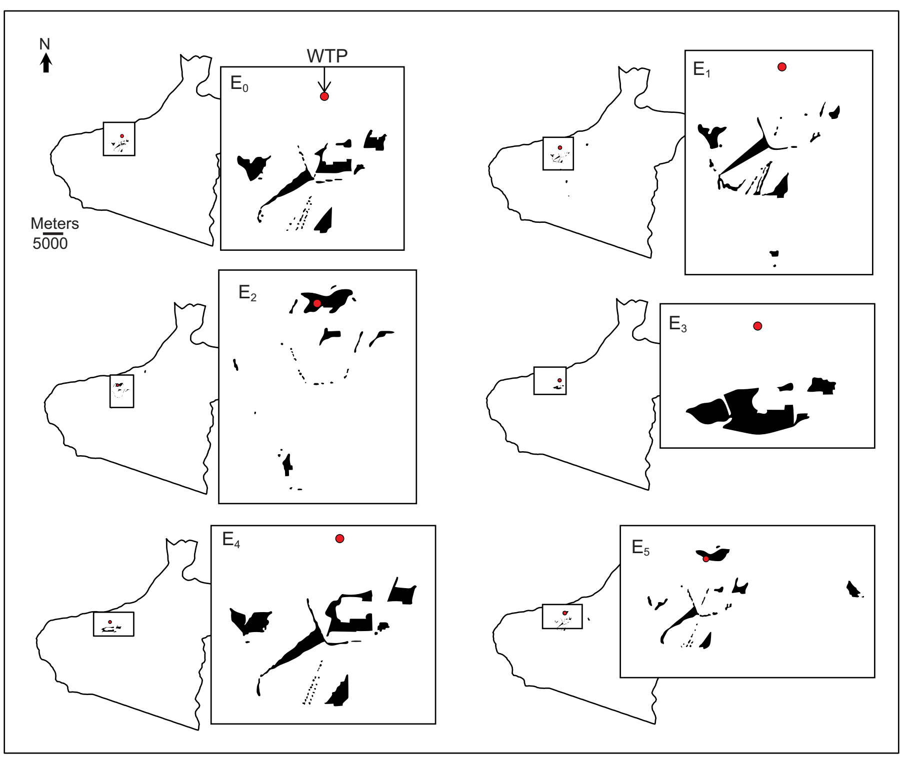

Fig. 5. Best suitable areas for different scenarios. E0: original case; E1: Scenario 1; E2: Scenario 2; E3: Scenario3; E4: Scenario 4; E5: Scenario 5.

different values. The highest value was assigned to E4 with 93 %, which means that the influence of the health criterion was minimal. This can be explained by the rest of the criteria, although not specific, maintaining a distance to the urban zone. There was also a high coincidence in E1 of 63 %, which means that the influence of the economic criterion would be relatively low. The E2 presented the lowest value (3.9 %), which means that the environmental criterion had a major influence on the final result, followed by E3 with 43 %, indicating that the technical criterion also had a considerable influence. Finally, in E5 the percentage was 56 %, showing an intermediate influence if all the criteria assume the same weight.

The information about the quality and quantity of the produced TDW and the potential geographic distribution for irrigation in peri-urban areas could be a useful tool for designing public policies for water and sanitation management. The aptitude modeling developed to evaluate sites for irrigation with TDW is flexible, allowing one to consider different criteria and weights, as well as methods to obtain the weights. The factors and constraints established in the model are not the only ones to be considered in a scenario where TDW is used for irrigation. As the criteria used could be adjusted to each case, additional criteria, such as economic ones, will be taken into account to further improve the quality of the methodological tool in future studies. The criteria can be adjusted according to the case. Similarly, the maximum and minimum values adopted by the factors are debatable. These can be modified by establishing larger or smaller buffer areas depending on schemes of greater or lesser protection of the population and the environment. In addition, other weighting methods can be used to compare the results obtained. Notably, one advantage of the method is that the importance of a factor does not depend only on its weight, but decision rules play a significant role in the final result.

It is important to consider that the hectares classified as "best areas" are intrinsically related to the available amount of effluent and crop irrigation needs. However, this does not necessarily mean that irrigation must be performed in these areas because there could be technical, economic, or social limitations. In these cases, it is more suitable to select areas or sites within the "high" aptitude range obtained in the previous classification. Under the same assumptions, it is possible to continue with the areas considered to have the medium and low aptitude, but those discarded in the constraint analysis should not be selected.

Concerning other experiences, the identification of reliable and feasible areas for treated wastewater irrigation has a positive impact on the overall water balance and slightly reduces the water "footprint" of agriculture (Hoekstra et al. 2011), even if the impact is mostly near urban areas. The identification of reliable areas could also contribute to a healthy impulse of new norms and policies, especially given the context in most Latin American countries, where lack of legislation, deficits in sanitation infrastructure, and weak governmental institutions support unplanned and informal reuse schemes, thus intensifying the negative effects of the practice (Gatto et al. 2015).

FINAL REMARKS

In this work, we developed a model that integrates MCE and GIS tools to identify and classify potential areas for irrigation with TDW. The combination of both tools was useful for storing, analyzing, and representing georeferenced data to assist and support decision-making. The criteria, their weights, and valuations established in the model were based on previous experiences from around the world and visions from local farmers and members of key institutions. Six constraints and 10 factors were defined and clustered into the following categories: legal, health, economic, technical, and environmental criteria. Altitude, land-use planning, and slope were found to be the most restrictive criteria, while distance to urban areas and distance to surface water were the least restrictive. A large area, covering 3158 ha, was identified as suitable for irrigation with TDW in Cafayate. This area greatly exceeds the surface that could be irrigated with the currently available effluents. However, the decision process regarding the final selection of suitable irrigation sites involves institutional, socio-cultural, and political considerations that have not been included in this study. Although high aptitude areas near the WTP were found, the best areas varied according to the scenarios made in the sensitivity analysis.

This tool can be very useful for making decisions related to the integrated water resource management (IWRM) in the region (UNEP 2014). The use of TDW in the appropriate sites can involve different strategies and pose different problems: the utilization of nutrients, mitigation of impacts associated with effluents discharged in surface water, post-treatment of effluents on the soil, conservation of groundwater, among others. In the context of the presented case study, this method can also be considered to evaluate the potential reuse of treated wastewater from the projected new WTP. Given the risks involved in reusing treated wastewater for groundwater resources, a profound study should be conducted to determine the vulnerability of the aquifer, in particular in areas classified as "apt". Such a study would make it possible to optimize the method and solve the difficulties with data availability, by focusing assessment efforts on an identified area in the suitability analysis. To complete the model, it would be interesting to include an indicator of economic viability that combines the aptitude of the territory with the economic cost of applying the TDW from the treatment system and transportation to the final destination.

The tool presented in this work allows us to integrate a number of factors involved in the suitability assessment of sites for the safe development of the TDW in a real case. Nevertheless, it could be modified to meet the needs of other regions and/or objectives. In this way, it can be extrapolated to other contexts considering the particularities of each case. In addition, these studies could be complemented by other data such as aquifer vulnerability, land tenure, and pre-existing irrigation infrastructure. Similar studies could be recommended for evaluating new potential locations of wastewater treatment systems, in order to prioritize in advance locations with the highest potential for reuse activities.

ACKNOWLEDGMENTS

This research was funded by CONICET (Project PIP 11220150100331), and the National University of Salta (Project CIUNSa 2435).

REFERENCES

Alinezhad A. and Khalili J. (2019). SMART method. In: New methods and applications in multiple attribute decision making (MADM) (Alinezhad A. and Khalili J., Eds.). Springer, Cham, Germany, pp 1-7. https://doi.org/10.1007/978-3-030-15009-9_1

Anane M., Kallali H. and Jellali S. (2008). Ranking suitable sites for soil aquifer treatment in Jerba Island (Tunisia) using remote sensing, GIS and AHP-multicriteria decision analysis. Int. J. Water 4, 121-135. https://doi.org/10.1504/IJW.2008.018151

Anane M., Bouziri L., Limam A. and Jellali S. (2012). Ranking suitable sites for irrigation with reclaimed water in the Nabeul-Hammamet region (Tunisia) using GIS and AHP-multicriteria decision analysis. Resour. Conserv. Recycl. 65, 36-46. https://doi.org/10.1016/j.resconrec.2012.05.006

Asawa G.L. (2008). Irrigation and water resources engineering. New Age International Publisher, New Delhi, India, 624 pp.

Bell B. and Morse S. (2008). Sustainability Indicators: Measuring the immeasurable? Earthscan Publications, London, UK, 258 pp.

Belton V. and Stewart T.J. (2001). Multiple criteria decision analysis: An integrated approach. Kluwer Academic, Boston, USA, 343 pp.

Borrego-Marín M.M., Riesgo L. and Berbel J. (2018). Methodology and criteria for the allocation of reused water in agriculture. In: Multicriteria analysis in agriculture. Multiple criteria decisions making (Berbel J., Bournaris T., Manos B., Matsatsinis N. and Viaggi D., Eds.). Springer, Cham, Germany, pp 185-198. https://doi.org/10.1007/978-3-319-76929-5_8

Bossel H. (1999). Indicators for sustainable development: Theory, method, applications. A report to the Balaton Group. International Institute for Sustainable Development (IISD), Winnipeg, Canada, 125 pp.

Brahim Neji H. and Turki S. (2015). GIS-based multicriteria decision analysis for the delimitation of an agricultural perimeter irrigated with treated wastewater. Agric. Water Manage. 162, 78-86. https://doi.org/10.1016/j.agwat.2015.08.020

Chang N.B., Parvathinathan G. and Breeden J.B. (2008). Combining GIS with fuzzy multicriteria decision-making for landfill siting in a fast-growing urban region. J. Environ. Manage. 87 (1), 139-153. https://doi.org/10.1016/j.jenvman.2007.01.011

Crook J., Mosher J.J. and Casteline J.M. (2005). Status and role of water reuse. An international view. Global Water Research Coalition, London, UK, 39 pp.

Declercq R., Loubier S., Condom N. and Molle B. (2017). Socio-economic interest of treated wastewater reuse in agricultural irrigation and indirect potable water reuse: Clermont-Ferrand and Cannes case studies' cost-benefit analysis. Irrig. Drain. 69 (S1), 194-208. https://doi.org/10.1002/ird.2205

De Prada J., Degioanni A.J., Cisneros J.M., Gil H.A. and Plevich O. (2014). Análisis multicriterio y selección interactiva del uso agrario de aguas residuales tratadas, Adelia María, Córdoba, Argentina. Eur. Sci. J. 10 (2), 419-441. https://doi.org/10.19044/esj.2014.v10n2p%25p

Duong K. and Saphores J. (2015). Obstacles to wastewater reuse: An Overview. WIREs Water 2, 199-214. https://doi.org/10.1002/wat2.1074

FAO (2003). Review of world water resources by country. Food and Agriculture Organization, Water Reports 23, Rome, Italy, 127 pp.

Gatto D'Andrea M.L., Salas Barboza A.G.J., Garcés V., Rodríguez-Álvarez M.S., Iribarnegaray M.A., Liberal V.I., Fasciolo G.E., van Lier J.B. snd Seghezzo L. (2015). The use of (treated) domestic wastewater for irrigation: current situation and future challenges. Int. J. Water and Wastewater. Treatment 1 (2). https://doi.org/10.16966/2381-5299.107

Gatto D'Andrea M.L. (2018). Evaluación del potencial de reutilización de aguas residuales domesticas en la provincia de Salta. Ph.D Thesis, Universidad Nacional de Salta, Salta, Argentina, 302 pp.

Gdoura K., Anane M. and Jelalli S. (2015). Geospatial and AHP-multicriteria analyses to locate and rank suitable sites for groundwater recharge with reclaimed water. Resour. Conserv. Recycl. 104, 19-30. https://doi.org/10.1016/j.resconrec.2015.09.003

Gemitzi A., Tsihrintzis V., Christouc O. and Petalas C. (2007). Use of GIS in siting stabilization pond facilities for domestic wastewater treatment. J. Environ. Manage. 82, 155-66. https://doi.org/10.1016/j.jenvman.2005.12.022

Gómez–López M.D., Bayo J., García–Cascales M.S. and Angosto J.M. (2009). Decision support in disinfection technologies for treated wastewater reuse. J. Clean. Prod. 17 (16), 1504-1511. https://doi.org/10.1016/j.jclepro.2009.06.008

Hadipour A., Rajaee T., Hadipour V. and Seidirad, S. (2016). Multi-criteria decision-making model for wastewater reuse application: A case study from Iran. Desalin. Water Treat. 17 (30), 13857-13864. https://doi.org/10.1080/19443994.2015.1060905

Hoekstra A.Y., Chapagain A.K., Aldaya M.M. and Mekonnen M.M. (2011). The water footprint assessment manual. Setting the global standard. Earthscan, London, UK, 228 pp.

Jaramillo M.F. and Restrepo I. (2017). Wastewater reuse in agriculture: A review about its limitations and benefits. Sustainability 9, 1734. https://doi.org/10.3390/su9101734

Jiménez B. and Asano T. (2008). Water reuse: An international survey of current practice, issues and needs. Scientific and Technical Report No. 20, IWA Publishing, London, UK.

Kallali H., Anane M., Jellali S. and Tarhouni J.N. (2007). GIS-based multi-criteria analysis for potential wastewater aquifer recharge sites. Desalination 215 (1-3), 111-119. https://doi.org/10.1016/j.desal.2006.11.016

Kihila J., Mtei K.M. and Njau K.N. (2014). Wastewater treatment for reuse in urban agriculture – The case of Moshi Municipality, Tanzania. Phys. Chem. Earth. 72-75, 104-110. https://doi.org/10.1016/j.pce.2014.10.004

Lahdelma, R., Salminen, P. and Hokkanen, J. (2000). Using multicriteria methods in environmental planning and management. Environ. Manage. 26 (6), 595-605. https://doi.org/10.1007/s002670010118

Lazarova V., Levine B., Sack J., Cirelli G., Jeffrey P., Muntau H. and Brissaud F. (2001). Role of water reuse for enhancing integrated water management in Europe and Mediterranean countries. Water Sci. Technol. 43 (10), 25-33. https://doi.org/10.2166/wst.2001.0571

Malczewski J. (2000). On the use of weighted linear combination method in raster GIS: Common and best practice approaches. T. GIS 4 (1), 5-22. https://doi.org/10.1111/1467-9671.00035

Malczewski J. (2004). GIS-based land-use suitability analysis: A critical overview. Prog. Plann. 62, 3-65. https://doi.org/10.1016/j.progress.2003.09.002

Miller G.W. (2006). Integrated concepts in water reuse: Managing global water needs. Desalination 187 (1-3), 65-75. https://doi.org/10.1016/j.desal.2005.04.068

Mustajoki J., Hämäläinen R.P. and Salo A. (2005). Decision support by interval SMART/SWING – Incorporating imprecision in the SMART and SWING methods. Decision Sci. 36 (2), 317-339. https://doi.org/10.1111/j.1540-5414.2005.00075.x

Nassar A., Najar H., Dawood O. and Abunada, Z. (2015). Comprehensive decision approach for sustainable wastewater reuse using multicriteria decision analysis – GIS. J. Eng. Res. Technol. 2 (1), 1-6.

Pasuello A., Cadiach O., Pérez Y. and Schuhmacher M. (2012). A spatial multicriteria decision making tool to define the best agricultural areas for sewage sludge amendment. Environ. Int. 38, 1-9. https://doi.org/10.1016/j.envint.2011.07.013

Pedrero F., Albuquerque A., Marecos do Monte H., Cavaleiro V. and Alarcón J.J. (2011). Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. Resour. Conserv. Recycl. 56, 105-116. https://doi.org/10.1016/j.resconrec.2011.08.003

Poole G, Sanden B, and Hays T. (2004). Soil, water, and crop production considerations in municipal wastewater applications to forage crops. Proceedings. National Alfalfa Symposium, University of California, San Diego. December 13-15.

Silva F., Albuquerque A., Marecos do Monte H., Cavaleiro V. and Carvalho A. (2012). Site selection for reclaimed water using GIS tools. IWA Regional Conference on Water Purification and Reuse, Crete, Greece.

Urkiaga A., de las Fuentes L., Bis B., Chiru E., Balasz B. and Hernández F. (2008). Development of analysis tools for social, economic and ecological effects of water reuse. Desalination 218 (1), 81-91. https://doi.org/10.1016/j.desal.2006.08.023

UNEP (2014). Towards integrated water resources. Management international experience in development of river basin organizations. United Nations Environment Programme, Khartoum, Sudan, 32 pp.

UN-Water (2016). Metadata on suggested indicators for global monitoring of the sustainable development goal 6 on water and sanitation. UN-Water, 42 pp.

US-EPA (2006). EPA-625-R-06-016. Process design manual for land treatment of municipal wastewater. Manual. Center for Environmental Research Information, United States Environmental Protection Agency, Washington, D.C., USA, 93 pp.

US-EPA (2012). EPA-600-R-12-618. Guidelines for water reuse. Manual. Office of Wastewater Management, United States Environmental Protection Agency, Washington, D.C., USA, 643 pp.

Van Buuren J. and Hendriksen A. (2010). A learning and decision methodology for drainage and sanitation improvement in developing cities. In: Social perspectives on the sanitation challenge (van Vliet B., Spaargaren G., Oosterveer P., Eds.). Springer, pp 87-103.

Van Cuy S. and Siegrist R.L. (2007). Virus removal within a soil infiltration zone as affected by effluent composition, application rate, and soil type. Water Res. 41, 699-709. https://doi.org/10.1016/j.watres.2006.07.021

WHO (2006). Guidelines for the safe use of wastewater, excreta, and greywater. World Health Organization, Geneva, Switzerland, 182 pp.