WASTEWATER NATURAL TREATMENT USING MULTI-CRITERIA DECISION ANALYSIS TECHNIQUE

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ABSTRACT

Wastewater production is the potential water resource in Egypt, which increases as the population grows, and the demand on fresh water increases. The principle objective of wastewater treatment is generally to allow human and industrial effluents to be disposed off without danger to human health or unacceptable damage to the natural environment. But shortage of irrigation water sources in arid and semi- arid regions brings out the issue of using treated wastewater to meet the demand for agriculture sector. The most appropriate wastewater treatment to be applied before effluent use in agriculture is that which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements. Natural treatments depend on natural physical and chemical response as well as on the unique biological components in each process. The natural wastewater treatment requires relatively low capital investment when flat land is available at reasonable price.

The objective of this research is to develop a management system to assist the decision maker in selecting, among many alternatives, the best suitable natural wastewater treatment alternative systems that can be used in rural areas of Egypt for reuse in agriculture purpose using multi criteria decision analysis technique. These natural wastewater treatment systems are Waste Stabilization Ponds, Constructed Wetland, Aquaculture system and Overland Flows water. The selection among the alternatives treatment is based on a set of evaluation criteria. These criteria are land requirement, initial and operational cost, removal efficiency of several parameters (i.e. BOD, Fecal coliform) and wastewater reuse potential for agriculture that include suspended solids and total nitrogen. The management system is tested using data represent average of Egypt. The study revealed that the developed decision support system could assist the decision maker in selecting the best natural treatment system that its effluent could be reused in agricultural in rural areas. Moreover, the wetland treatment is the best alternative system to be applied in the rural areas of Egypt.

Keywords: Wastewater, Natural treatment, Wetland, Overland flow

INTRODUCTION

In many arid and semi-arid countries water is becoming an increasingly scarce resource. In addition, planners are forced to consider alternative sources of water that might be economically and effectively used to promote further development. At the same time, with population growth at a high rate, the need for increased food production is an urge. Whenever good quality water is scarce, water of marginal quality or low quality will have the potential to be considered for use in agriculture. Use of wastewater in agriculture could be an important consideration when its disposal is being planned and treated. The quality of treated effluent used in agriculture has a great influence on the performance of wastewater – soil – plant. For irrigation, the required quality of effluent will depend on crops to be irrigated, the soil conditions and the system of effluent distribution adopted. The most appropriate wastewater treatment to be applied before effluent use in agriculture is that which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements Arar [1].

Natural treatments depend on natural physical and chemical response as well as on the unique biological components in each process. The natural wastewater treatment requires relatively low capital investment when flat land is available at reasonable price. In addition, they reduce effectively BOD, nutrients, and pathogen concentrations. Tawfic [12] reported that the performance of the natural treatment (i.e. in-steam wetland treatment system) under Egyptian condition is expected to be equivalent to the primary to secondary conventional treatment based on the designed detention time and aquatic species used.

The objective of this research is to develop a management system to assist the decision maker in selecting among several alternatives the best suitable natural wastewater treatment system that can be effectively used in rural areas of Egypt considering the acceptability of its effluent for reuse in agriculture purpose using multi criteria decision analysis technique.

Wastewaters Characteristics

Municipal wastewater is mainly comprised of water (99.9%) together with relatively small concentrations of suspended, dissolved organic and inorganic solids. Among the organic substances present in wastewater are carbohydrates, fats, soaps, proteins, synthetic detergents and their decomposition compounds. Ammonia and ammonium salts are always present, as a decomposition product of complex nitrogenous organic matter. The most important **physical characteristics** of wastewater are its solid content as it affects the aesthetics, clarity, and color of the water. Also, temperature of wastewater is important primarily because it affect aquatic and biological life in the receiving body of water. **The chemical characteristics** of wastewater can adversely affect the environment in many different ways. Toxic materials can affect food chain and public health. Nutrients can cause eutrophication of lakes. **Biological characteristics** is needed to measure water quality for such uses as drinking and agriculture, and to assess the degree of treatment of the wastewater before reuse it or discharge it to the environment Sundstrom et al. [11]. **Coliform bacteria** are always present in very large numbers in feces (the average adult excretes about 2,000,000,000 coliforms each day). There presence in water indicates that fecal pollution of the water has occurred and that the water may therefore contain pathogenic organisms. Two parameters are very important for wastewater reuse or discharge; they are biological oxygen demand (BOD) and chemical oxygen demand (COD). BOD is an indication for the potential of a polluted water or effluent to consume oxygen. The main sources of organic matter affecting the BOD concentration are raw sewage wastewater and industrial wastes. Unpolluted water typically has BOD values of 2 mg/l. The average value of the BOD for different governorates in Egypt is 418 mg/ L while the COD equals 616 mg/l Chemonics [2].

QUALITY PARAMETERS OF WASTEWATER REUSED IN AGRICULTURE

Parameters of Health Significance

The principle health hazards associated with chemical constituents of wastewater, arise from the contamination of crops or groundwater. The discovery of the association between irrigation with wastewater and health problems resulted in the development of standards and guidelines aimed at protecting public health against sewage borne diseases. The coliform level is almost parallel to that required for drinking water. Such effluent requires a complete biological treatment followed by heavy chemical disinfecting. A less stringent guideline for effluent irrigation has been issued by WHO [15]; for instance the demand for crops eaten raw is 100 coliform/100 ml in 80% of the samples taken for laboratory analysis. Health problems resulting from wastewater use were limited and almost exclusively associated with the consumption of fresh produce irrigated with untreated sewage water. Further more, irrigation with partially treated wastewater even through not approaching the quality of drinking water, was not associated with negative health effects Feigin et al. [7].

Parameters of Agriculture Significance

The quality of irrigation water is of particular importance in arid zones where extremes of temperature and law relative humidity result in high rates of evaporation with consequent deposition of salt, which tends to accumulate in the soil profile. The physical and mechanical properties of the soil, such as dispersion of particles, stability of aggregates, soil structure and permeability, are very sensitive to the type of exchangeable ions present in irrigation water FAO [6]. Another aspect of agricultural concern is the effect of Total Dissolved Solids (TDS) in the irrigation water on the growth of plants. Traditionally, irrigation water is grouped into various quality classes to guide the user to the potential advantages as well as problems associated with its use and to achieve optimum crop production. The suitability of water for irrigation will greatly depend on the climatic conditions, physical and chemical properties of the soil, the salt tolerance of the crop grown and the management practices. Thus, classification of water for irrigation will always be general in nature and applicable under average use conditions Pescod [9].

WASTEWATER TREATMENT

The principle objective of wastewater treatment is generally to allow human and industrial effluents to be disposed off without danger to human health or unacceptable damage to the natural environment. The wastewater must be treated to meat the required quality for reuse in agriculture and to avoid health hazards. Trttner, Richard and Susan J.E. Woods [13] reported that there are seven specific contaminants of concern in wastewater treatment. These include: suspended solids, biodegradable organics, pathogens, nutrients, refractory organic compounds, heavy metals, and inorganic salts. Primary, suspended solids, biodegradable organics and pathogens are the contaminants of greatest immediate concern in municipal wastewater.

Natural Treatment Alternative Systems

Natural treatment system are define as all waste management processes that depend on natural responses, such as gravity force for sedimentation, or on natural components, such as biological organisms. Natural systems for effective wastewater treatment are available in three major categories; aquatic, terrestrial, and wetland concepts.

The natural treatment alternatives systems that under consideration here are as follows:

1. Waste Stabilization Facultative Ponds (WSFP),
2. Free Water Surface Wetland Systems (FWS-WS),
3. Aquaculture Systems (AS) and
4. Overland Flow (OF).

Waste stabilization ponds

Waste stabilization ponds are large shallow basins enclosed by earthen embankments in which raw sewage is treated by entirely natural processes involving both algae and bacteria. Since these processes are unaided by man the rate of oxidation is rather slow and as a result long hydraulic retention times are employed 30 - 50 day not being uncommon Mara et al.[8]. There are three major types of ponds; facultative, maturation and anaerobic ponds. A forth type is the high rate pond which is still largely experimental. The only mechanical or monitoring and control equipment required for wastewater pond systems are flow measurement devices, sampling systems, and pumps Reed et al. [10]. The removal of pathogens is considerably greater than in other methods of sewage treatment. The effluent from a series of three ponds usually contains less than 5000 FC/100ml. Where as the final effluent from a conventional works (human Tank effluent) typically contains about 5,000,000 FC/100ml.

Wetland systems

Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. Constructed wetlands have been used for treating septic tank and imhoff tank effluents from housing complexes. Moreover, providing tertiary treatment to effluents from aerated lagoons and conventional sewage treatment plants to meet more stringent BOD and suspended solids standards. The population that can be served is dependant on the land area available, climate, soil, and other factors Cheremisinoff [3]. Constructed wetlands are classified into two types free water surface (FWS) systems with shallow water depth and subsurface flow (SF) systems with water flowing laterally through sand or gravel El sayed [5]. The major wetland system components having some influence in the treatment process in wetlands includes the plants, soils, bacteria and animals. Their function and the system performance in turn influenced by water depth, temperature, and pH and dissolved oxygen concentration.

Aquaculture systems

Aquaculture is defined as the use of aquatic plants or animals as a component in a wastewater treatment system. Aquaculture treatment systems can use one major type of plant or animal in a monoculture operation, or use a variety of plants and animals in a polyculture media. Aquatic plants have the same basic nutritional requirements as plants growing on land and are influenced by many of the same environmental factors. The floating aquatic plants with the greatest known potential for wastewater treatment include water hyacinths, duckweed, pennywort, and water ferns. Water hyacinth (eihhornia crassipes) is a perennial, freshwater aquatic macrophyte (water tolerant vascular plants) with rounded, upright, shiny green leaves and spikes of lavender flower.

Overland flow

There are three types of land treatment systems namely Slow Rate (SR), Overland flow (OF), and Rapid Infiltration (RI). Overland flow is a land treatment process in which wastewater is treated as it flows down carefully graded grass covered slopes. In contrast to the SR process, in which surface run off is avoided, in the OF method, surface runoff is a design requirement, the treated runoff being collected at the bottom of the slopes. To achieve the required runoff the soil must either be slowly permeable. Wastewater is either sprinkler or surface applied to the top of the slope and treatment occurs during the slow travel of the water in thin sheet flow down the slope Reed et al. [10]. The grass used on the OF flow slope is important for ability to provide a support media for microorganisms, to minimize erosion, and to take up nitrogen and phosphorus. The grass should be an enduring species, have high moisture tolerance, have a long growing season, and be suited to the local climatic conditions.

MULTI-CRITERIA DECISION ANALYSIS TECHNIQUE

A multi-criteria evaluation technique assists the decision maker in choosing among a finite numbers of alternatives according to their preferences. The formulation of the problem and solution by the multi-criteria evaluation technique followed the procedure of Voogd [14].

The natural treatment alternatives systems that under consideration here are listed below as mentioned before:
1. Waste Stabilization Facultative Ponds (WSFP),
2. Free Water Surface Wetland Systems (FWS-WS),
3. Aquaculture Systems (AS) and
4. Overland Flow (OF).

A set of evaluation criteria are selected and classified as follow:

1. BOD removal efficiency (BODre)
2. Land requirement (Lr)
3. Pathogen removal (Pr)
4. Hydraulic rate (Hr)
5. Detention time (Dt)
6. Total Cost (Tc)
7. Total Suspended Solid (TSS)
8. Total Nitrogen (TN)

The BOD removal efficiency, hydraulic rate and detention time are classified as technical criteria while the total cost is an economic criterion. Meanwhile, pathogen removal is a public health criterion and the reuse criteria are described with suspended solid and total nitrogen. Each criterion can be defined and calculated for each wastewater natural alternative system based on the design criteria of these systems:

1. **BOD removal efficiency** is the efficiency of each wastewater natural treatment alternative system in removing the BOD of the wastewater influent and can be calculated from the design equation of each system.

For (WSFP)

$$\frac{C_e}{C_i} = \frac{1}{\left[1 + k_1 \frac{t}{n}\right]^n} \tag{1}$$

C_i, and C_e = influent and effluent BOD concentration (mg/l)
t = detention time (day), n = number of ponds in series
k_1: constant factor depend on temperature
$k_1 = 0.3\,(1.05)^{T-20}$

For (FWS-WS)

$$A = \frac{Q(\ln C_i - \ln C_e - 0.6539)}{65\, K_t\, d} \tag{2}$$

Q = volumetric flow rate m^3/day,

K_t = the rate constant at water temperature (day^{-1})
d = Depth of the pond (m)

For (AS)

The removal of BOD in a hyacinth pond is caused by the same factors for conventional stabilization ponds. The efficiency of BOD removal will be directly related to the density of the plant cover and the depth of water in the system Reed et al. [10].

For (OF)

$$\frac{C_e - c}{C_i} = A' e^{(-K'Z/q^{N'})} \tag{3}$$

C_e = effluent BOD concentration at point Z (mg/l)
c = residual BOD at end of slope = 5 mg/l
Ci = BOD concentration of applied wastewater (mg/l)
Z = slope length (m),
q = application rate (m^3/h.m)
A',K',N' = empirical constants

2. **Land requirement** is the land area required for each wastewater natural treatment alternative system.

For (WSFP)

$$A = \frac{Qt}{d} \tag{4}$$

Q = volumetric flow rate m^3/day, t = detention time (day)
d = pond depth (assumed to be between 1 and 1.5 m)

For (FWS-WS)

$$A = \frac{Q(\ln C_i - \ln C_e - 0.6539)}{65\, K_t\, d} \tag{5}$$

K_t = the rate constant at water temperature (day^{-1}),
d = Depth of the pond (m)

For (AS)

Hyacinth systems can be designed for treatment of raw wastewater, primary effluent, upgrading of existing secondary treatment systems, or for advanced secondary or even tertiary treatment. As with other pond systems, the critical design parameter is the organic loading of the system Reed et al. [10]. Table (1) is presenting empirical data for aquaculture pond design for secondary treatment level.

Table (1) Suggested criteria for secondary treatment with Hyacinth ponds Reed et al. [10]

Factor	Criteria
Effluent requirements	BOD<30mg/l, SS<30mg/l
Wastewater input	Untreated
Organic loading	
Entire system surface	50 kg/ha.day BOD
First cell in system	100 kg/ha.day BOD
Water depth	<1.5 m
Maximum area, single basin	0.4 ha
Total detention time	>40 day
Hydraulic loading	+200 m3/ha.day
Water temperature	>10 oC
Basin Shape	Rectangular L:W > 3:1
Influent flow diffusers	Recommended
Mosquito control	Necessary
Harvest Schedule	Seasonal or annual
Multiple cells	Essential, 2sets of 3 basins, each recommended

For (OF)

$$A_s = \frac{QZ}{10{,}000 * qP} \tag{6}$$

A_s = surface area required (ha), Q = Wastewater flow rate (m^3/day)
Z = slope length, q = application rate (m^3/h.m)
P = period of application (h)

3. **Pathogen removal**

For (WSFP), bacteria, parasite, and virus removal is very effective in multiple-cell wastewater stabilization ponds with suitable detention time.

$$\frac{FC_e}{FC_i} = \frac{1}{(1 + t k_1)^n} \tag{7}$$

n = number of cells
FC_e and FC_i = effluent and influent fecal coliform concentration per 100 ml
k_1 = temperature-dependent rate constant = 2.6 $(1.19)^{(T-20)}$

For (FWS-WS), pathogen removal in many wetland systems is due to essentially the same factors as in facultative pond systems.

For (AS), the removal of pathogens in pond type systems is due to natural die-off, sedimentation and adsorption.

For (OF)
Since some form of preliminary treatment and/or a storage pond typically precedes land treatment systems, there should be little concern with parasites. The removal of bacteria and viruses in land treatment systems is due to a combination of filtration, adsorption, and radiation. The major concerns relate to the potential for contamination of surface vegetation or off-site run-off. The persistence of bacteria or viruses on plant surface could then infect humans or animals if the plants were consumed raw.

4. **Hydraulic rate** is the effluent quantity per unit area per unit time.

5. **Detention time** is the theoretical calculated time required for the influent to pass through the natural wastewater treatment system.

6. **Total cost:** the total cost of each wastewater natural alternative system includes the capital cost, and running cost which differ according to the required area and served population.

   Capital Cost = Land Requirement (area) cost +Excavation cost + Design cost + Development cost

   Running Cost = Labors salary + Operational cost + Maintenance cost

7. **Total suspended solid**

   For (WSFP), the occasional high concentrations of the suspended solids, which can exceed 100 mg/l, is the major disadvantage of pond system but it is limited to 2 to 4 month of the year. In addition, the solids are primarily composed of algae and other pond deteriorates not wastewater solids Reed et al. [10].

   For (FWS-WS), Suspended solids removal is very effective in both types of constructed wetlands. Most of the removal occurs with in the few meters beyond the inlet, owing to the quiescent conditions and the shallow depth of liquid in the system Reed et al. [10].

   For (AS), the removal of suspended solids occurs through entrapment in the plant root zone and by gravity sedimentation in the quiescent water beneath the surface mat of hyacinth plants. Reed et al. [10]

   For (OF), with exception of algae, wastewater solids will generally not be limiting in OF system design. Suspended solids are effectively removed on the slopes by sedimentation and filtration because of the low velocity and shallow depth of flow Reed et al. [10].

8. **Total nitrogen**

For (WSFP), nitrogen removal is some way related to pH, detention time and temperature in the pond system.

$$N_e = N_i\, e^{\{-kt[t+60.6(pH-6.6)]\}} \tag{8}$$

N_e and N_i = effluent and influent total nitrogen (mg/l)
kt = temperature dependent, rate constant (d^{-1}, pH^{-1})
t = detention time (day)
$k_t = k_{20}\, \theta^{T-20}$
θ = constant = 1.039
T = water temperature ^oC,
k_{20} = temperature factor = 0.28

For (FWS-WS), nitrogen removal is very effective in both the free water surfaces constructed wetlands the total nitrogen removal is up to 79 percent at nitrogen loading rates up to 44Kg/(ha.day) in a variety of wetland systems Reed et al.[10].

For (AS), Plant uptake ammonia volatilization and nitrification/de-nitrification all contribute to nitrogen removal in hyacinths systems.

$$\frac{N_e}{N_i} = e^{-kt} \tag{9}$$

N_e and N_i = total nitrogen in system effluent and influent (mg/l)
k = rate constant depend on temperature and plant density (day^{-1})
= Assume 0.5
t = detention time in system (days)

For (OF), Nitrogen removal is dependent on adequate BOD/nitrogen ratios, adequate detention time (low application rates and long slopes), and temperature. Nitrification and de-nitrification account for most of the nitrogen removal. Soil temperature below 4^{o}C will limit the nitrification reaction. De-nitrification appears to be most effective when screened raw or primary effluent is applied because of the big BOD/Nitrogen ratio Reed et al [10]. Up to 90% of ammonia removal was reported at 0.10 m^3/(h.m).

Priorities

Priorities can be represented as quantitative numbers; in this study the weighing vector has the same weight for all evaluation criteria that equal one.

Evaluation of Wastewater Natural Alternative Treatment Systems

Wastewater natural treatment systems were evaluated using the Weighted Summation Method (WSM). The basic component of WAM was called "simple multi- attribute procedures". The utility of each alternative U1 is determined by the summation of the weighted numerical values of each criterion. The alternative, which has the greatest utility, is the best alternative.

$$U_j = \sum_{i=1}^{m} w_i \bullet s_{ij} \qquad (10)$$

$$O_{ptimal} = \max Uj \quad \text{for all j}$$

Where s_{ij} is the standardized value of criterion score.

The standardize method used, when the higher is better:

$$\text{Standardized Score} = \frac{score - \min .score}{\max raw \cdot score - \min raw.score} \qquad (11)$$

And when the lower is the better:

$$\text{Standardized Score} = \frac{\max raw \cdot score - score}{\max raw \cdot score - \min raw.score} \qquad (12)$$

The first standardization method yields results where the highest level is equal to 1 and the lowest level is equal to 0. This formula is useful in standardizing the evaluation Matrix that will be analyzed by the weighing summation technique, which will be used in this study. Also, it is useful in case of using any other evaluation techniques, which utilize the magnitude of individual scores Voogd [14].

TESTING THE DEVELOPED SYSTEM

The developed system was tested with data representing average of Egypt, for population range from 1000-20000 capita El Saadi [4]. The impact matrix has to be filled with the impact scores. These scores describe the impact of each wastewater natural treatment alternative system on each criterion. Impacts are expressed in the criteria decided upon at an earlier stage. Calculation steps of the multi – criteria decision analysis using Weighted Summation Method are presented in Tables (2 and 3). Table (2) shows the impact matrix, which filled with the calculated and assumed scores.

Table (2) Impact Matrix

Criteria	Unit	WSFP	FWS-WS	AS	OF
BOD removal (BODre)	(%)	93	93	94	93
Land requirement (Lr)	(m^2)	10.96	2.85	34.63	4.36
Pathogen removal (Pr)	(%)	99.5	95.4	99.5	95.4
Hydraulic rate (Hr)	(m/year)	12.74	51.23	4.06	33.7
Detention time (Dt)	(Days)	28.65	2.14	40	*
Total Cost (Tc)	(L.E/capita/year)	83.45	21.26	248.44	30.8
Total Suspended Solid (TSS)	(mg/l)	40	10	25	10
Total Nitrogen (TN)	(mg/l)	10^{-7}	8	10^{-6}	6

* Continuous flow

Table (3) shows the standardized matrix, which filled with the scores after the standardization process as discussed before. As all criteria have the same weight, so the standardized and the appraisal matrices are the same. It could be seen from the appraisal matrix represented in table (3) and Fig. (1) that ranking of the suggested natural treatment alternative systems is as follows;

1. Free Water Surface Wetland Systems (FWS-WS),
2. Waste Stabilization Facultative Ponds (WSFP)
3. Overland Flow (OF) and
4. Aquaculture Systems (AS)

The best natural treatment alternative system is the Free Water Surface Wetland System (FWS-WS). This is because that the wetland treatment systems are the most economic natural treatment systems as both capital and running cost are estimated 17.72 and 3.54 L.E /Capita /year respectively. Meanwhile, they give the maximum hydraulic rate (51.23 m/year), the minimum detention time (2.14 days) and their effluent accepted for reuse.

Table (3) Standardized Matrix (Appraisal Matrix)

Criteria	WSFP	FWS-WS	AS	OF
BOD removal (BODre)	0	0	1	0
Land requirement (Lr)	0.744808	1	0	0.952486
Pathogen removal (Pr)	1	0	1	0
Hydraulic rate (Hr)	0.184015	1	0	0.628365
Detention time (Dt)	0.299789	1	0	*
Total Cost (Tc)	0.726252	1	0	0.958007
Total Suspended Solid (TSS)	0	1	0.5	1
Total Nitrogen (TN)	1	0	1	0.25
Total Score	**3.95**	**5.00**	**3.50**	**3.79**

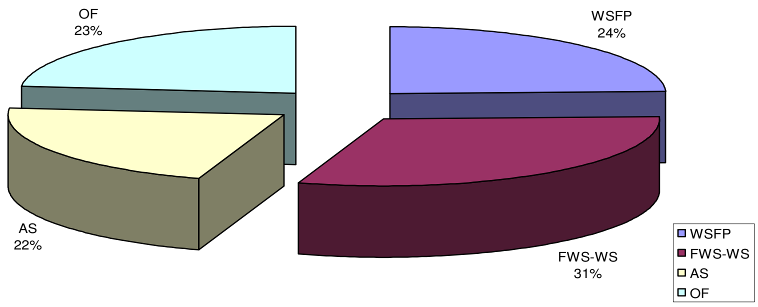

Figure (1) Ranking of Wastewater Natural Alternative Treatment Systems

CONCLUSIONS

Based on the study results; the following could be concluded:

1. The developed system can assist the decision–maker in selecting the best wastewater natural treatment alternative system that its effluent could be used in agriculture in rural area for crops not eaten uncooked and the reused water not exposed to public.

2. The wetland treatment is the best alternative system to be applied in the rural areas of Egypt as its effluent accepted for reuse and its physical and financial aspects are reasonable.

RECOMMENDATIONS

1. It is recommended to evaluate the effluent of treatment systems for reuse based on the trace metal contents to avoid the toxicity of those materials in the reuse.
2. The environmental impact assessment of wastewater treatment should be recommended taking into consideration the socio-culture influence.
3. A sensitivity analysis for the developed system could be carried out.

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