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# IMPROVEMENT OF PARTIALLY TREATED WASTEWATER QUALITY BY SOIL AQUIFER TREATMENT IN UPPER EGYPT

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## Abstract

Egypt is a semi-arid country and needs other water sources to cover shortages. Soil aquifer treatment (SAT) system is a natural advanced treatment technology of partially treated wastewater with no chemical additives. The present study evaluates the SAT system in west of the Sohag region for wastewater treatment and reuse. The measurements were concerned with hydrogen ion (pH), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), boron (B), total coliform (TC), fecal coliform (FC), heavy metals (HM), and major cations ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$). Results indicated that the pH values of the reclaimed water ranged from 7.53 to 7.71. DO concentration was exceeded 4 mg/l for the reclaimed water. The SAT system's efficiency in removing BOD, COD, TSS, TC, and FC was 98.3%, 91 %, 90.7%, 99.99%, and 99.99%, respectively. While TDS and B concentrations increased slightly after the SAT system as it moved through the aquifer's vadose zone. On the other hand, HM concentrations were completely removed with a removal efficiency of nearly 100%. According to the Food and Agriculture Organization (FAO) and the Egyptian Code of Practice (ECP), reclaimed water is suitable for irrigation. Moreover, reclaimed water suitability for irrigation was assessed based on sodium adsorption ratio (SAR), electrical conductivity (EC), magnesium hazard (MH), total hardness (TH), and Kelley ratio (KR). It was found that extracted water at 1500 m is suitable for irrigation when considering the SAR, EC, and MH values. On the other hand, the reclaimed water at the same distance is present under hard to very hard category, reflecting its unsuitability for irrigation purposes. Based on KR, samples are unsuitable for irrigation if KR is considered. The cost of the SAT system is less than 34% the tertiary treatment cost. The artificial aquifer recharge by partially treated wastewater presents an attractive tool applied in Egypt to be safely reused in unrestricted irrigation and reuse wastewater in safe ways while preserving the environment.

Keywords: Artificial recharge, Egypt, Soil aquifer treatment, Wastewater reuse, Wastewater treatment.

## 1. Introduction

Egypt is a semi-arid country and covers one million square kilometres, and it is situated in the south-eastern part of the Mediterranean Sea. It is water-stressed due to limited natural water resources, increasing population, dryness, and increased demand for industrial, domestic, agricultural sectors, and reclaimed lands that need potable water [1]. The primary source for water supply in Egypt is the Nile River, which provides 55.5 BCM/y, which accounts for more than 97% of the water budget, and the 3% remaining comes from renewable, fossil groundwater, and a few showers of rainfall [2]. The irrigation with raw or diluted wastewater continued to increase in several developing countries due to the scarcity of freshwater resources. The use of treated wastewater provides a dependable alternative source for irrigation, which consumes 80-85% of freshwater resources in arid and semi-arid regions [3].

Soil aquifer treatment (SAT) system is an advanced treatment technology of partially treated wastewater with no chemical addition and little energy. It is an effective natural dilution and economically feasible tertiary treatment for reuse in arid and semi-arid regions to produce refreshed water [4-7]. In this technique, partially treated wastewater is recharged through soil strata that provide additional treatment to improve water quality [8, 9]. The recharged water passage vertically within the unsaturated soil layers (vadose zone), then horizontally in the aquifer to the recovery wells. The vadose zone acts as a filter for the groundwater by removing a wide range of contaminants [10, 11] by various biochemical and physical soil processes [7]. SAT can be used for the treatment of primary, secondary, or tertiary effluents. This method is an essential technique for managing and preserving natural groundwater volumes [12-14]. The most advantages of the SAT system are the probability of treated wastewater storage in the aquifer [15-17] and reducing evaporation of stored water [18].

Furthermore, the SAT system improves the physical, chemical, and microbial quality [16, 19] of source water by passage through the soil [20]. Additionally, applying the SAT system can also be exploited as a part of the saltwater interference barrier system along coastal zones [19, 21]. Another advantage of the system is groundwater level restoration in depleted aquifers [22-24]. It can improve groundwater quality where groundwater of lower quality [25]. The cost of the SAT system is considered less than that of the conventional treatment methods [5, 26], and it is expected to be less than the cost of the above-ground treatments by 40% with effluent quality equals to or better than that of conventional wastewater treatment [4]. Moreover, its operation is simple, and no chemical or expensive treatment units and equipment are required. On the other hand, water reuse is confirmed to limit arbitrary wastewater discharges to aquatic environments and enhance urban water supply security [18]. SAT system has been carried out in many countries to improve partially treated wastewater quality [27]. There are three commonly employed recharge methods, as shown in Fig. 1, that can be used explicitly for the SAT system (a) infiltration or spreading basins [28, 29], (b) vadose zone infiltration [30, 31], and (c) direct injection or recharge wells [32-35].

Infiltration basins may become a sustainable recharge method due to their low operation and maintenance costs [36, 37]. It plays a significant role in maintaining aerobic conditions in the recharging wastewater effluent and allowing aerobic oxidation of the dissolved organic carbon (DOC) and ammonium ($NH^{+4}$). The bane of all soil aquifer treatment systems is clogging the soil surface, reducing the infiltration rates. Clogging occurred by physical, biological, and chemical processes [4]. To prevent this, the recharged water should be of adequate quality to decrease suspended soil accumulation.

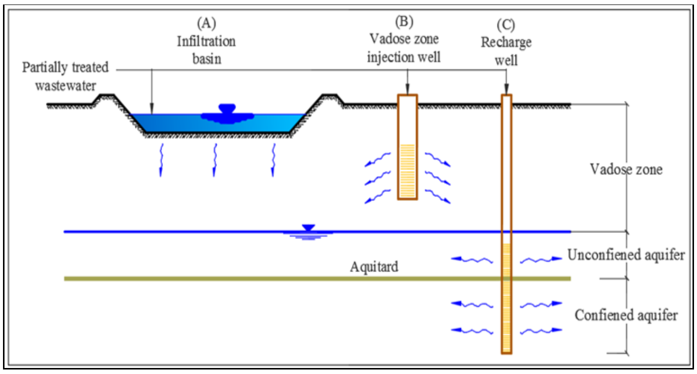



**Fig. 1. Commonly recharge methods for soil aquifer treatment [6].**

On the other hand, scraping or disking of basins has been effective in reducing the rate of clogging to a controllable level [38]. This technique can be accepted where a suitable site is available and located in permeable surface soil to get high infiltration rates and minimize land requirements. The vadose zone's depth should not contain layers of low permeability formations [4, 6] and free from fine-textured materials that excessively restrict downward flow. Moreover, the aquifer below the vadose zone should be unconfined and free from undesirable contaminants.

During SAT system, the water quality improves before it got dispersed and diluted in the aquifer. This is due to the major removal mechanisms occurring in the soil, including sand filtration, adsorption, biological degradation, chemical precipitation, physical adsorption of heavy metals and pollutants, ion exchange, nitrification, denitrification, and disinfection [36, 39, 40]. These mechanisms are more effective in removing contaminants. Some researchers showed the vital role of the thin upper layer of the soil in the removal process that occurs in the SAT [24, 41-44]. Sequential flooding/drying periods at the SAT system significantly control oxygen availability [7, 21, 43]. The SAT scheme's cyclic operation aims to increase the infiltration rate, maximize nitrification, and remove nitrogen [6]. The ratio of wetting/drying in a successful SAT system is always less than one. More than one infiltration basin is used to dry one and keep the other in service frequently. Drying periods range from one to two weeks for primary effluent and two to three days for secondary effluent. Long drying periods increase aeration [20] of the soil by allowing oxygen to penetrate to greater depths, while long wet periods increase the depths at which ammonia ($NH_3$) is adsorbed to the soil media. On the other hand, in conjunction with adsorbents, the SAT system may treat the wastewater containing metals and other contaminants to a superior degree [39, 45, 46]. Many methods can be used to remove some pollutants from water with high efficiency and low operating costs [47, 48].

This paper aims to solve the water shortage problems in Egypt, to evaluate the natural dilution of partially treated wastewater quality after the SAT system to be reused in unrestricted irrigation in Egypt. This will be environmentally safe and publicly accepted rather than disposing it into surface waterways; and assess the safe disposal and reuse of partially treated wastewater for environmental benefits. On the other hand, estimate the system's efficiency and purification capacity, and analyse the performance of the physical, biological, and chemical processes occurring during the SAT.

## 2. Materials and methods

### 2.1. Wastewater treatment plant description

The wastewater treatment plant is located 10 km west of Sohag city, as shown in Fig. 2, and serves people living in the western part of the Nile Valley. The plant was constructed in 1995 (the oldest wastewater treatment facility in Sohag governorate). The treatment capacity of the plant is more than 40,000 $m^3$/day. Wastewater is treated by primary treatment followed by an aerobic activated-sludge process and clarifiers. The secondary effluent is then allowed to irrigate wooden forests that have an area of 500 acres.

**Fig. 2. West of Sohag wastewater treatment plant (source: Google earth).**

### 2.2. Site description

The studied area is situated west of the Nile River (floodplain) in Sohag governorate, as shown in Fig. 3. It covers a part that extends from the western edge of the Nile Valley's old, cultivated lands up to the lower Eocene limestone plateau. It represents the major potential area for land reclamation and development. The economy of the area depends mainly on crop production. Crops are cultivated in two or three-year crop rotation, including winter, summer, and autumn crops. The main crops grown in the study area are vegetables, distributed mainly in the different markets within Sohag governorate.

The groundwater in the study area is commonly the only water resource for drinking and irrigation purposes, where surface water resource is insufficient and limited during the dry months of the year. There is a considerable distance between the reclaimed lands and the surface water (Nile River and irrigation canals). One filed recharge site was selected to treat the partially treated wastewater effluent (SAT system) for groundwater recharge. Currently, the recharged water comes from the west of the Sohag wastewater treatment plant. This site is bounded by the cultivated floodplain from the east and the Eocene limestone plateau from the west. The groundwater depth in the study area nearly 25 m [49] and the flow direction is in the northeast direction [50].

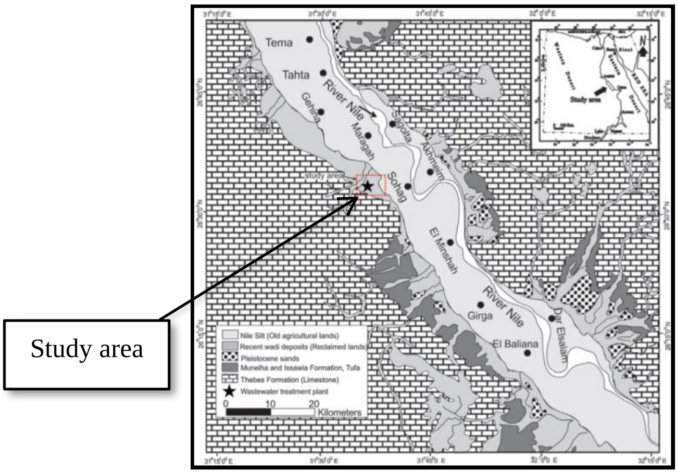



**Fig. 3. Location and geological map of the study area, showing the location of wastewater treatment plant at west of Sohag [51].**

The recharge site consists of eight infiltration basins, as shown in Fig. 4. Each basin is alternately filled with secondary treated wastewater (wetting/drying periods) from a single outlet at the basin edge, which delivers the partially treated wastewater from the plant, as shown in Fig. 5.

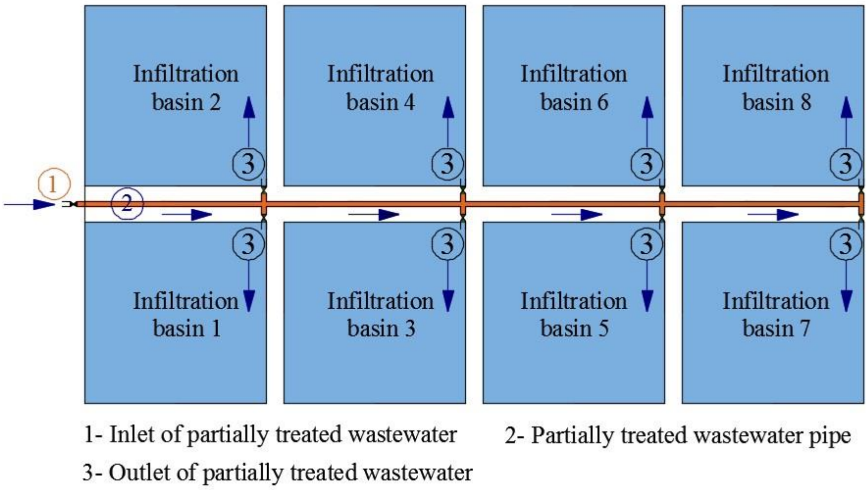



**Fig. 4. Plan of infiltration basins.**

**Fig. 5. Outlet of partially treated wastewater at the basin edge (source: site visit).**

## 2.3. Sampling and analysis

In this study, the secondary effluent from the treatment plant is artificially recharged into the aquifer through the vadose (unsaturated) zone via infiltration basins, as shown in Fig. 6. Samples were collected from four different locations around the infiltration basin and transported to the laboratory. The recharged water and the reclaimed water samples were analysed for hydrogen power (pH), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), boron (B), total coliform (TC), fecal coliform (FC), heavy metals (HM), and major cations ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$) at the laboratory in Neda, and El-Kola wastewater treatment plant. The laboratory measurements were performed according to standard methods for examining water and wastewater 23rd edition [52]. The reclaimed water samples results were compared to the Egyptian Code of Practice [53] limits and Food and Agriculture Organization [54] for wastewater reuse.

Percentage of removal efficiency by the SAT system was calculated using Eq. (1):

$$\text{Removal (\%)} = \left(1 - \frac{Eff}{Inf}\right) \times 100 \quad (1)$$

where *Removal* is the percentage of removal efficiency, *Inf* is the concentration in the recharged water, and *Eff* is the concentration in the reclaimed water. The plurality of concentrations was measured as mg/l except for total coliforms, and fecal coliform was measured as colony-forming units by 100 ml of sample (CFU/100).

**Fig. 6. Infiltration basins in the recharge site (source: Site visit).**

## 2.4. Experimental procedure

Reclaimed water quality is determined by analysing water samples obtained from the site's recovery wells W1, W2, W3, and W4, which are located at 500, 750, 1000, and 1500 m, respectively, from the infiltration basin, as shown in Fig. 7. Hydrogen power (pH), and dissolved oxygen (DO) were directly measured in the field, and the remaining measurements were performed in the laboratory. Recharged and reclaimed water samples were collected in one-litre plastic bottles; their caps were right away closed to prevent air entry and kept in a cooler with ice to reduce biochemical reactions. The samples were transported from the field to the laboratory within one hour to be analysed for physical, chemical, and biological parameters.

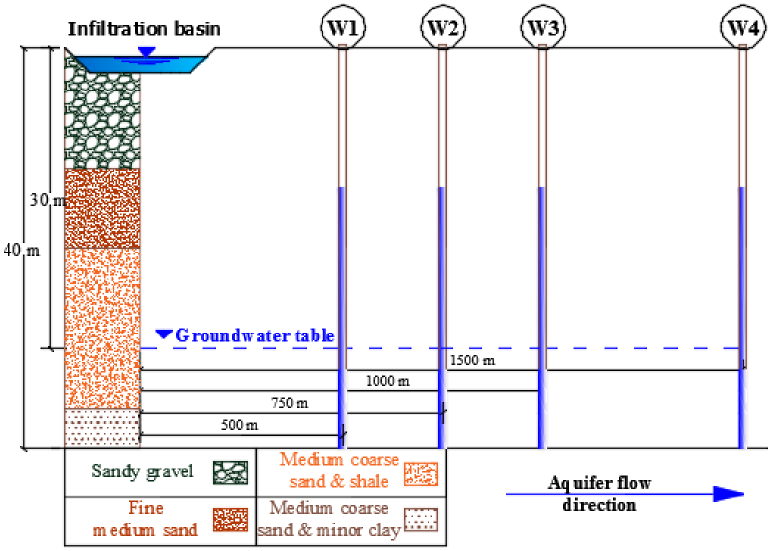


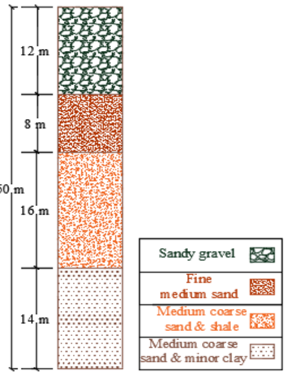

**Fig. 7. Recovery wells locations from the infiltration basin.**

## 2.5. Soil exploration

Mechanical drilling is becoming the most common soil exploration method to a depth of up to 60 m. The drill is composed of a machine made of steel and has a sharp edge capable of digging the soil. The drill works manually or mechanically with a three-leg drilling tower and a towering crane Fig. 8(a). Water is added during work, and the output of the drill is lifted out in batches. This method is economical and stable up to a depth of 5 m in the soil. However, if drilling more than 5 m, packaging pipes are used. This method is suitable for soil with a large proportion of gravel or rock.

The soil column was excavated, with an average of 50 m in-depth, as presented in Fig. 8(b). The soil from the infiltration basin was sandy gravel from 0 up to 12 m, fine-medium sand from 12 up to 20 m, medium-coarse sand with shale from 20 up to 36 m, and medium-coarse sand with minor clay from 36 up to 50 m in depth.

(a)




(b)

**Fig. 8. (a) Mechanical auger drilling;**
**(b) Soil profile descriptions from ground surface up to 50 m.**

## 3. Results and discussions

The efficiency of the SAT system in removing pollutants from the partially treated wastewater was evaluated by comparing water quality data for the recharged water (partially treated wastewater from the wastewater treatment plant before SAT) and the reclaimed water samples from the recovery wells (groundwater samples collected around the infiltration basins after SAT), to give insight into the treatment being provided by the system. The analytical results of the study area are shown in Table 1.

**Table 1. Physicochemical characteristics for all samples in the study area.**

| Parameters | Infiltration basin | Distances from the infiltration basin | | | |
|---|---|---|---|---|---|
| | | 500 m | 750 m | 1000 m | 1500 m |
| pH | 7.38 | 7.71 | 7.63 | 7.53 | 7.63 |
| DO (mg/l) | 0.8 | 4.1 | 4.6 | 4.9 | 5.8 |
| BOD (mg/l) | 120 | 9 | 4 | 3 | 2 |
| COD (mg/l) | 294 | 38 | 33 | 29 | 26 |
| TSS (mg/l) | 97 | 18 | 14 | 11 | 9 |
| TDS (mg/l) | 680 | 3320 | 2245 | 2600 | 1060 |
| B (mg/l) | 0.1 | 1.05 | 0.537 | 1.09 | 1.166 |
| FC (CFU/100 ml) | 40000 | 40 | 36 | 7 | 1 |
| TC (CFU/100 ml) | 90500 | 72 | 54 | 12 | 1 |
| $Mn^{2+}$ (mg/l) | 0.3 | 0 | 0 | 0 | 0 |
| $Al^{3+}$ (mg/l) | 0.15 | 0 | 0 | 0 | 0 |
| $Cr^{6+}$ (mg/l) | 0.01 | 0.0324 | 0.0287 | 0.0542 | 0.0657 |
| $Cu^{2+}$ (mg/l) | 0.01 | 0 | 0 | 0 | 0 |
| $Zn^{2+}$ (mg/l) | 0.05 | 0 | 0 | 0 | 0 |
| $Cd^{2+}$ (mg/l) | 0.01 | 0 | 0 | 0 | 0 |
| $Pb^{2+}$ (mg/l) | 0.01 | 0 | 0 | 0 | 0 |
| EC (µS/cm) | 1360 | 6205 | 4388 | 4739 | 2340 |
| $Ca^{2+}$ (mg/l) | 8.1 | 58.076 | 200.91 | 176.16 | 254.53 |
| $Mg^{2+}$ (mg/l) | 3.16 | 26.354 | 87.048 | 85.229 | 141.67 |
| $Na^{2+}$ (mg/l) | 6.9 | 423.39 | 752.48 | 754.7 | 961.45 |

### 3.1. Hydrogen ion concentration (pH)

pH is a term used to express the intensity of the acid or alkaline condition of a solution. Fig. 9 shows the values of pH in the recharged and the reclaimed water.

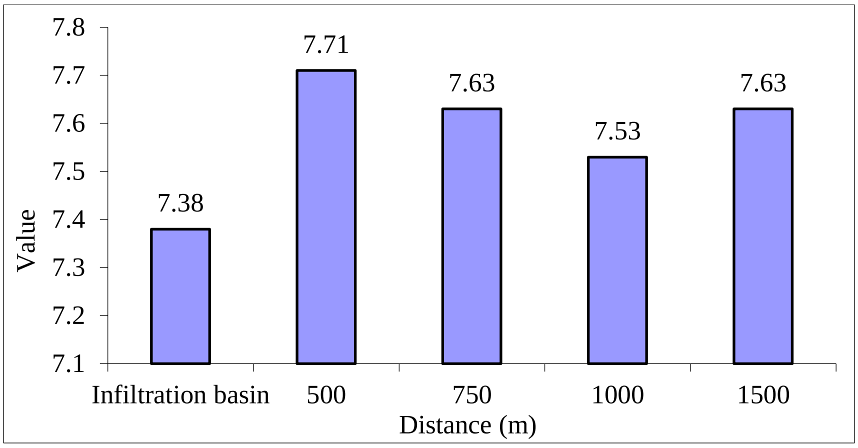



**Fig. 1. Hydrogen ion (pH) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

It is observed that the pH values ranged from 7.53 to 7.71. The results indicated a general increase in the reclaimed water's pH values compared to the recharged water. The higher values are attributed to the higher content of bicarbonate ($HCO_3$) ions in the groundwater than the recharged water. Furthermore, this increase may be due to the production of $CO_2$ during the biodegradation of organics. All the water samples fall in the safe limit of pH standard (6-8.5) for irrigation purposes [55]. According to FAO and ECP, the pH of the reclaimed water was in the range of the recommended levels. It is acceptable for reuse in agriculture.

### 3.2. Dissolved oxygen (DO)

Dissolved oxygen concentrations were measured at different distances 500, 750, 1000, and 1500 m from the infiltration basin as shown in Fig. 10 to study the system's efficiency on bacteria and organism’s removal.

The results showed that the DO concentration in the recharged water was lower than that of the reclaimed water. This is due to the microorganisms which use the available oxygen to break down organic material into carbon dioxide, water, and energy. The DO concentration increases with the increase in distance from the infiltration basin. The concentration at 500 m was 4.1 mg/l, at 750 m was 4.6 mg/l, at 1000 m was 4.9 mg/l, and at 1500 m was 5.8 mg/l. This increase is due to the additional lateral movement through the aquifer and natural mixing by groundwater. Reclaimed water at 1500 m exceeds 4 mg/l. So, it is more suitable for irrigation.

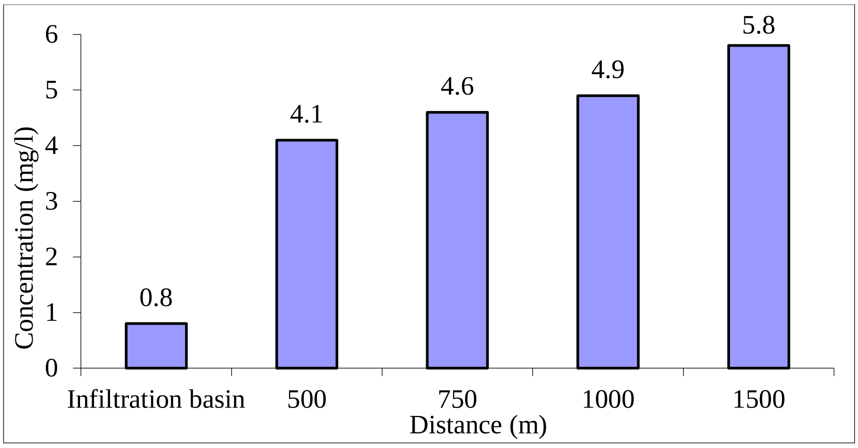



**Fig. 2. Dissolved oxygen (DO) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

## 3.3. Biochemical oxygen demand (BOD)

The biochemical oxygen demand of wastewater is another criterion for judging the suitability of wastewater for irrigation. The recharged water has a high concentration of 120 mg/l and has been naturally treated by the system. The high concentration is due to microorganisms that consume the amount of oxygen to oxidize organic matter of wastewater. It is clear from Fig. 11 that the BOD concentration was decreased with an increase in distance from the infiltration basin. The natural dilution can explain this by groundwater and the other lateral movement through the aquifer.

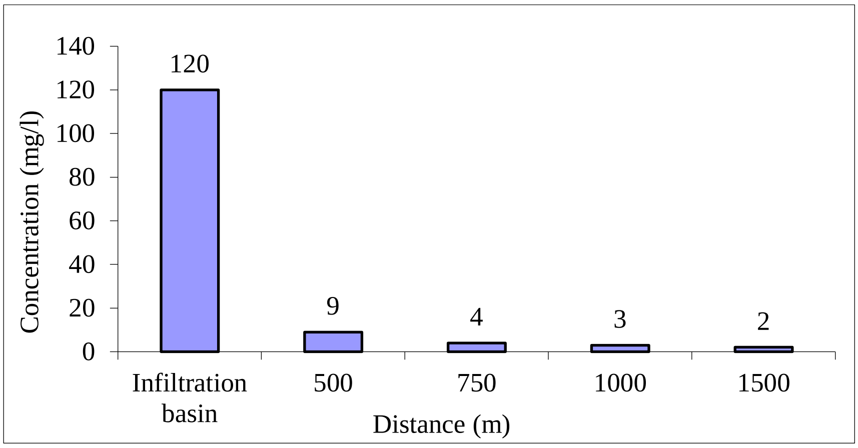



**Fig. 3. Biochemical oxygen demand (BOD) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

The reduction of BOD concentration at the vadose zone is attributed to the following major processes: filtration through the upper soil layer, biodegradation in the soil by aerobic and anaerobic bacteria, and adsorption by the soil particles through the vadose zone. The removal efficiency was 92.5%, 96.6%, 97.5%, and 98.3% at

500, 750, 1000, and 1500 m, respectively. This confirms that organic matter has no contamination, and the reclaimed water is suitable for irrigating all plants according to FAO and ECP.

## 3.4. Chemical oxygen demand (COD)

The concentration of COD in the recharged water was generally higher than those of the reclaimed water at different distances from the infiltration basin (Fig. 12). The concentration of COD was 294 mg/l in the recharged water. The concentration at 500, 750, 1000, and 1500 m from the infiltration basin was 38, 33, 29, and 26 mg/l with a removal efficiency of 87%, 88.88%, 90%, and 91% respectively.

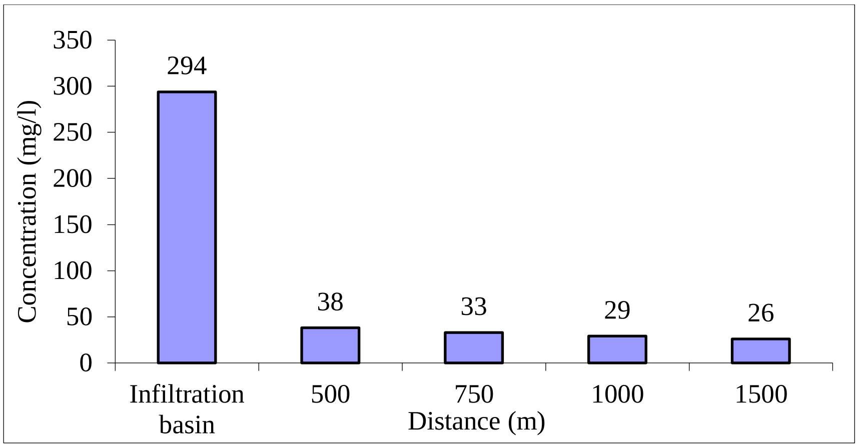



**Fig. 4. Chemical oxygen demand (COD) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

The COD concentration significantly decreased with the increase in distance from the infiltration basin as shown in Fig. 12. The farther wells to the infiltration basins showed a lower level of contaminants compared to the closer wells. This is due to the natural dilution by groundwater and the other lateral movement through the aquifer.

## 3.5. Total suspended solids (TSS)

Figure 13 shows the TSS concentration between the recharged and the reclaimed water. The concentration of TSS in the reclaimed water was less than the recharged water.

In the SAT system, TSS removal is achieved through infiltration, percolation, and sorption. Thus, the removal efficiency was very high for suspended solids because of the two main processes: filtration through the vadose zone and biodegradation. It was observed that the TSS concentration decreased with the increase in distance from the infiltration basin. It was 18 mg/l at 500 m with a removal efficiency of 81.4%, 14 mg/l at 750 m with removal efficiency of 85.6%, 11 mg/l at 1000 m with a removal efficiency of 88.7%, and 9 mg/l at 1500 m with removal efficiency of 90.7%. Lower contaminants were observed at farther wells compared to closer wells. This is due to the natural dilution by mixing the recharged water with groundwater and the other lateral movement through the aquifer. According to ECP, the TSS concentration in the reclaimed water at a distance further away from 750 m belongs to grade A, suitable for irrigating all plants by the treated wastewater.

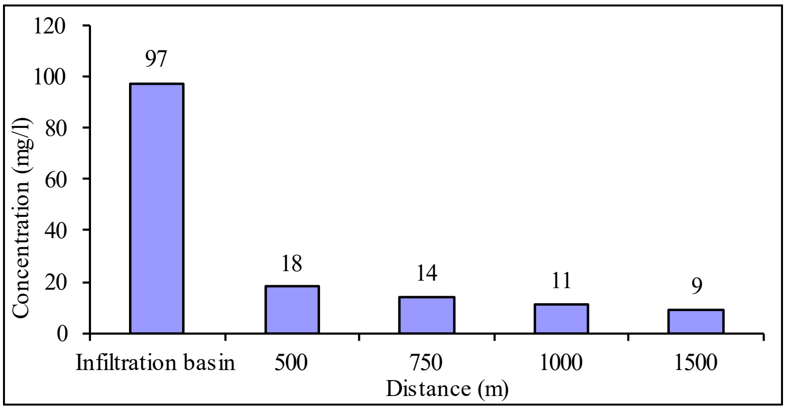



**Fig. 13. Total suspended solids (TSS) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

## 3.6. Total dissolved solids (TDS)

In general, total dissolved solids concentration increased after the SAT system, as shown in Fig. 14. This may be attributed to the dissolution and leaching of some minerals, salts, and dissolved materials originating from the vadose zone. The evaporation of wastewater from the infiltration basin also increases the TDS of the recharged water. Furthermore, fertilizers used in agriculture around the region increase the TDS in the groundwater. TDS of the reclaimed water increased significantly as it moves through the vadose zone from 680 to 3320 mg/l at the first well, located at about 500 m from the infiltration basin. The concentration at the second well, which located at about 750 m, was 2600 mg/l, at the third well, which located at about 1000 m, the concentration was 2245 mg/l, and at the fourth well, which located at about 1500 m the concentration was 1060 mg/l.

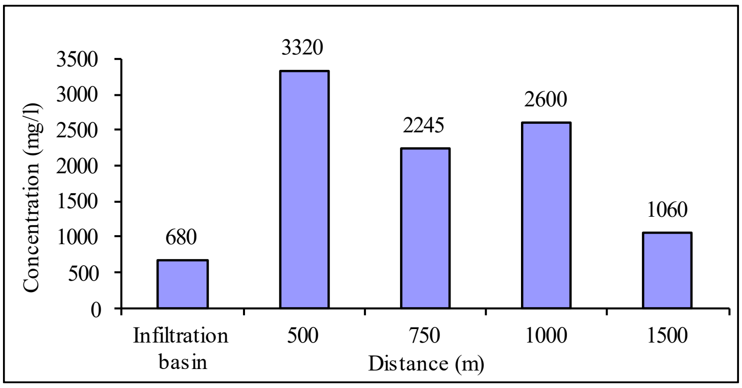



**Fig. 14. Total dissolved solids (TDS) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

It is observed that the concentration of TDS is irregular with distance from the infiltration basin. The concentration of the reclaimed water is higher than the recharged water, and hence, no further improvement of water quality in terms of TDS can be observed. This high concentration is due to the high TDS concentration of the groundwater, which can be attributed to the limestone formation of the aquifer and leaching of some minerals, salts, and dissolved materials originating from the soil media. According to ECP, the reclaimed water at a distance of 1500 m is valid for irrigation in both long and short-term usage. According to FAO guidelines, it is slight to moderate restricted for irrigation, and it can be used with specific crops.

## 3.7. Boron concentration (B)

The measured values of boron concentration were presented in Fig. 15. Irregular distribution of B concentration at different distances from the infiltration basin was observed. As shown in Fig. 15, the boron concentration in the recharged water was 0.1 mg/l. It was not removed through the vadose zone or the aquifer and reached to 1.05 mg/l at 500 m from the infiltration basin. The concentrations were 0.5370, 1.09, and 1.166 mg/l at distances 750, 1000, and 1500 m, respectively. This is due to leaching of boron from the vadose zone to the aquifer or its presence in the groundwater with a concentration higher than the recharged water.

According to FAO, and ECP the reclaimed water concentrations are much less than the permissible limits. Therefore, it is safe for agricultural reuse.

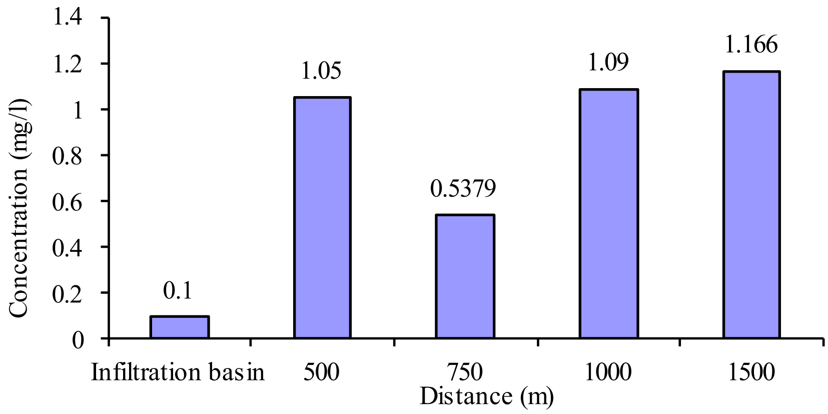



**Fig. 15. Boron (B) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

## 3.8. Fecal coliforms (FC)

Fecal coliforms (FC) concentration in the recharged water was 40000 CFU/100 ml, most of this concentration was removed in the vadose zone, but some penetrated to the aquifer as shown in Fig. 16. The concentration of FC at the first production well was reduced to 40 CFU/100 ml after approximately 30 m of travel through the vadose zone and 500 m through the aquifer. This is due to the impact of travel time during percolation through the vadose zone and the major removal mechanisms occurring in the soil that includes sand filtration, adsorption, and biological degradation. In the SAT system, wastewater bacteria are removed effectively by percolation through the soil. Sorption at the soil surface and inter-grain contacts coupled with sedimentation.

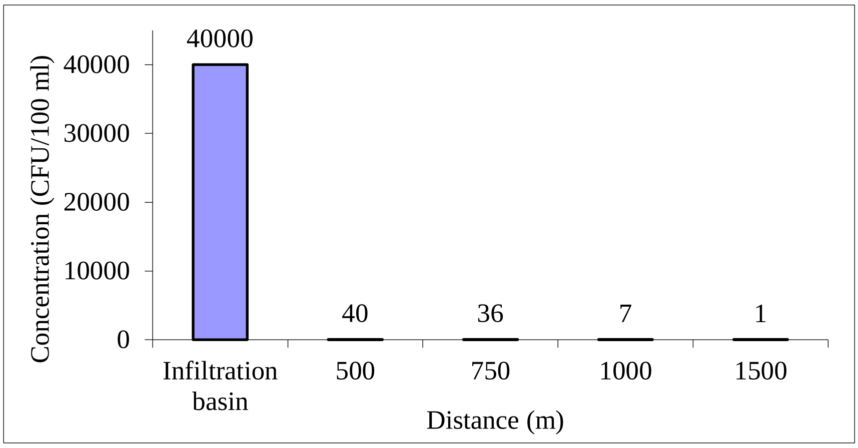



**Fig. 16. Fecal coliforms (FC) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

It is also clearly noticed that additional lateral movement through the aquifer was necessary to produce renovated water that was completely free of fecal coliforms at all times. The corresponding FC concentrations in the reclaimed water from the second, third, and fourth wells, located at approximately 750, 1000, and 1500 m, were 36, 7, and 1 CFU/100 ml, respectively. The reduction of fecal coliforms concentrations is due to the additional lateral movement through the aquifer and the natural dilution by groundwater. The results showed that the FC concentration after the SAT system at a distance of more than 750 m is suitable for irrigating all plants that can be irrigated by the treated wastewater according to FAO and ECP limits.

## 3.9. Total coliform (TC)

Figure 17 illustrates the relation between total coliform (TC) concentration in the recharged and the reclaimed water at different distances from the infiltration basin. TC concentration in the recharged water was 90500 CFU/100 ml. It was reduced to 72 CFU/100 ml at a distance of 500 m from the infiltration basin. The figure shows that the TC concentration significantly decreased with the increase in distance from the infiltration basin. It is noticed that the concentration of TC after a lateral movement of 750 m through the aquifer was 54 CFU/100 ml, the concentration was 12 CFU/100 ml at a distance of 1000 m, and the concentration was 1 CFU/100 ml at a distance of 1500 m. The decrease in the concentration with distance is due to the natural dilution with the groundwater.

Generally, the results showed that the count of TC bacteria in the reclaimed water was decreased compared to the recharged water. In the SAT system, TC was removed effectively by percolation through the soil, sorption at the soil surface, and inter-grain contacts coupled with sedimentation processes that eliminate many pathogens. On the other hand, the removal rates improvement can be explained by the depth of the vadose zone that increases the sand particles' available surface area. This may significantly capture the coliform of the recharged water. Consequently, the vadose zone acts as an efficient filter against TC transfers from the aquifer's infiltration basins surface.

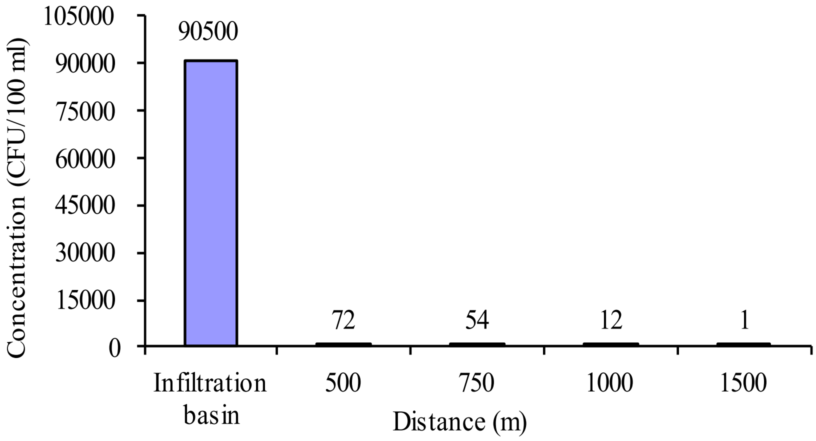



**Fig. 17. Total coliform (TC) concentrations for the recharged water and the reclaimed water at different distances from the infiltration basin.**

## 3.10. Heavy metals analysis (HM)

Heavy metals are one of the most permanent pollutants in wastewater, and discharge of high amounts into water bodies leads to several health and environmental impacts. The concentrations of $Mn^{2+}$, $Zn^{2+}$, $Cd^{2+}$, $Pb^{2+}$, $Al^{3+}$, $Cu^{2+}$, and $Cr^{6+}$ were analysed.

**Table 2. Heavy metal concentrations of the reclaimed water at different distances from the infiltration basin.**

| Parameters | Infiltration basin | Samples at different distances from basin | | | |
|---|---|---|---|---|---|
| | | 500 m | 750 m | 1000 m | 1500 m |
| $Mn^{2+}$ (mg/l) | 0.3 | 0 | 0 | 0 | 0 |
| $Al^{3+}$ (mg/l) | 0.15 | 0 | 0 | 0 | 0 |
| $Cr^{6+}$ (mg/l) | 0.01 | 0.0324 | 0.0287 | 0.0542 | 0.0657 |
| $Cu^{2+}$ (mg/l) | 0.01 | 0 | 0 | 0 | 0 |
| $Zn^{2+}$ (mg/l) | 0.05 | 0 | 0 | 0 | 0 |
| $Cd^{2+}$ (mg/l) | 0.01 | 0 | 0 | 0 | 0 |
| $Pb^{2+}$ (mg/l) | 0.01 | 0 | 0 | 0 | 0 |

The results of the heavy metal analysis are given in Table 2. The concentrations of studied heavy metals were completely removed from the recharged water. However, $Cr^{6+}$ showed irregular distribution with respect to distance from the infiltration basin, and its concentrations were in all distances much higher than the recharged water. The concentrations of HM are below the permissible limits given by FAO and ECP. So, the reclaimed water is suitable for irrigation purposes.

## 4. Reclaimed Water Quality Evaluation for Irrigation Purpose

To evaluate reclaimed water quality for irrigation uses after the SAT system, Electrical conductivity (EC), Sodium adsorption ratio (SAR), Kelley's ratio (KR), Total hardness (TH), and Magnesium hazard (MH) were studied.

### 4.1. Electrical conductivity (EC)

EC is a measure of water capacity to convey electric current. From Table 3, the EC values indicated that reclaimed water at a distance of 1500 m from the infiltration basin is classified as permissible water category.

According to the EC grading standards, as suggested by [56], water is suitable for irrigation purposes. While, at a distance of 500, 750, and 1000 is unsuitable for irrigation.

**Table 3. Quality of reclaimed water based on electrical conductivity [56].**

| EC (μS/cm) / Location | Excellent <250 | Good 250-750 | Permissible 750-2250 | Doubtful 2250-5000 | Unsuitable >5000 |
|---|---|---|---|---|---|
| **Infiltration basin** | - | - | 1360 | - | - |
| **500 m from basin** | - | - | - | - | 6205 |
| **750 m from basin** | - | - | - | 4388 | - |
| **1000 m from basin** | - | - | - | 4739 | - |
| **1500 m from basin** | - | - | 2340 | - | - |

(-) = None

### 4.2. Sodium adsorption ratio (SAR)

Sodium adsorption ratio (SAR) is an important parameter for measuring the suitability of reclaimed water for irrigation. Its value was calculated using Eq. (2) of Raghunath [57]:

$$SAR = \frac{Na^{2+}}{\sqrt{(Ca^{2+}+Mg^{2+})/2}} \quad (2)$$

All concentrations are expressed in meq/l.

**Table 4. Quality of reclaimed water based on SAR [58].**

| SAR (meq/l) / Location | Excellent <10 | Good 10-18 | Doubtful 18-26 | Unsuitable >26 |
|---|---|---|---|---|
| **Infiltration basin** | 0.52 | - | - | - |
| **500 m from basin** | - | 11.58 | - | - |
| **750 m from basin** | - | 11.16 | - | - |
| **1000 m from basin** | - | 11.67 | - | - |
| **1500 m from basin** | - | 11.98 | - | - |

(-) = None

The classification for SAR is given in Table 4. The SAR values of the reclaimed water samples were found to be in the range of 10-18 and are classified as suitable for irrigation [58]. So, the reclaimed water is suitable for irrigation purposes.

## 4.3. Kelley's ratio (KR)

To evaluate the effect of sodium on quality of the reclaimed water for irrigation KR is used [59]. KR is calculated by Eq. (3). All the ionic concentrations are expressed in meq/l.

$$kR = \frac{Na^{2+}}{(Ca^{2+}+Mg^{2+})} \quad (3)$$

**Table 5. Quality of reclaimed water based on Kelley's ratio [59].**

| KR % / Location | Suitable < 1 | Unsuitable > 1 |
|---|---|---|
| **Infiltration basin** | 0 | - |
| **500 m from basin** | - | 4 |
| **750 m from basin** | - | 2 |
| **1000 m from basin** | - | 2 |
| **1500 m from basin** | - | 2 |

(-) = None

The reclaimed water was classified for irrigation based on KR, as shown in Table 5. KR less than 1 % is suitable for irrigation, but it is unsuitable if the ratio is high. In the present study, the reclaimed water samples are unsuitable for irrigation purposes, with more than 1 of Kelly's ratio.

## 4.4. Magnesium hazard (MH)

MH for irrigation water was calculated using the following formula [60]. All the concentrations are expressed in meq/l.

$$MH = \frac{Mg^{2+}}{(Ca^{2+}+Mg^{2+})} \times 100 \quad (4)$$

**Table 6. Quality of reclaimed water based on magnesium hazard [61].**

| MH % / Location | Suitable < 50 | Unsuitable > 50 |
|---|---|---|
| **Infiltration basin** | 39 | - |
| **500 m from basin** | 43 | - |
| **750 m from basin** | 2 | - |
| **1000 m from basin** | 44 | - |
| **1500 m from basin** | 48 | - |

(-) = None

Magnesium hazard (MH) value of more than 50% is considered unsuitable for irrigation. From Table 6, it is seen that all of the reclaimed water samples have a magnesium ratio of less than 50 % and hence are suitable for irrigation purposes.

## 4.5. Total hardness (TH)

Total hardness (TH) is an essential factor in evaluating the reclaimed water for irrigation purposes. TH is calculated by Eq. (5) [56]:

$$TH = 2.497\ Ca^{2+} + 4.115\ Mg^{2+} \quad (5)$$

All the concentrations are expressed in mg/l.

**Table 7. Classification of reclaimed water quality based on hardness [62].**

| TH (mg/l) / Location | Soft <75 | Moderate hard 75-150 | Hard 150-300 | Very hard >300 |
|---|---|---|---|---|
| **Infiltration basin** | 33 | - | - | - |
| **500 m from basin** | - | - | 253 | - |
| **750 m from basin** | - | - | - | 860 |
| **1000 m from basin** | - | - | - | 791 |
| **1500 m from basin** | - | - | - | 1219 |

(-) = None

According to [62], all collected water samples are hard to very hard water, which labels these waters unsuitable for irrigation purposes. The high values of total hardness are due to the high dissolution of the limestone rocks present in the study area. Furthermore, fertilizers in the region also contribute to this increase as they mostly contain $Mg^{2+}$.

## 5. Cost analysis

The economic comparison between the SAT system and the tertiary treatment stage was presented in Table 8. The capital cost of the tertiary treatment stage is 150 million EGP, according to the Sohag Water and Wastewater Company, Egypt. The total capital cost of the SAT system in west of the Sohag region, including pipelines to the infiltration basin, storage system, land required for the infiltration basin, wells, and pumping system, were estimated to be 4.6 million EGP. The SAT system's construction cost in the study area is less than the cost of the tertiary treatment stage by 96.6%. Operation and maintenance (O&M) cost of the SAT system and the tertiary treatment stage is 4.0 and 6.0 million EGP/year, respectively. Considering the cost of producing $m^3$/day of treated water according to O&M cost. The cost of the SAT system is less than the cost of tertiary treatment by 34%. SAT operation is simple, and no chemical additives or expensive treatment units are required. Therefore, the SAT is economically feasible to carry out in Sohag city.

**Table 8. Economic comparison between the SAT system and the tertiary treatment stage in west of Sohag, Egypt.**

| Parameter | Unit | SAT system | Tertiary treatment |
|---|---|---|---|
| **Capital cost** | (Million EGP/Unit) | 4.6 | 150.0 |
| **Chemicals, operation and energy cost/year** | (Million EGP/Unit) | 4.0 | 6.0 |
| **Cost/ $m^3$/day** | (EGP/ $m^3$) | 0.27 | 0.41 |

## 6. Conclusions

Improvement of partially treated wastewater quality was studied using the SAT system. The obtained results concluded that the efficiency of the system in removing biochemical oxygen demand, chemical oxygen demand, total suspended solids, total coliform, and fecal coliform was 98.3%, 91 %, 90.7%, 99.99%, and 99.99%, respectively. The dissolved oxygen concentration was highly increased in the reclaimed water, so the wastewater quality was improved. $Mn^{2+}$, $Zn^{2+}$, $Cd^{2+}$, $Pb^{2+}$, $Al^{3+}$, and $Cu^{2+}$ were completely removed from the recharged water with a removal efficiency of 100%.

The vadose zone acts as a filter for the aquifer recharge, and it is more effective in removing contaminants that come from the land surface. The suitable distance for extracting the recharged water with acceptable quality is 1500 m from the infiltration basin. Different methods like SAR, MH, EC, KR, and TH were used to evaluate the reclaimed water quality for irrigation purposes. SAR and MH indicated that the reclaimed water at different distances is suitable for irrigation. EC reveals that the sample at a distance of 1500 m is suitable for irrigation purposes.

On the other hand, KR and TH indicated that the reclaimed water is unsuitable for irrigation purposes. Wastewater treatment using the SAT system achieved ECP and FAO limits for unrestricted irrigation. Economically the studied system is feasible to implement in Sohag city, and a cost saving of 34% was achieved. Finally, this system presents an attractive tool can be applied in Egypt to be safely reused in unrestricted irrigation, safeguard public health, and limit adverse environmental impact.

**Nomenclatures**

| | |
|---|---|
| Al | Aluminium |
| B | Boron |
| BOD | Biochemical oxygen demand |
| Ca | Calcium |
| Cd | Cadmium |
| COD | Chemical oxygen demand |
| Cr | Chromium |
| Cu | Copper |
| DO | Dissolved oxygen |
| EC | Electrical conductivity |
| EGP | Egyptian pound |
| FC | Fecal coliform |
| HM | Heavy metals |
| KR | Kelley's ratio |
| MH | Magnesium hazard |
| Mg | Magnesium |
| Mn | Manganese |
| Na | Sodium |
| Pb | Lead |
| pH | Hydrogen power |
| SAR | Sodium adsorption ratio |
| SAT | Soil aquifer treatment |
| TC | Total coliform |

| | |
|---|---|
| TDS | Total dissolved solids |
| TH | Total hardness |
| TSS | Total suspended solids |
| Zn | Zinc |

**Abbreviations**

| | |
|---|---|
| APHA | American Public Health Association |
| ECP | Egyptian Code of Practice |
| FAO | Food and Agriculture Organization |

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