Simulation of managed aquifer recharge by recycling treated wastewater in Nigeria

Sobowale A.[1*], Dideoluwa F. P.[1], Adeniyi A. R.[2], Sakariyawo S. O.[3], Tijani M. N.[4] and Igboro S. B.[5]

(1. Department of Agricultural and Bioresources Engineering, Federal University of Agriculture, Abeokuta, 110001, Nigeria;
2. Covenant University, Ota, 112104, Nigeria;
3. Department of Plant Physiology and Crop Production, Federal University of Agriculture, Abeokuta, 110001, Nigeria.
4. Department of Geology, University of Ibadan, Ibadan, 200005, Nigeria;
5. Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, 810107, Nigeria)

Abstract: The study evaluated the potential of recycling treated industrial effluent for groundwater quality and quantity restoration using a laboratory–scale soil aquifer treatment (SAT) simulator. SAT has the potential to reverse groundwater level decline being experienced in the North-eastern part of Nigeria and saltwater intrusion and groundwater quality deterioration in the coastal zones of the country. Soil column depth (SDC) and hydraulic loading rate (HLR) were optimized for the best treatment performance. Results show that HLR of 14.6 mm min^{-1} at an SCD of 1.5 m gave maximum removal efficiency for all parameters (hydrogen ion concentration (pH), temperature, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), bio-chemical oxygen demand (BOD$_5$), total hardness (TH), chloride (Cl$^-$), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na$^+$), potassium (K$^+$) and bacterial count (BC)) tested in comparison with HLR 16.98 and 20.37 mm min^{-1} and SCD of 0.5 and 1.0 m. This renders the wastewater adequate for aquifer storage and subsequent reuse. Further evaluation of the results indicates that surface spreading system will be best suited for the Sudan and Sahel Savannah areas of the country, while direct injection into wells is recommended for the southern and coastal areas. Given that Nigeria has a vast potential for managed aquifer recharge (MAR), the implication is that the implementation requires policy and regulatory frameworks to enable bulk wastewater producers to put their effluents to positive use and thus to enhance environmental sustainability.

Keywords*:* industrial effluent; soil; aquifer; treatment; groundwater; sustainability

Citation: Sobowale, A., F. P. Dideoluwa, A. R. Adeniyi, S. O. Sakariyawo, M. N. Tijani, and S. B. Igboro. 2024. Simulation of managed aquifer recharge by recycling treated wastewater in Nigeria. Agricultural Engineering International: CIGR Journal, 26(2): 9-22.

1 Introduction

Water is the most important substance on earth after air and is basic for the sustenance of living things. As a universal solvent, water is required for drinking, culinary activities, sanitation services, and irrigation of cultivated lands, processing of crops, industrial manufacturing, firefighting, power generation, and recreational activities and it also plays a pivotal role in ecosystem maintenance. Satisfying all these competing needs requires reliable sources of water supply in adequate quantity and quality to meet the growing needs of a rapidly increasing world

---

Received date: 2023-04-14 **Accepted date:** 2023-11-02

***Corresponding author: Sobowale A,** Department of Agricultural and Bioresources Engineering, Federal University of Agriculture, Abeokuta, Nigeria. Tel: +234 806 210 1020. Email: sobowalea@funaab.edu.ng.

population. Across the globe, there is a great challenge of increasing water scarcity (Abel et al., 2013; Cosgrove and Loucks, 2015), partly due to the increasing hydrological drought experienced in different parts of the world and caused by the climate change phenomenon (IPCC, 2019).

As population is rapidly increasing in different parts of the globe, there is increasing pressure on the available water resources and a strong competition for good quality water supply among different sectors (WHO and UNICEF, 2013). With a world population projected to rise from 7.2 billion in 2014 to 9.3 billion by 2050 (UN, 2012, freshwater supply is limited and cannot meet the growing demand (Abel et al., 2013). Understanding the finite nature of water resources and their limit in time and space is pivotal to the sustainability of this important resource. Nonetheless, continuous availability of water in appropriate quality and quantity has been a subject of debate for several decades (Richey et al., 2015). The sustainable development goals (SDGs) of the United Nations (UN) lay credence to the central role of water in human development (WWAP, 2015). According to UN (2012), ensuring a water-secure world is a fundamental step towards a sustainable future, with dignity and equity for everyone, this implies that anything possible and everything possible must be done to safeguard continuous availability of water across the globe. A look at recent statistics indicate that 748 million people lack access to water, 2.5 billion people do not have access to sanitation and 65% of global population will be urban by 2050 (WWAP, 2015); this has implications when water, sanitation and hygiene (WASH) and urbanization is considered.

Furthermore, the current growth rates of agricultural water demand are unsustainable with expected food production increase of 60% by 2050. Also energy demand for water will increase to 66% by 2035 (WWAP, 2015), while water demand in manufacturing sector will increase by 400% from 2000 to 2050. On top of these, the impact of the climate change on water resources cannot be overlooked, as it will affect availability and distribution of rainfall, snowmelt, river flows and groundwater, and further deteriorate water quality.

According to FAO (2007), water scarcity is defined as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully. This implies that imbalances between availability and demand, the quality degradation of groundwater and surface water, inter-sectoral competition, and interregional and international conflicts play critical roles in the global water crisis. Several researchers have pointed out that arid and semi-arid regions affected by droughts and wide climate variability will be worst hit by water scarcity (Jury and Vaux Jr, 2005; Hussain and Mumtaz, 2014; Deng and Zhao, 2015). Mekonnen and Hoekstra (2016) posited that about 4 billion people, representing nearly two-thirds of the world population, experience severe water scarcity during at least one month of the year; this calls for concern and concerted efforts to stem the tide.

Obviously, the surface water system seems to be the most vulnerable element within the water cycle; however, Richey et al. (2015) reports that a third of the world’s biggest groundwater systems are also already in distress. From recent statistics, Nigeria was described as a water stressed country (McNally et al., 2019); the total renewable water resources according to AQUASTAT® is 1,158 m^3/yr/capita, indicating that the nation is very vulnerable to slip into the water scarcity mark in the Falkenmark’s water scarcity index. The increasing variability of annual renewable water occasioned by the climate change problem and the unregulated groundwater pumping particularly in the conflict ridden Northeastern region of the Nigeria leading to an unprecedented lowering of the phreatic surface require stringent measures in order to avert severe water shortages in the region. The implementation of integrated water resources management (IWRM) in the country is long overdue and measures to increase water availability needs to be pursued vigorously. One veritable measure that has been successfully used in developed countries is wastewater recycling particularly for large water users such as food and beverage industries; the effluents from these industries can be treated onsite and used to recharge the groundwater system. In Nigeria, industries discharge their treated effluents into rivers and streams; leading to increased pollution loads of the surface water bodies in the country particularly around industrial hubs. There is still evidence of untreated discharges into surface water bodies especially from local abattoirs and domestic sources which leads to deterioration of quality (Oke and Sangodoyin, 2015; Ighalo and Adeniyi, 2020). Pollutants from such untreated discharges often find their ways to the groundwater systems across the nation (Fashae and Obateru, 2021).

The development and implementation of cost effective and environmentally sound treatment technologies with low energy and chemical footprint are desired to alleviate surface water pollution and provide effective IWRM through wastewater reuse for artificial groundwater recharge. A planned land applications of effluents such as soil aquifer treatment (SAT) is a managed aquifer recharge (MAR) system that has the potential to treat wastewater for subsequent reuse (Abel et al., 2013). SAT utilizes physical, chemical and biological processes during infiltration of treated wastewater through the soil strata / column to improve water quality. Treatment benefits are initially achieved during vertical infiltration of wastewater through the unsaturated zone and eventually during its lateral movement in the saturated zone. There are basically three SAT systems commonly employed for effluent treatment including infiltration or spreading basins, vadose zone infiltration and direct injection or recharge wells (Metcalf et al., 2007).

The key factors that determine which SAT system to adopt at the planning stage are: available information about soil, hydrogeology, land cost and wastewater pre-treatment requirements (Bouwer, 2002). While infiltration (recharge) basins are applicable where land is readily available and an unconfined aquifer with a vadose zone exists, direct injection wells may be used where these conditions are not favorable (Metcalf et al., 2007). Three different parts of the soil underlying a spreading basin provide additional purification: the top few meters of soil (infiltration zone), the area just below the surface and between the top layer of the groundwater (vadose zone), and the soil layers where groundwater is present (aquifer) (FAO, 2007). It also has an aesthetic advantage over conventionally treated sewage because the water recovered from SAT system is not only colorless and odour-free but it comes from a well, drain or from drainage to a stream or low area, rather than from a sewer or sewage treatment plant. SAT has a great potential for stemming the water shortages experienced in the urban areas of Nigeria. With the dwindling supply of portable water from surface water sources, many residents of major cities now depend heavily on groundwater. It is therefore necessary to identify various means of solving the precarious water shortages by using technologies that are cost effective and environmentally sustainable.

Therefore, arising from the above background, the objective of this study was to evaluate the potentials of using a pre-treated industrial effluent to simulate groundwater recharge using a laboratory – scale SAT simulator as a precursor to the implementation of MAR in Nigeria.

2 Materials and methods

2.1 Simulator construction and experimental design

A laboratory – scale SAT simulator for artificial groundwater recharge was constructed using PVC pipes of 100 mm diameter with column heights of 1.7 m. The bottom of the pipes was sealed with a 100 mm PVC pipe cap using silicon gum to prevent leakages. The sand columns were mounted on a pre-fabricated wooden stand as shown in Figure 1. Sampling holes were drilled at depth 0.6 m, 1.1 m and 1.6 m from the top of the pipe and retrofitted with 0.4 mm diameter transparent tubes for water sample collection. In order to achieve soil column depth (SCD) of 0.5 m, 1 m and 1.5 m in the experimental setup, a space of 0.1 m was earmarked for coarse gravel at the bottom of the columns and another 0.1 m was earmarked for ponding of water at the top of the sand columns. Three effluent buckets, retrofitted with taps and shower heads were used to deliver the effluent into the sand columns under gravity and room temperature at a hydraulic loading rate (HLR) of 14.6, 16.98 and 20.37 mm min^{-1}. The experimental design was a completely randomized design (CRD) with three replicates consisting of 392 laboratory experiments. The setup made it possible to evaluate the effect of SCD on the quality of effluents and to assess the impact of HLR on removal of biodegradables during passage through the soil columns.

2.2 Effluent source and washed river sand collection

The source water used for the study was collected from the final effluent tank of the wastewater treatment plant (WWTP) of the Nigerian Breweries PLC., Ota, Ogun state, Nigeria. The plant is an automated anaerobic – aerobic wastewater treatment plant that combines the trio of primary, secondary and tertiary treatment of wastewater, and has a design capacity 4543 m^3 day^{-1} with a peak flow of 284 m^3 hr^{-1}. Washed river sand (WRS) was obtained from Ole River, located at 7°13'28"N, 3°26'59"E at the Federal University of Agriculture, Abeokuta, Nigeria. The sand sample used for the filling the column of the simulator plays a key role in the performance of the sand column; in order to ensure better representativeness, homogenized sand particles (< 2 mm) was selected for the experiment in line with the recommendation of DEMEAU (2012). Each simulator was dry packed with 21 kg of sand and compacted with a rammer to simulate natural conditions.

2.3 Sand characterization and grain size analysis

The WRS collected from the Ole River was found to be adequate for use in the soil column experiment in accordance with the guideline provided by DEMEAU (2012). Grain size distribution of the sand was determined by sieve analysis according to Das (2008), using US standard sieves. Coefficient of uniformity was also determined to evaluate the level of gradation of the sand column using Equation 1:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

where D_{60} (mm) is the diameter through which 60% of the total soil mass is passing and D_{10} (mm)is the diameter through which 10% of the total soil mass is passing; $C_u > 6$ indicates a well graded sample (Das, 2008).

2.4 Analytical methods and data analysis

Effluent water quality was analyzed using standard methods described by the American Public Health Association (APHA-AWWA-WEF, 1999) before and after treatment in the soil column; removal efficiencies of contaminants at selected HLR and SCD was also determined using Equation 2. Parameters considered includes hydrogen ion concentration (pH), temperature, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), bio-chemical oxygen demand (BOD_5), total hardness (TH), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+) and bacterial count (BC). The source water is a tertiary treated industrial effluent from the factory and the assumption of the study was that heavy metals issues are non-existent owing to the fact that alcoholic and non-alcoholic beverages which are for human consumption were produced with the water of drinking quality status. All tests were carried out at the Environmental Chemistry Laboratory of the Federal University of Agriculture, Abeokuta, Nigeria. The suitability of the water collected at the optimized HLR and SCD for drinking, industrial, domestic, and irrigation purposes was evaluated by comparing the values of different water quality parameters with those of the World Health Organization guidelines. Removal efficiencies of all parameters tested in the effluents at varying HLR and SCD was determined using Equation 2.

$$E(\%) = (1 - \frac{C_{at}}{C_{bt}}) \times 100\% \qquad (2)$$

Where E is removal efficiency, C_{bt} (mg L^{-1}) is concentration of parameter before treatment and C_{at} (mg L^{-1}) is concentration of parameter after treatment.

The results obtained from the experimental runs were compiled in a spread sheet (MS Excel®) and analyzed for Fisher's least square difference (LSD), analysis of variance (ANOVA), treatment effects, and contaminant removal efficiencies using R® statistical software at (p<0.05).

3 Results and discussion

3.1 Washed river sand gradation and suitability

The grain size analysis indicated that the sample comprised of 17.84%, 81% and 1.14% of gravel, sand and silt/clay, respectively. Figure 2 shows the river washed sand gradation chart which revealed a good sandy curve; the coefficient of uniformity (C_u) obtained was 7, indicating that the sand particles are well graded (Das, 2008) and very suitable to be used in the sand column. Lewis and Sjöstrom (2010) reported that undisturbed soil samples pose a better representation of the natural soil column; however, the cost of achieving this may be prohibitive. It is also important to point out that preferential flow paths usually occur in packed sand columns; this often leads to a portion of the influent water traveling more quickly through the sand column (resulting in a lower residence time) and therefore significantly biasing the experimental result. Bergström (2000) recommended a number of measures that can be used to overcome this limitation such as ensuring a column diameter – soil grain diameter ratio > 40 and roughening the side wall of the column material; the former was however chosen for the experimental setup due to ease of implementation. It should also be noted that soils from proposed MAR sites will provide better representativeness during implementation. This will however require adequate characterization of the site because of soil variability issues.

The EC observed in all treatments and replicates ranged between 2,315 – 2,960 µS cm^{-1}. These values are indicative that the water is slightly saline. Aghazadeh et al. (2017), report that groundwater samples with EC between 1,500 and 3,000 µS cm^{-1} can be classified as having medium salt enrichment. Literature show that there is a strong relationship between EC and TDS in water (Al Dahaan et al., 2016; Rodríguez-Rodríguez et al., 2018). The TDS obtained from all treatments and replicates ranged between 1,139 – 1,438 mg L^{-1}; there was, however, slight variation across the replicates for the TDS. WHO (2004) suggests that the presence of high levels of TDS in drinking-water (> 1,200 mg L^{-1}) may be objectionable to consumers while water with extremely low concentrations of TDS may also be unacceptable because of its flat, insipid taste. From the study, a correlation coefficient of 0.87 was established between EC and TDS.

The chloride (Cl^-) concentration across treatment and replicates ranged from 230 – 320 mg L^{-1}; this seems to be a good range for a treated industrial effluent, it is expected that natural dilution and mixing will occur when the effluent gets into the natural system. The World Health Organization recommends a threshold value of 250 mg L^{-1}, above which there could be detectable taste in the water (WHO, 2004).

The TSS found across treatments and replicates were generally low as expected. The source water being a treated effluent has undergone screening, hence the value ranging from 0 – 0.3 mg L^{-1} across treatment and replicates was not a surprise. Drinking water is not supposed to have any solids suspended in it; the values obtained when compared with the value of 11 mg L^{-1} for the source water indicate the adequacy of the sand column to filter any suspended solid to the barest minimum and same will occur if the source water is recharged to groundwater via infiltration basin or through injection wells.

According to WHO (2004), hardness in water is usually caused by dissolved calcium and, to a lesser extent, magnesium. Depending on pH and alkalinity, hardness above about 200 mg L^{-1} can result in scale deposition, particularly on heating. Soft waters with a hardness of less than about 100 mg L^{-1} have a low buffering capacity and may be more corrosive to water pipes. Water containing calcium carbonate at concentrations below 60 mg l^{-1} is generally considered as soft; 60–120 mg L^{-1}, moderately hard; 120–180 mg l^{-1}, hard; and more than 180 mg L^{-1}, very hard (McGowan, 2000). The hardness of the water across all treatments and replicates in the study range from 130 to 200 mg L^{-1}, indicating that the sand column significantly reduced the hardness of the source water. This can be closely linked to the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the treated water which range from 25 to 74 mg lL^{-1} and 88 to 132 mg L^{-1}, respectively. The taste threshold for the Ca^{2+} is in the range of 100–300 mg L^{-1}, depending on the associated anion, and the taste threshold for Mg^{2+} is probably lower than that for calcium (WHO, 2004). Literature shows that DO content of water is influenced by the source of water, raw water temperature, treatment and chemical or biological processes taking place in the distribution system (Khatri and Tyagi, 2015). The results obtained from the study indicate that DO across treatment and replicates range from 0 to 6.4 mg L^{-1}; while pre-treatment value was zero, thus showing that oxygenation took place at the top of the sand column. This is a common occurrence with the use of infiltration basin for groundwater recharge.

Depletion of DO in water supplies can encourage the microbial reduction of nitrate to nitrite and sulphate to sulphide; it can also cause an increase in the concentration of ferrous iron in solution, with subsequent discoloration at the tap when the water is aerated. No health-based guideline DO value is recommended by WHO. Concentration of DO influence many biogeochemical processes in groundwater systems (Schilling and Jacobson, 2015); it regulates the valence state of trace metals and constrains the bacterial metabolism of dissolved organic species (Rose and Long, 1988).

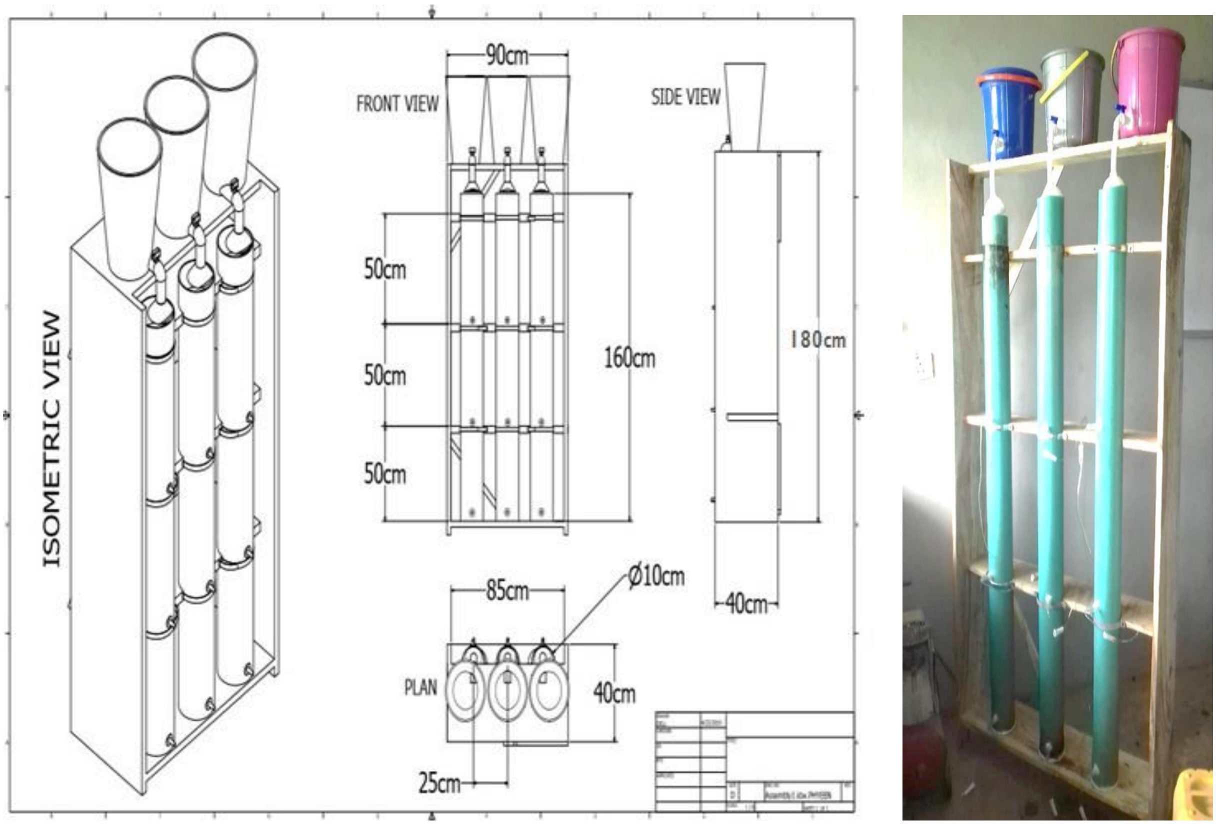

Figure 1 Experimental setup and technical specifications

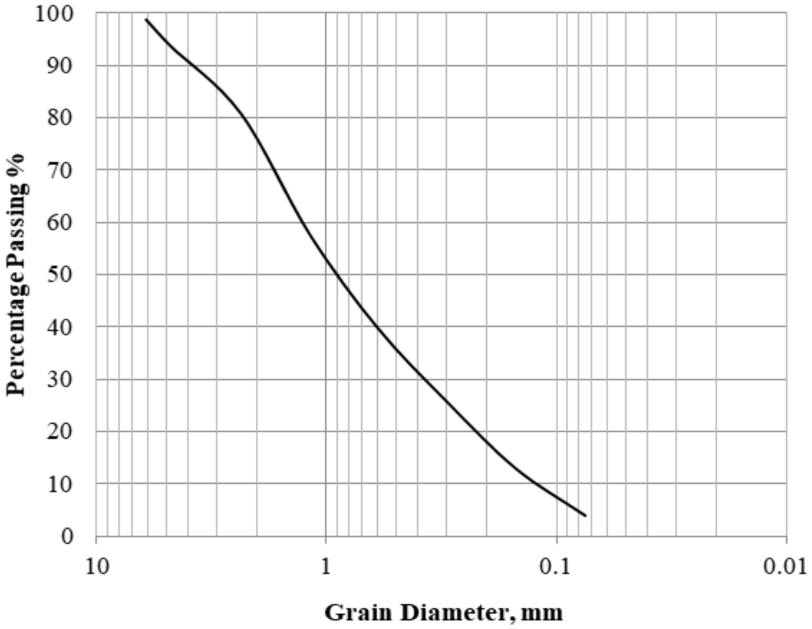

Figure 2 Washed river sand gradation chart

Biochemical oxygen demand (BOD) is an essential parameter used to characterize wastewater and the effectiveness of treatment system; BOD values across treatments and replicates range between 0 – 3.8 mg L^{-1}, indicating the presence of dissolved microorganisms in the water as it passes through the sand column. A critical look at the result of the BC obtained from the samples across treatment and replicates (20,000 – 510,000 CFU mL^{-1}) shows that the sand column significantly reduced the BC in the water; this will naturally be the case as water infiltrates the soil in natural systems. Sidhu et al. (2015), posited that site-specific subsurface conditions such as groundwater chemistry can have considerable influence on the decay rates of pathogens in water. The present study has shown that recharging treated industrial effluent will further provide additional treatment down the groundwater system especially for pathogens. Barba et al. (2019) describe MAR as a naturally based, passive and efficient technique with broad implications for the biodegradation of pollutants dissolved in water.

Sodium (Na^+) found in the water samples varied from 162 – 195 ppm across treatments and replicates, indicating a reduction from 220 ppm in the raw water. There is, however, the possibility of further reduction as the soil depth increases in natural systems; WHO (2004), suggests that sodium in potable water are typically less than 20 mg L^{-1}, they can greatly exceed this in some countries; concentrations in excess of 200 mg L^{-1} may give rise to unacceptable taste in the water.

The potassium (K^+) concentration in the water samples range from 11 to 16 ppm across all treatments and replicates; these values are lower than that obtained in the control, indicating that the sand column reduced the concentration of K^+. Adimalla and Venkatayogi (2018), suggests that k^+ concentration in groundwater should not exceed 12 mg Ll^{-1} to render it fit for drinking purpose without treatment; further movement of the water down the natural soil is expected to bring down the k^+ concentration in the water.

3.3 Interaction of water quality parameters with changes in HLR and SCD

SAT systems must be designed appropriately in order to achieve effective operations and high removal efficiencies of contaminants; this is made possible by ensuring that optimum operating conditions are implemented. Among the chief factors to consider are the HLR and SCD for infiltration basins, constructed wetlands and unconfined aquifers. Other considerations include travel time/travel distance, redox conditions, soil type, wetting and drying cycles, and climatic considerations (Dong et al., 2011; Abel et al., 2013; Chen et al., 2013). Figure 3 shows the variations of temperature, pH, TSS, TDS, EC and hardness in water with changes in HLR and SCD. Temperature and pH seem to be fairly stable in the system with an average value of 27.2ºC and 7.8 respectively.

The optimum HLR that gave maximum TSS removal was 14.6 mm min^{-1}, with zero value attained between 1 and 1.2 m of SCD. In the case of TDS removal, HLR of 14.6 mm min^{-1} also gave the best condition for treatment of dissolved solids in the water at a SCD between 0.5 and 0.7 m; this is the optimum that can be achieved within the scope of the study. The optimum reduction of EC in the water was achieved with a HLR of 20.37 mm min^{-1} and a SCD of 0.6 m; it was however surprising to note that EC increased in the water below this optimum depth. In natural systems, the EC is expected to drop as the water comes in contact with older groundwater because of expected mixing in the aquifer, provided that the aquifer water is not saline.

Figure 3 also shows that hardness of the water declined as SCD increases, the lowest value was however achieved at a HLR of 14.6 mm min^{-1} and SCD of 1.25 m.

The variations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, DO and BOD_5 in the water with changes in HLR and SCD is presented in Figure 4. $Ca^{2+}$and Mg^{2+} removal from the water was found to increase with SCD in all treatments and replicates; optimum reduction in these cations was found to occur at SCD of 1.5 m and HLR of 14.6 mm min^{-1}. This implies that improved removal may be possible at lower HLR and higher SCD. Na^{+} and K^{+} reduction in the water was found to increase with SCD and reducing HLR in the system; optimum values were obtained at HLR of 14.6 mm min^{-1} and SCD of 1.5 m. This is of significant importance for the design of infiltration basins. DO and BOD_5 were however found to behave in a different way from previously considered parameters; there was evidence of increasing DO and BOD_5 with SCD at the beginning of the soil column up to a peak value ranging between 0.5 – 0.8 m depth, followed by a decline in values as the SCD approaches 1.5 m. This increase must have been due to the aeration that took place at the top of the sand column; this explains the presence of microorganisms to a certain depth in the system as shown by the pattern displayed by the BOD_5. The decline beyond SCD of 0.8 m indicates the increasing consumption of oxygen by the microorganisms present. HLR of 14.6 mm min^{-1} was found to present the best condition for the removal of DO and BOD_5.

Figure 5 presents the variations of BC and chloride obtained in the water with changes in SCD and HLR; there was a marked reduction in the bacterial load of the water as it travels down the soil column, this is expected as the DO concentration diminishes down the soil column. The curve began to flatten out as the water passes beyond 0.8 m soil depth at a fairly constant HLR, indicating an optimum HLR of 14.6 mm min^{-1}. Griebler and Lueders (2009) report that the total number of bacteria found in groundwater ecosystems may vary by several orders of magnitude between 10^2 and 10^6 cells per cm^3 of groundwater and between 10^4 and 10^8 cells per cm^3 of sediment; these numbers are expected to reduce as soil passage progresses. Chloride in the water also presented similar trend as the water passes down the soil column. Maximum Chloride removal was achieved at SCD and HLR of 1.5 m and 14.6 mm min^{-1}, respectively.

The results emphasize the importance of SCD and HLR in the design of SAT for MAR, a vast majority of the parameters tested revealed reduced concentration with increasing soil depth; however, Barquero et al. (2019) opined that wetting and drying cycles in infiltration basins also play an important role in SAT systems performance when reclaimed water is being used. Bonneau et al. (2018) recommends that infiltration basins for SAT systems should be located in soils that are permeable enough to give high infiltration rates. This requirement is important where treated effluent flows are large, where basin areas are not too large and where evaporation losses from the basins can be minimized. The soils, however, should also be fine enough (preferably < 2 mm) to provide good filtration and quality improvement of the effluent as it passes through. Thus, the best surface soils for SAT systems are in the fine sand, loamy sand, and sandy loam range. Materials deeper in the vadose zone should be granular and preferably coarser than the surface soils. Soil profiles consisting of coarse-textured material on top and finer-textured material deeper down should be avoided because of the danger that fine suspended material in the effluent will move through the coarse upper material and accumulate on the deeper, finer material to cause clogging of the soil profile at some depth, where removal of the clogging material would be very difficult.

Table 1 Means for water quality parameters

	TSS (mg L^{-1})	**Cl (mg L^{-1})**	**k (ppm)**	**Na (ppm)**	**TDS (mg L^{-1})**	**Temp (°c)**	**pH**	**E.C (µS cm^{-1})**	**B.C (CFU ml^{-1})**	**Hardness (mg L^{-1})**	**Ca (mg L^{-1})**	**Mg (mg L^{-1})**	**DO (mg L^{-1})**	**BOD (mg L^{-1})**
Control	11	340	20	220	1458	28.7	7.78	2912	3000000	220	84	136	0	0
HLR (mm min^{-1})														
20.37	0.04	277.78	15.22	190	1338.00	27.36	7.83	2672.33	334444	175.56	62.44	113.11	3.88	2.47
16.98	0	262.22	13.78	176.67	1325.89	27.28	7.87	2610.56	115444	156.67	48.89	107.78	3.66	2.28
14.6	0	246.67	12.56	162.22	1283.33	27.18	7.91	2533.33	71666	142.22	36.56	105.67	3.07	2.17
LSD ($p<0.05$)	0.05	8.86	0.76	11.28	55.04	0.45	0.03	102.4	55130	4.48	3.07	5.65	1.39	0.89
SCD (m)														
0.5	2.78	298.33	15.92	195.83	1333.2	27.69	7.85	2692	213222	187.50	64	123.5	2.38	1.78
1.0	2.76	280.83	15.58	185.83	1356.8	27.66	7.83	2658	186778	173.33	58.17	115.17	2.69	1.73
1.5	2.75	265.83	14.67	180	1363.9	27.54	7.89	2698	121556	160	51.75	108.25	2.88	1.68
LSD ($p<0.05$)	0.04	7.52	0.65	9.77	47.67	0.38	0.02	88.6	47744	3.876	2.659	4.89	1.21	0.77
WHO	nil	<250	nil	<20	<1,200	nil	6.5-8.5	nil	nil	<250	<250	<200	No value	No value

Note: HLR – hydraulic loading rate (mm min^{-1}); SCD – soil column depth (m); LSD – Least square Difference

3.4 Removal efficiency of treatment process

Removal efficiency remains the most commonly applied index for the suitability of SAT systems, apart from giving a rapid assessment, it has been accepted in the water and wastewater treatment circle as a standard test. The variation of the SCD and HLR in the experimental setup gives the opportunity to optimize the process for greater efficiency. The soil column with HLR of 14.6 mm min^{-1} at the highest SCD of 1.5 m, gave the maximum removal efficiency in all parameters while the soil column with HLR 20.37 mm min^{-1} showed the least removal efficiency in all parameters as shown in Table 2.

Table 2 Improvement of effluent quality through soil column passage

Parameters	unit	Inflow (control)	Outflow			Removal efficiency (%)		
			20.37 mm min^{-1}	16.98 mm min^{-1}	14.6 mm min^{-1}	20.37 mm min^{-1}	16.98 mm min^{-1}	14.6 mm min^{-1}
TSS	mg L^{-1}	11	0.044	0	0	99	100	100
TDS	mg L^{-1}	1458	1208	1139	1139	17	18.4	22
E. Conductivity	µS cm^{-1}	2912	2385	2355	2341	18	19.1	20
Chloride	mg L^{-1}	340	250	240	230	26.5	29.4	32.3
Potassium	Mg L^{-1}	20	12	11	11	40	45	45
Sodium	mg L^{-1}	220	150	130	130	31.8	41	41
Bacterial count	CFU mL^{-1}	300×10^4	6.8×10^4	4.2×10^4	2.5×10^4	97.7	98.6	99.1
Calcium	mg L^{-1}	84	46	32	26	45.2	62	69
Magnesium	mg L^{-1}	136	108	104	94	20.6	23.5	30.8
Hardness	mg L^{-1}	220	140	140	130	36.4	36.4	41

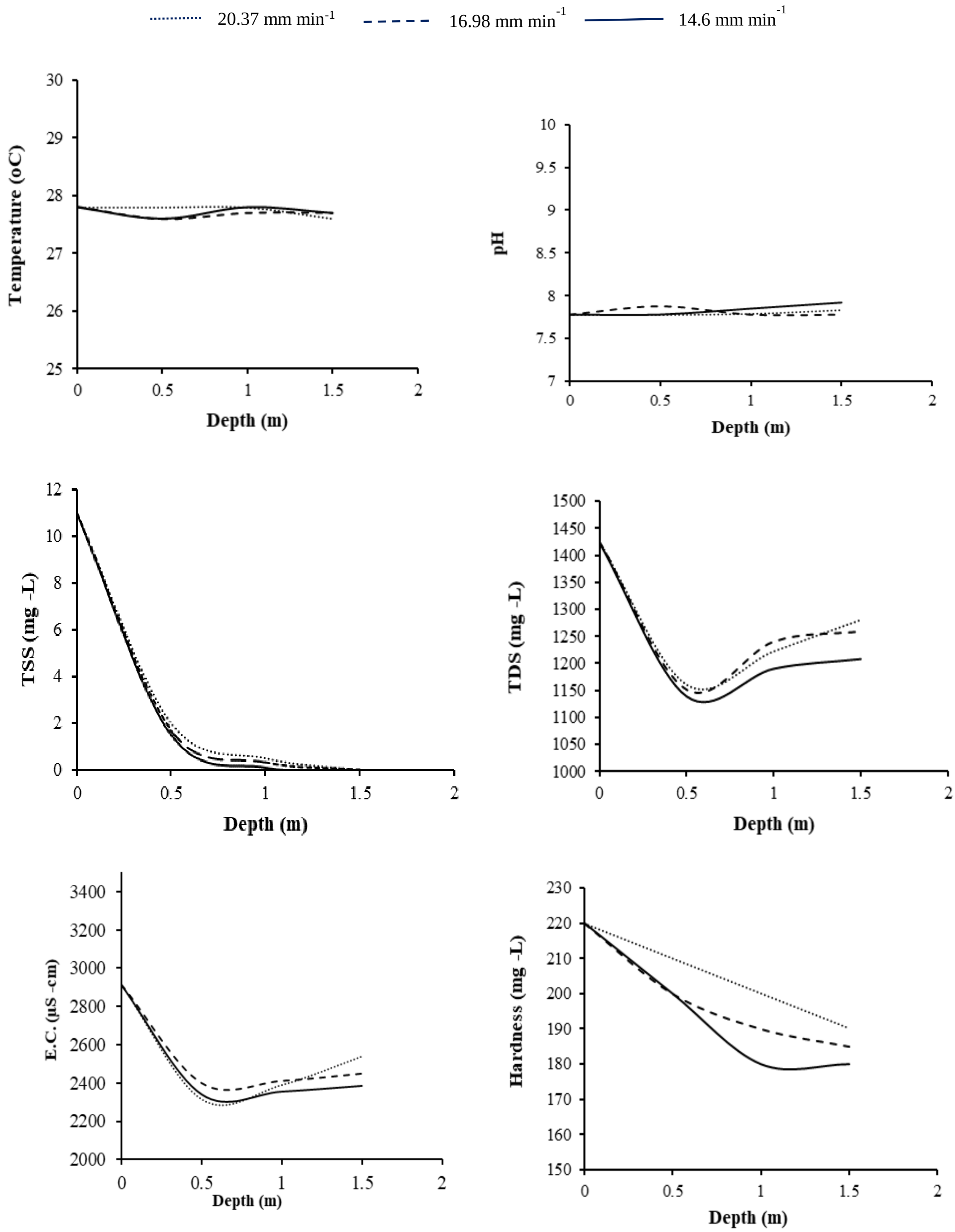

Figure 3 Variations of temperature, pH, TSS, TDS, EC and Hardness in water with changes in hydraulic loading rate and soil column depth

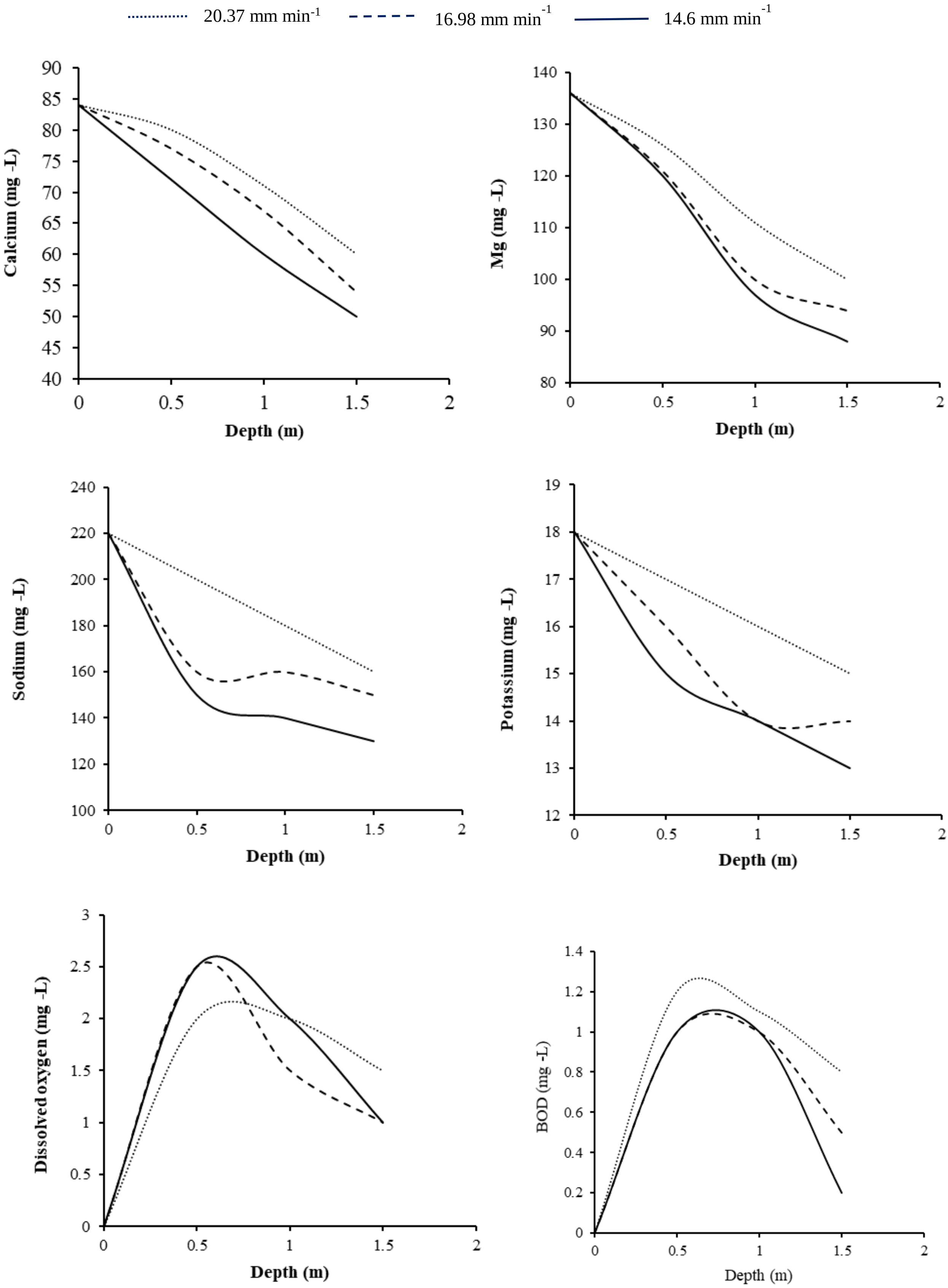

Figure 4 Variations of Ca^{2+}, Mg^{2+}, Na^{+}, k^{+}, DO and BOD_5 in water with changes in hydraulic loading rate and soil column depth

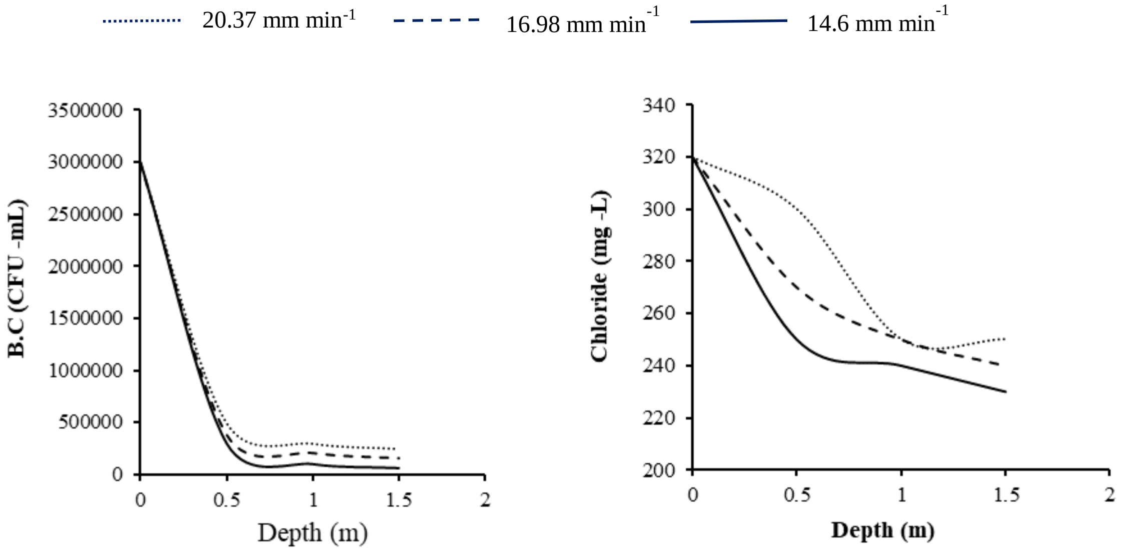

Figure 5 Variations of bacterial count and chloride in water with changes in hydraulic loading rate and soil column depth

3.5 Implications for MAR in Nigeria

The study revealed that treated industrial effluents can be used to recharge depleted aquifers in Nigeria. Pertinent among the results obtained is the further treatment of the effluent that occurred within the soil column of the simulator which reveal what will also happen in real practice; the data obtained from the study will provide important inputs to the design of SAT systems across the country. The water stress experienced in the Sudan and Sahel Savannah regions of Nigeria where drinking water supply is largely from groundwater sources and the reported lowering of the phreatic surface, as well as the rapidly increasing saltwater intrusion in the coastal areas of the country calls for an immediate response to combat the worrisome deterioration of Nigeria’s groundwater system, particularly in urban centres. Many of the urban centres houses a number of industries which generate huge volumes of wastewater, this treated wastewater can be recharged into aquifers via available technologies instead of discharging them into surface water bodies for onward release to the Atlantic Ocean.

Reports from the southern city of Lagos indicate serious groundwater quality deterioration which has a grave impact on public health (Healy et al., 2020). The government need to provide the necessary stimulus and policy framework that will make the implementation of MAR feasible as soon as possible. This is an intervention directed at ensuring environmental sustainability and is perfectly in line with SDGs. There is presently no coordination and regulation of groundwater development in the country leading to arbitrary development and abstraction of groundwater; the absence of a regulatory framework makes unsanitary practices possible and this has far reaching effects on public health.

As a way of encouraging industry participation in MAR, incentives could be given to participating companies in the form of tax waivers or similar instruments; this would be a reward mechanism for participating in environmental restoration via MAR. Identification of potential MAR sites may not be possible without first carrying out a comprehensive mapping of our groundwater systems; this will involve a series of studies in the various hydrogeological settings in the country to establish the regional groundwater flow system at the catchment scale.

4 Conclusion

The study evaluated the potentials of recycling treated industrial effluent for the purpose of groundwater recharge and quality restoration through MAR using a laboratory – scale SAT simulator. The results revealed further treatment of the effluent in the sand column. Optimization of HLR and SCD show that HLR of 14.6 mm min^{-1} at an SCD of 1.5 m gave maximum removal efficiency for all parameters tested. The study demonstrates the potential and potency of MAR in environmental restoration, groundwater quality improvement and reducing pollution load of surface water. The removal efficiencies obtained from the study were generally satisfactory for a SCD range of 0.5 m – 1.5 m of the simulator; further treatment is expected in the real recharge scenario were recharge water may travel as 30 – 40 m to get to the aquifer depending on the lithology of the area where the MAR scheme will be constructed. Nigeria has a vast potential for its implementation to enhance environmental sustainability, this requires policy intervention from the government which will enable bulk wastewater producers to put their effluents to positive use.

Acknowledgement

This work was possible with the support of the Water and Wastewater Laboratory of the Federal University of Agriculture, Abeokuta. The management of Nigerian Breweries PLC, Ota are also appreciated for their support and cooperation during the research.

References

Abel, C. D. T., S. K. Sharma, E. Buçpapaj, and M. D. Kennedy. 2013. Impact of hydraulic loading rate and media type on removal of bulk organic matter and nitrogen from primary effluent in a laboratory-scale soil aquifer treatment system. *Water Science and Technology*, 68(1): 217-226.

Adimalla, N., and S. Venkatayogi. 2018. Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangana State, South India. *Applied Water Science*, 8: 44.

Al Dahaan, S., N. Al-Ansari, and S. Knutsson. 2016. Influence of groundwater hypothetical salts on electrical conductivity total dissolved solids. *Engineering*, 8(11): 823-830.

APHA-AWWA-WEF. 1999. Standard methods for the examination of water and wastewater. 19th ed. Washington, USA: American Public Health Association, American Water Works Association, World Environment Foundation.

Aghazadeh, N., Chitsazan, M. and Golestan, Y. 2017. Hydrochemistry and quality assessment of groundwater in the Ardabil area, Iran. *Appl Water Sci.* **7**, 3599–3616.

Barba, C., A. Folch, N. Gaju, X. Sanchez-Vila, M. Carrasquilla, A. Grau-Martínez, and M. Martínez-Alonso. 2019. Microbial community changes induced by managed aquifer recharge activities: linking hydrogeological and biological processes. *Hydrology and Earth System Sciences*, 23(1): 139–154.

Barquero, F., T. Fichtner, and C. Stefan. 2019. Methods of in situ assessment of infiltration rate reduction in groundwater recharge basins. *Water*, 11(4): 784.

Bergström, L. 2000. Leaching of agrochemicals in field lysimeters – a method to test mobility of chemical in soil. In *Pesticide/Soil Interactions: Some Current Research Methods*, eds. J. Cornejo, P. Jamet, and F. Lobnik, pt 2, ch. 1, 279-285. Paris: INRA.

Bonneau, J., T. D. Fletcher, J. F. Costelloe, P. J. Poelsma, R. B. James, and M. J. Burns. 2018. Where does infiltrated stormwater go? Interactions with vegetation and subsurface anthropogenic features. *Journal of Hydrology*, 567: 121-132.

Bouwer, H. 2002. Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal*, 10(1): 121- 142.

Chen, Q., W. Dong, J. Ma, Q. Li, X. Gao, S. Ding, and J. Zhang. 2013. Effects of hydraulic loading rate on nutrient removal in multi-stage constructed wetland. *Advanced Materials Research*, 864–867: 1498–1502.

Cosgrove, W. J., and D. P. Loucks. 2015. Water management: Current and future challenges and research directions. *Water Resources Research*, 51(6): 4823-4839.

Das, B. M. 2008. *Advanced Soil Mechanics*. 3rd ed. New York: Taylor & Francis.

DEMEAU. 2012. Guidelining protocol for soil-column experiments assessing fate and transport of trace organics. European Union Seventh Framework Programme (FP7/2007-2013). Available at: www.demeau-fp7.eu. Accessed 4 March 2018.

Dong, Y., P. R. Wiliński, M. Dzakpasu, and M. Scholz. 2011. Impact of hydraulic loading rate and season on water contaminant reductions within integrated constructed wetlands. *Wetlands*, 31: 499–509.

Deng, X., and C. Zhao. 2015. Identification of Water Scarcity and Providing Solutions for Adapting to Climate Changes in the Heihe River Basin of China. *Advances in Meteorology*, 2015: 279173.

FAO. 2007. Coping with Water Scarcity Challenge of the Twenty-First Century, United Nation Food and Agricultural Organization, Rome. Available at:

http://www.fao.org/3/a-aq444e.pdf. Accessed 12 February 2019.

Fashae, O. A., and R. O. Obateru. 2021. Geospatial assessment of surface water pollution and industrial activities in Ibadan, Nigeria. In *Spatial Modeling and Assessment of Environmental Contaminants: Risk Assessment and Remediation*, eds. P. K. Shit, P. P. Adhikary, and D. Sengupta, ch. 12, 189-211. Available at: https://link.springer.com/book/10.1007/978-3-030-63422-3.

Griebler, C., and T. Lueders. 2009. Microbial biodiversity in groundwater ecosystems. *Freshwater Biology*, 54(4): 649 – 677.

Healy, A., K. Upton, S. Capstick, G. Bristow, M. Tijani, A. MacDonald, I. Goni, Y. Bukar, L. Whitmarsh, S. Theis, K. Danert, and S. Allan. 2020. Domestic groundwater abstraction in Lagos, Nigeria: a disjuncture in the science-policy-practice interface? *Environmental Research Letters*, 15(4): 045006.

Hussain, M., and S. Mumtaz. 2014. Climate change and managing water crisis: Pakistan's perspective. *Reviews on Environmental Health*, 29(1-2): 71-78.

Ighalo, J. O., and A. G. Adeniyi. 2020. A comprehensive review of water quality monitoring and assessment in Nigeria. *Chemosphere*, 260: 127569.

IPCC. 2019. Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. UNEP, WMO. Available at: https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf. Accessed 24 June 2020.

Jury, W. A., and H. Vaux Jr. 2005. The role of science in solving the world's emerging water problems. *PNAS*, 102(44): 15715-15720.

Khatri, N., and S. Tyagi. 2015. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science*, 8(1): 23-39.

Lewis, J., and J. Sjöstrom. 2010. Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments. *Journal of Contaminant Hydrology*, 115(1-4): 1-13.

McGowan, W. 2000. *Water Processing: Residential, Commercial, Light-industrial*. 3rd ed. Lisle, IL: Water Quality Association.

McNally, A., K. Verdin, L. Harrison, A. Getirana, J. Jacob, S. Shukla, K. Arsenault, C. Peters-Lidard, and J. P. Verdin. 2019. Acute water scarcity monitoring for Africa. *Water*, 11(10): 1968.

Mekonnen, M. M., and A. Y. Hoekstra. 2016. Four billion people facing severe water scarcity. *Science Advances*, 2(2): e1500323.

Metcalf, E., T. Asano, F. Burton, H. Leverenz, R. Tsuchihashi, and G. Tchobanoglous. 2007. *Water Reuse: Issues, Technologies, and Applications*. NewYork, USA: Mc-Graw Hill.

Oke, A. O., and A. Y. Sangodoyin. 2015. Evaluation of surface water quality characteristics in ogun watershed of south western Nigeria using principal component analysis. *Journal of Science and Technology (Ghana)*, 35(1): 89-101.

Richey, A. S., B. F. Thomas, M. H. Lo, J. T. Reager, J. S. Famiglietti, K. Voss, S. Swenson, and M. Rodell. 2015. Quantifying renewable groundwater stress with GRACE. *Water Resource Research*, 51(7): 5217–5238.

Rodríguez-Rodríguez M., A. Fernández-Ayuso, M. Hayashi, and F. Moral-Martos. 2018. Using water temperature, electrical conductivity, and pH to characterize surface–groundwater relations in a shallow ponds system (Doñana National Park, SW Spain). *Water*, 10(10): 1406.

Rose, S., and A. Long. 1988. Monitoring dissolved oxygen in groundwater: some basic considerations. *Groundwater Monitoring and Remediation*, 8(1): 93-97.

Schilling, K. E., and P. Jacobson. 2015. Field observation of diurnal dissolved oxygen fluctuations in shallow groundwater. *Groundwater*, 53(3): 493-497.

Sidhu, J. P. S., S. Toze, L. Hodgers, K. Barry, D. Page, Y. Li, and P. Dillon. 2015. Pathogen decay during managed aquifer recharge at four sites with different geochemical characteristics and recharge water sources, *Journal of Environmental Quality*, 44(5): 1402-1412.

UN. 2012. The Millennium Development Goals Report, United Nations Statistics Division, New York. Available at: https://www.un.org/millenniumgoals/pdf/MDG%20Report%202012.pdfhttp://mdgs.un.org/unsd/mdg/Resources/Static/Products/Progress2012/English2012.pdf. Accessed 15 February 2018.

WHO. 2004. Guidelines for drinking – water quality. Vol.1: 3rd ed. Geneva: World Health Organization.

WHO and UNICEF 2013. Progress on sanitation and drinking-water - 2013 update. ISBN 978 92 4 150539 0, pp.40

WWAP. 2015. The United Nations World Water Development Report 2015: Water for a Sustainable World, United Nations World Water Assessment Programme, UNESCO, Paris. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000231823. Accessed 15 October 2015.