RADON (\(^{222}\text{Rn}\)) OCCURRENCE IN QUATERNARY DEPOSITS, ANNUAL DOSAGE AND GROUNDWATER RECIRCULATION IN HASHYIMIA, BABYLON, IRAQ

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ABSTRACT

During many tests on ground water sample that were carried out in the labs of Babylon environment directorate, Radon among many pollutants was encountered in concentrations exceeded the allowable limits according to WHO. Hashyimia unconfined aquifer with an area of about 100 Km\(^2\) was found to be polluted with Radon (\(^{222}\text{Rn}\)) with concentrations exceed the maximum permitted value according to WHO (100 Bq/liter) in many locations. Preliminary tests with Alpha GUAR PQ2000 PRO, Alpha PUMP and Aqua KIT device of many GW samples reveal that their concentrations reach 113 Bq/liter after 3 hrs since a continuous pumping start. Geologically Hashyimia is consisted of a quaternary deposits of unconsolidated and finer grained of flood plains of the Euphrates River which mainly consist of clay, silt, sand and gypsum layers. A mathematical estimation of GW velocity (<1 cm/day) proved that \(^{222}\text{Rn}\) origin is created by the local geologic formation of the aquifer and instantaneously the aquifer endures concentrations rise during the pumping process. It is found that the annual dosage reaches (453 SV year\(^{-1}\)) with residence time of (12 day\(^{-1}\)). A mathematical model has been designed to simulate and execute the theory of GW recirculation and purification against \(^{222}\text{Rn}\) infection using the property of radon releasing during an exposure to air. The results indicates that 216 and 112 pumping and injecting wells are needed to recycle 100% strategic GW storage of the selected polluted sector respectively. It is concluded that \(^{222}\text{Rn}\) is instantaneously produced by unknown source around the pumping well during a continuous pumping process and its concentration increases to a constant values.

Keywords: Piezometric Velocity; Infection; Residence time; Annual dosage; Recirculation
INTRODUCTION

Many researchers such as Ellins et al. (1990), Yoneda et al. (1991) and Hoehener and Surbeck (2004) used $^{222}\text{Rn}$ concentrations as a hydrological tracers to evaluate GW quantities and its interference with surface water by using different mathematical techniques. Whereas Loomis (1987) investigated the relation of radon concentration and aquifer lithology at north California. Dixon (1989) summarized radon sources in ground water whereas Ellins et al. (1990) focused on GW spatial and temporal variations. Schubert et al. (2011) used a fast electronic techniques called RAD7 and solid state nuclear track detectors CR39 for radon concentration in GW. Their test indicates that radon concentrations reach 2050 Bq/m$^3$ in south Lehais. Hammood and Al-Khalifa (2011) encountered radon existence in surface and GW at Dhi-Qar, Iraq. They tested 58 samples with different locations by Emanometer techniques. Their results were ranged from (116 – 601) and (355 – 681) Bq/m$^3$ in surface and GW respectively. Abojassim (2013) used also RAD7-H$_2$O for radon evaluation at Kufa, Iraq. The concentrations range was (9.3 – 8.8) Bq/m$^3$ and the average annual dose was (0.54 – 31.78) µS. Whereas Nada (2013) found in Akashat that GW radon concentrations in the range of (8.02 – 11.7) Bq/liter but Khalid (2013) found that an average radon concentration in Hilla River was 0.103 and finally Wasan (2014) indicates that an average radon concentrations in Shomaly, Iraq of 128 drinking water samples was 0.29 Bq/liter. In this research, a recirculation process to purify the strategic GW storage against radon infection with high concentrations by replacement it totally or partially with fresh water from Hillah River in addition to provide consumers with water of less concentrations of radon by exposing the polluted water to atmosphere before use.

GEOGRAPHY AND STUDY SIGNIFICANCE

Hashyimia area of 110 km$^2$ located between longitudes (44° 36’ – 44° 47’) and latitudes (32° 18’ – 32° 27’) in the middle of Iraq. Hillah River passes the area from the west toward the southern-east with many local streams to convey water to agricultural fields. 80000 persons live in the area, most of them work in agriculture and eventually consumeda contaminated groundwater with radon for drinking and agriculture causing hazardous diseases. Figure (1) Shows the geographic features.
Fig. 1: Simplified Geologic Map (Based on Geologic Map of Iraq)

**GEOLOGICAL SETTING**

Quaternary deposits cover most parts of the area. The sediments are unconsolidated and finer grained than the underlying pebbly sandstone of Dibdibba and Injana Fns, Al-Siddiki (1978). Quaternary deposits represent flood plain sediments of Euphrates River which are composed of clay, silt and sand deposits of chemical gypsum and salt resulting GW evaporation. Sissakian *et al.* (2000) indicated that gypsum deposits reach 4.92% under the influence of intensive evaporation of over saturation solution. In addition to depression fill sediments these deposits accumulate due to Euphrates River floods which generally consist of fine sand, silt and silt loam layers, Parsons (1957). Where dry marsh deposits are spread in small area and consist of silts and clay with organic materials as indicated in the geologic map (Fig. 1). Al-Jubouri (2003) illustrated that the area composed of a succession of mud, and sand layers and shale with a little amount of gravel in deep layers.

Lee and Falcon (1952) outlined that a tectonic Mesopotamian plain as a huge sedimentary basin represents a large syclorium fold and tectonically active in falling or subsidence stage with small local minor uplift. The formation of the syncline related with the orogeny that occurs in the Zagros zone which still going on till now to supply...
the study area with erosion and weathering matters of mountainous lands with a permanent downward movement. The Mesopotamian plain tectonic existence interprets why marshes and swamps areas are survived, because the continuous decline of the Tigris and Euphrates sediment has not yet filled these low areas (Al-faraji, 1990).

**MATERIALS AND METHODS**

There are 140 samples of polluted groundwater with radon were collected and brought to the laboratory of Babylon Environmental Directorate, each seven samples for one well of the twenty scattered wells.

The device of AlphaGUARD PQ2000 PRO should be setup as shown in Figure (2). The device is a collection of *AlphaGUARD PQ2000 PRO*, *AquaKIT* and *AlphaPUMP*.

![Setup of AlphaGUARD PQ2000 PRO, AlphaPUMP and AquaKIT](image)

**Fig. 2: Setup of AlphaGUARD PQ2000 PRO, AlphaPUMP and AquaKIT, (Manual of AlphaGUARD PQ2000 PRO)**

**Standard Steps of Specimen Testing**

The manual includes 10 standard steps that had been followed for testing the contaminated water with radon, they are as follow:

1. Setup the equipment *AlphaGUARD PQ2000 PRO*, *AlphaPUMP* and *AquaKIT*.
2. Switch on the AlphaGARD monitor and chose a measuring mos of 1 min Flow.
3. Bring the three-way taps at degassing and security vessel into 3 o'clock position foreseen for sampling.
4. Dock the plastic injection with a water sample that to be measured to the vertical connection socket of the degassing vessel.
5- Emptying the plastic injection slowly into the degassing vessel.
6- Bring the three-way taps of the degassing and security vessel immediately into the 6 o'clock position for a measuring mode.
7- Remove the plastic injection of a vertical connection socket of the degassing vessel.
8- Set the AlphaPUMP performance level switch to a flow rate of 0.3 L/min.
9- Bring the operation mode switch of AlphaPUMP in position "ON"
10- After 10 min rotating operation switch mode of AlphaPUMP to position "OFF"

**Existence of Radon in Hashyimia**

A short term pumping period has been conducted to trace a radon concentration by drilling 20 randomly scattering wells. The locations of these wells were selected depending on many private and social circumstances such as owner's permission, administration priorities, abilities and possibilities. Figure (3) presents the observation wells location.

Preliminary testing of polluted GW samples obtained from an open well offered concentrations less than the dangerous limits. It is worth to mention that water with radon concentrations of 1000 Bq/L or more are significantly inconvenient for any consuming whereas for concentration equals or exceeds 100 Bq/l are of significant importance and can be used for human consumption after some types of remediation according to WHO.

![Fig. 3: Wells Locations over Hashyimia Area](image)
Anyway, a continuous pumping of (3 hours) duration was carried out and samples were taken at each half an hour and kept in a closed pockets to prevent radon releasing to maintain real $^{222}\text{Rn}$ concentrations in the polluted GW. Table (1) includes the initial ($C_{\text{gw}}^\text{w}$) and final ($C_{\text{gw}}^\infty$) conc after testing by using Alpha GUAR PQ2000 PRO, Alpha PUMP and Aqua KIT device.

To facilitate the data analysis and mathematical modeling process, the model domain is discretized into a number of horizontal (columns) and vertical (rows) meshes. Briefly the number of columns = 41 and rows = 38 with square mesh dimensions of 333m*333m were used.

### Table 1: Groundwater Velocity, Residence Time, and Annual Dosage

<table>
<thead>
<tr>
<th>Well Site</th>
<th>$C_{\text{gw}}^\text{w}$ (Bq/L)</th>
<th>$C_{\text{gw}}^\text{w}$/Eq.(11)</th>
<th>$C_{\text{gw}}^\infty$</th>
<th>$T_{\text{gw}}$ (day$^{-1}$)</th>
<th>$V_{\text{gw}}$ cm$^3$ day$^{-1}$</th>
<th>$V_{\text{gw}}$ cm$^3$ day$^{-1}$</th>
<th>Annual Dosage Rate mSV Eq.(13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>16</td>
<td>0.15534</td>
<td>10.26311</td>
<td>3.18</td>
<td>0.9388728</td>
<td>0.295243</td>
<td>0.263165</td>
</tr>
<tr>
<td>W2</td>
<td>11</td>
<td>0.211538</td>
<td>8.561236</td>
<td>3.18</td>
<td>0.9842803</td>
<td>0.309522</td>
<td>0.13286</td>
</tr>
<tr>
<td>W3</td>
<td>9</td>
<td>0.140625</td>
<td>10.81161</td>
<td>3.18</td>
<td>0.927971</td>
<td>0.291815</td>
<td>0.16352</td>
</tr>
<tr>
<td>W4</td>
<td>13</td>
<td>0.149425</td>
<td>10.47708</td>
<td>3.18</td>
<td>0.9343721</td>
<td>0.293828</td>
<td>0.222285</td>
</tr>
<tr>
<td>W5</td>
<td>19</td>
<td>0.172727</td>
<td>9.678367</td>
<td>3.18</td>
<td>0.952275</td>
<td>0.299458</td>
<td>0.28105</td>
</tr>
<tr>
<td>W6</td>
<td>17</td>
<td>0.161905</td>
<td>10.03497</td>
<td>3.18</td>
<td>0.9438736</td>
<td>0.296816</td>
<td>0.268275</td>
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<tr>
<td>W7</td>
<td>10</td>
<td>0.133333</td>
<td>11.10508</td>
<td>3.18</td>
<td>0.9226701</td>
<td>0.290148</td>
<td>0.191625</td>
</tr>
<tr>
<td>W8</td>
<td>15</td>
<td>0.170455</td>
<td>9.751345</td>
<td>3.18</td>
<td>0.9504744</td>
<td>0.298891</td>
<td>0.22484</td>
</tr>
<tr>
<td>W9</td>
<td>18</td>
<td>0.189474</td>
<td>9.168339</td>
<td>3.18</td>
<td>0.9656773</td>
<td>0.303672</td>
<td>0.242725</td>
</tr>
<tr>
<td>W10</td>
<td>12</td>
<td>0.106061</td>
<td>12.36633</td>
<td>3.18</td>
<td>0.903867</td>
<td>0.284235</td>
<td>0.288715</td>
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<tr>
<td>W11</td>
<td>8</td>
<td>0.111111</td>
<td>12.10993</td>
<td>3.18</td>
<td>0.9071676</td>
<td>0.285273</td>
<td>0.18396</td>
</tr>
<tr>
<td>W12</td>
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<td>0.106195</td>
<td>12.35934</td>
<td>3.18</td>
<td>0.903867</td>
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<td>0.288715</td>
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<tr>
<td>W13</td>
<td>7</td>
<td>0.106061</td>
<td>12.36633</td>
<td>3.18</td>
<td>0.903767</td>
<td>0.284203</td>
<td>0.16663</td>
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<tr>
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<td>26</td>
<td>0.240741</td>
<td>7.84851</td>
<td>3.18</td>
<td>1.010485</td>
<td>0.317763</td>
<td>0.27594</td>
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<tr>
<td>W15</td>
<td>11</td>
<td>0.13253</td>
<td>11.13837</td>
<td>3.18</td>
<td>0.92207</td>
<td>0.289959</td>
<td>0.212065</td>
</tr>
<tr>
<td>W16</td>
<td>31</td>
<td>0.279279</td>
<td>7.030115</td>
<td>3.18</td>
<td>1.048491</td>
<td>0.329714</td>
<td>0.283605</td>
</tr>
<tr>
<td>W17</td>
<td>12</td>
<td>0.11215</td>
<td>12.05863</td>
<td>3.18</td>
<td>0.9078677</td>
<td>0.285493</td>
<td>0.273385</td>
</tr>
<tr>
<td>W18</td>
<td>28</td>
<td>0.269231</td>
<td>7.232063</td>
<td>3.18</td>
<td>1.038189</td>
<td>0.326475</td>
<td>0.26572</td>
</tr>
<tr>
<td>W19</td>
<td>17</td>
<td>0.223684</td>
<td>8.253533</td>
<td>3.18</td>
<td>0.9948821</td>
<td>0.312856</td>
<td>0.19418</td>
</tr>
<tr>
<td>W20</td>
<td>14</td>
<td>0.205882</td>
<td>8.710605</td>
<td>3.18</td>
<td>0.9793795</td>
<td>0.307981</td>
<td>0.17374</td>
</tr>
</tbody>
</table>

### Methodology of $^{222}\text{Rn}$ Concentration Determination
Radon concentration estimating basically depends upon the indicated radon concentration in the monitor. This value is not the required radon concentration since some of radon is diluted by air within the measurements setup and small part of it
remains diluted in a watery phase. To quantify the diluted radon, the interior volume of the measurement set-up ($V_{\text{system}}$) is required. The remaining quantity of radon can be determined by introducing the coefficient $k$. Briefly, Eq. (1) is the basic form for radon estimation.

$$C_{\text{water}} = \frac{C_{\text{air}} \cdot \left( \frac{V_{\text{system}} - V_{\text{sample}}}{V_{\text{sample}}} + k \right)}{1000}$$

Where $C_{\text{water}}$: Radon conc in ware sample (Bq L$^{-1}$), $C_{\text{air}}$: Radon concentration in the measuring setup after spelling the radon (Bq m$^{-3}$), $C_{0}$: Initial concentration in the measuring setup before sampling (Bq m$^{-3}$), $V_{\text{system}}$: Interior volume of the measuring system (mL), $V_{\text{sample}}$: is the measuring water sample volume (mL), and $k$: is the radon distribution coefficient. Briefly, the radon concentrations were estimated for 140 samples and represented graphically in Figures (4 to 7).

**Fig. 4:** S-Curve of Radon Concentration for Wells (No.1, 2, 3, 4 and 5)

**Fig. 5:** S-Curve of Radon Concentration for Wells (No.6, 7, 8, 9 and 10)
TEMPORAL VARIATION OF RADON

The results of a short continuous pumping period for the twenty scattered wells shown in Figures (4 to 7) reveal that some of these wells, namely as well No. 1, 5, 6, 12, 14, 16, 17 and 18, as included in Table (1), exceeds the allowable limits of radon concentration [100 Bq L\(^{-1}\)] at the end of pumping period (3 hrs) in GW according to WHO.

The physical interpretation for the ascending concentrations of radon with time during a continuous pumping process is attributed to a prevention of radon releasing to atmosphere. Anyway Figures (4 to 7) reveals that around the vicinity of the pumping wells the initial concentrations were in minimum values corresponding to radon liberation from the polluted GW into air. But as a pumping process was continued, the confined GW in deep bearing stratums and fractures moved toward the centers of the pumping wells and/or generated immediately during the pumping process. The tested specimens were immediately taken corresponding to a standard process during the pumping process before liberation. This interprets why radon concentrations exceed [100 Bq L\(^{-1}\)]. An inspection of Figures (4 to 7) one observes the followings:
1- Some wells reach a constant radon concentration such as Wells No.1, 5, 6, 10 and 16, after (3hrs).
2- Other wells still show increasing in radon concentration after (3 hrs) of pumping process.
3- It is observed that (Well No. 17) of Figure (7) still reflects a sharp increasing in radon concentration and its concentration is probably exceeding (140 or even 150 Bq L$^{-1}$) after 4hrs of continuous pumping process.
4- It is expected that radon concentrations are exceeded the presenting values of Figures (4 to 7) if the roof of pumping discharges increase to (10 or even 20L/s).

*Note: The mathematical model reveals that the safe yield of the unconfined aquifer of Hashyimia is (6.5 L/s).*

**SPATIAL VARIATION OF RADON**

Experimental and field applications of modeling processes and environmental remediation usually requires to construct a clear figure about a spatial distribution of any pollutant in surface and subsurface water alike. Accordingly, a spatial distribution contour map of the extreme radon concentrations in Hashyimia aquifer is shown in Figure (8). It indicates that a radon concentrations exceed the WHO allowable limits [100 BqL$^{-1}$] at three positions overall the study domain.

![Fig. 8: Spatial Distribution of Radon in Hashyimia Aquifer,[Bq L$^{-1}$]](image-url)
GRAUND WATER VELOCITY AND RESIDENCE OF $^{222}$Rn

The estimation of GW and piezometric velocities start by solving the complex integral of the form of Eq. (2) Drost et al. (1968) and Ghose et al. (2003).

$$\frac{C_{ww}}{C_{gw}} = \frac{v_{ww}}{C_{gw}} \pi \lambda r \frac{\pi/2}{\pi} \int -\pi/2 (1 - e^{\frac{-2\lambda r}{v_{ww}} \cos \theta}) \cos \theta d\theta$$  .................................. 2

Where $C_{ww}$ is a radon concentration at the beginning of pumping (Bq/L), $C_{gw}$ is radon concentration at the end of pumping (Bq/L), $\lambda$ is $^{222}$Rn decay constant (s$^{-1}$), $\alpha$ is a convergence factor (dimensionless) and annual dosage, $v_{ww}$ is groundwater concentration, $r$ is radius of the well and ($v_{ww}$) piezometric velocity in (cm/day).

Let $k = \frac{-2\lambda r}{v_{ww}}$ therefore Eq. (2) becomes

$$\frac{C_{ww}}{C_{gw}} = \frac{v_{ww}}{C_{gw}} \pi \lambda r \frac{\pi/2}{\pi} \int -\pi/2 (1 - e^{k \cos \theta}) \cos \theta d\theta$$  .................................. 3

But the exponential value $e^{k \cos \theta}$ may be expanded by Tylor expansion, Erwin Kreyszig (1972):

$$e^{k \cos \theta} = 1 + k \cos \theta + \frac{k^2 \cos^2 \theta}{2} + \frac{k^3 \cos^2 \theta}{3!} + \frac{k^4 \cos^4 \theta}{4!} + \ldots$$  .................................. 4

A Substitution of Eq. (4) in Eq. (3) offers:

$$\frac{C_{ww}}{C_{gw}} = \frac{v_{ww}}{C_{gw}} \pi \lambda r \frac{\pi/2}{\pi} \int -\pi/2 (1 + k \cos \theta + \frac{k^2 \cos^2 \theta}{2} + \frac{k^3 \cos^2 \theta}{3!} + \frac{k^4 \cos^4 \theta}{4!} + \ldots) \cos \theta d\theta$$  .................................. 5

A further simplification of Eq. (5) leads to:

$$\frac{C_{ww}}{C_{gw}} \pi \lambda r \frac{\pi/2}{\pi} \int -\pi/2 (k \cos^2 \theta - \frac{k^2 \cos^2 \theta}{2!} - \frac{k^2 \cos^4 \theta}{3!} - \frac{k^4 \cos^4 \theta}{4!} - \frac{k^5 \cos^6 \theta}{5!} - \ldots) d\theta$$  .................................. 6

A back substitution of K into Eq. (6) offers:

$$\frac{C_{ww}}{C_{gw}} \pi \lambda r \frac{\pi/2}{\pi} \int -\pi/2 \frac{2\lambda}{v_{ww}} \cos^2 \theta - \frac{2\lambda^2 r^2}{2v_{ww}^2} \cos^3 \theta + \frac{2\lambda^3 r^3}{3v_{ww}^3} \cos^4 \theta - \frac{2\lambda^4 r^4}{4v_{ww}^4} \cos^5 \theta + \frac{2\lambda^5 r^5}{5v_{ww}^5} \cos^6 \theta - \frac{2\lambda^6 r^6}{6v_{ww}^6} \cos^7 \theta + \frac{2\lambda^7 r^7}{7v_{ww}^7} \cos^8 \theta - \ldots) d\theta$$  .................................. 7

Entering the integration for each term of the right hand side of Eq. (7)
By substitution the integrals values into Eq. (8) and making the necessary arrangements we obtain:

\[
\frac{C_{gw}}{C_{gw}} = \frac{\nu_{gw}}{\nu_{gw}} \left[ \frac{2r\lambda}{\pi \nu_{gw}} \frac{\pi}{2} \cos^2 \theta - \frac{2^2 r^2 \lambda^2}{2! \nu_{gw}} \frac{\pi}{2} \cos^3 \theta + \frac{2^3 r^3 \lambda^3}{3! \nu_{gw}} \frac{\pi}{2} \cos^4 \theta - \frac{2^4 r^4 \lambda^4}{4! \nu_{gw}} \frac{\pi}{2} \cos^5 \theta + \frac{2^5 r^5 \lambda^5}{5! \nu_{gw}} \frac{\pi}{2} \cos^6 \theta - \frac{2^6 r^6 \lambda^6}{6! \nu_{gw}} \frac{\pi}{2} \cos^7 \theta + \frac{2^7 r^7 \lambda^7}{7! \nu_{gw}} \frac{\pi}{2} \cos^8 \theta - \frac{2^8 r^8 \lambda^8}{8! \nu_{gw}} \frac{\pi}{2} \cos^9 \theta \right] ...
\]

A cancellation and rearrangement of Equation (9) offer:

\[
\frac{C_{gw}}{C_{gw}} = 1 - \frac{2^2 \left( \frac{r\lambda}{\nu_{gw}} \right)^2}{\pi^2} + \frac{2^3 \left( \frac{r\lambda}{\nu_{gw}} \right)^3}{3!} \frac{\pi}{2} - \frac{2^4 \left( \frac{r\lambda}{\nu_{gw}} \right)^4}{4!} \frac{\pi}{2} + \frac{2^5 \left( \frac{r\lambda}{\nu_{gw}} \right)^5}{5!} \frac{\pi}{2} - \frac{2^6 \left( \frac{r\lambda}{\nu_{gw}} \right)^6}{6!} \frac{\pi}{2} + \frac{2^7 \left( \frac{r\lambda}{\nu_{gw}} \right)^7}{7!} \frac{\pi}{2} - \frac{2^8 \left( \frac{r\lambda}{\nu_{gw}} \right)^8}{8!} \frac{\pi}{2} + \cdots ...
\]

In this situation a computer program should be written to find the peizometric velocity \((V_{gw})\) in cm/day by using Equation (10) around the vicinity of the infected wells. Whereas a residence time, GW velocity and the annual dosage were estimated by Equations(11, 12 and 13), respectively.

\[
T_{gw} = \frac{\ln(C_{gw}/C_{gw})}{-\lambda} \hspace{1cm} 11
\]
\[
V_{gw} = \frac{\nu_{gw}}{\alpha} \hspace{1cm} 12
\]
\[
D_w = C_{gw} C_{Rw} D_{cw} \hspace{1cm} 13
\]

Whereas the residence time \((T_{gw})\) in day\(^{-1}\), GW velocity \((V_{gw})\) in cm/day, and \((D_w\) is the annual dosage in Sv year\(^{-1}\)) \(C_{gw}\) = 30 liters, WHO (2009), is the dose concentration factor = 3.5x10\(^{-9}\) Sv/Bq. Eq. (13), Drost et al. (1968). If the horizontal convergence factor \(\lambda\) is equal 0.18144 day\(^{-1}\) with radius of well of 5 cm, the forgoing parameters were estimated corresponding to Equations (11, 12 and 13) and listed in Table (1).

The guidance level value of radionuclide (100Bq/L) for radon, WHO (2008) that at an intake of 2 liters/day for 1 year will result in a committed effective dose of 0.1 mSv\(^{-1}\)}
which should not be exceeded. Accordingly the results of annual effective dose rate ranges between \((0.13 – 0.28 \text{ mSv}^{-1})\) reveal that all wells of Hashyimia are infected by radon pollution which larger than \(0.1 \text{ mSv}^{-1}\).

**RECYCLING THEORY OF GW**

Recycling theory was issued on the basis of a refining of a GW against radon infection. This theory is an effective tool to purify and rehabilitate the infected GW since radon can release as exposing to air. To execute the process of aeration, many steps should be conceptualized, among them are:

**Ground flow regime measurements and aquifer geometry**

Figure (9) presents the natural GWL of Hashyimia aquifer and the flowlines of most critical polluted sector (given a yellow color).

Briefly, field measurements of the unconfined aquifer reveal that the average thickness of the bearing layer is within 6 m.

![Fig. 9: Equipotential lines of Hashyimia GW flow Category and Flow lines of the polluted Sector](image)

**Development of a GW model**

A finite difference 2D model has been developed for the aquifer and the natural and simulated water table levels were compared as shown in Figure (10).
GW storage assessment

Samples were taken for different depths within the drilled wells to measure the specific gravity \( G_z \) and dry density \( \gamma_d \) of the geologic formations. The porosity \( n \) was estimated by using the following form:

\[
    n = 1 - \frac{\gamma_d}{G_z \gamma_W} \quad \text{……………… 14}
\]

Where: \( \gamma_W \) is a water unit weight.

Briefly, the porosity contour map is presented in Figure (11).

The net strategic GW storage corresponding to the natural field porosity and aquifer porous volume was estimated to be 44.4 MCM.
Safe Yield and Injection Capacity Evaluation

The safe yield of an aquifer may be defined as a maximum discharge that can be drawn from an aquifer provided that the resulting drawdown should be no more than (30%) of the bearing layer thickness. Whereas the injecting capacity is the maximum injection recharge that can be injected into the aquifer without flooding the well.

Subsequently, a pumping and injecting wells were arbitrary selected within the polluted sector for evaluating the amount of a safe yield and injecting capacity for recycling processes and remediation. The results were included in Table (2) and indicated in Figure (12), respectively.

Table 2: Safe yield and Injection Capacity

<table>
<thead>
<tr>
<th>Well Type</th>
<th>Safe Yield or Injecting capacity Liter/sec</th>
<th>Produced Drawdown, m</th>
<th>Required Wells Number for recirculation of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10% per year</td>
</tr>
<tr>
<td>Pumping</td>
<td>6.5</td>
<td>1.75</td>
<td>22</td>
</tr>
<tr>
<td>Injecting</td>
<td>11.65</td>
<td>-1.61</td>
<td>12</td>
</tr>
</tbody>
</table>
In order to rehabilitate the strategic storage of the aquifer against radon infection and since radon is instantaneously generated during pumping process from the original geologic formations, it is suggested to use a combined pumping and injection processes to ventilate the GW by air for releasing radon from water before any usage. This application was carried in the field by drilling a number of injecting wells along and adjacent Hillah River for recharging the necessary fresh water into the aquifer and instantaneously discharging an equal quantity of a polluted water into Kids and Sareaa Streams provided that the amount of the pumping water should be reduced from the water allocations of the foreign stream in order to rebalancing the hydrologic components and avoiding water losses.

CONCLUSIONS

It was concluded that:

- GW in all wells is polluted with annual radon dose exceeds 0.1mSv\text{y}^{-1} which is not allowed by WHO.
- Since the piezometric velocities of Table (1) for all the twenty wells are within 1cm day\text{^{-1}} are too small therefore a reasonable source of the radon is instantaneously emitted from the enterbedded quaternary beneath the testing well.
during the pumping process, but we couldn’t determine it. This interprets why the concentration of $^{222}\text{Rn}$ spatially increases to a constant level at the end of the pumping process.

REFERENCES


