

Workshop Volume on

Radon Contamination in Groundwater and Application of Isotopes in Groundwater Studies

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Radon - Occurrence, estimation and hydrological applications

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Abstract

This paper presents the latest research work on natural radioactivity of radon. The work evaluates the occurrence, estimation and analysis of radon gas in air and water followed at national and international levels. The observed concentration in groundwater and surface water supply from Bangalore city is provided along with the hydrological application and the associated health risk. The study emphasizes on further need of a detailed research in this field especially, the application of radon in hydrology.

Introduction

Background radiation levels are a combination of terrestrial (radium, thorium, radon, etc.) and cosmic radiation (photons, muons, etc.) Natural radioactivity is common in the rocks and soil that make up our planet. Over 60 radionuclides (radioactive elements) can be found in nature. The present day content of radioactivity in the sea is estimated to be nearly 10,000 exabecquerel (E_{bq} = 10¹⁸ Bq). Terrestrial radiation comes from radioactive elements that were present at the time the earth was formed. The surface of the Earth and the terrestrial crust happens to be an enormous reservoir of primordial radioactivity. Essentially, all substances contain radioactive elements of natural origin to some extent or the other.

Each radioactive element, or radionuclide, has a characteristic half-life. Half-life is a measure of the time taken for one half of the atoms of a particular radionuclide to disintegrate (or decay) into another nuclear form. Half-lives vary from millionths of a second to billions of years. The half-life of Uranium-238 is about 4.5 billion years, Uranium-235 about 700 million years, and Uranium-234 about 25 thousand years. In fact, very long half-life (and thus low radioactivity) is the reason why Uranium still exists. The chain of successive decays constitutes a radioactive family or series. In the Uranium and Thorium series (4n+2 / 4n+3) after consecutive transformation state Radium and Radon isotopes are built up. Radium is element 88 in the group IIA periodic table. It can exist in the form of different isotopes, ²²⁶Ra (α emitter, half life =1600 years and ²²⁸Ra (β emitter half life 5.8 years) are the most abundant. From the health point of view the two are also most radiotoxic; when ingested over a long period of time they deliver the highest radiation doses to bone, where radium tends to accumulate.

Radon (²²²Rn) and Thoron (²²⁰Rn) from the Uranium and Thorium decay chains are noble gases produced by the decay of their immediate respective parent nuclides, Radon decay products are divided into two groups; the short lived radon daughters ²¹⁸Po (A; 3.05m), ²¹⁴Pb

(B; 26.8m); ^{214}Bi (C; 19.7m), and ^{214}Po (C;164 μs) with effective half lives $\sim 30\text{min}$; and the long lived radon decay product is ^{210}Pb ($T_{1/2} = 22\text{y}$). Most important radionuclide in this chain is the lead isotope ^{212}Pb with half life of 10.6H. These daughter products of Radon being the isotopes of heavy metals get attached to the existing aerosol particles in the atmosphere. Their elimination from the atmosphere occurs either by radioactive decay or by other removal processes and surface deposition that is washout by rain.

^{238}U concentration in most rocks and soils is low (a few parts per million or less), the corresponding ^{226}Ra and ^{222}Rn concentrations are usually small as well. Larger concentrations of ^{222}Rn are typically associated with granitic rocks that contain elevated concentrations of ^{238}U (typically ten or more parts per million). Hall *et al.*, (1987) measured ^{222}Rn concentrations in waters from the granitic regions in excess of $3.7 \times 10^4 \text{ Bq L}^{-1}$. Larger than average ^{222}Rn have also been measured in other ^{238}U naturally enriched sites such as phosphate bearing rocks. The observably enhanced concentrations of ^{222}Rn in waters in granite regime are due to the moving out of Radon gas from the parent rock and dissolving in surrounding water under geologic pressure which tend to get released into atmosphere in normal atmospheric conditions.

It is found at low levels in virtually all rocks, soil, and water. Significant concentrations of Uranium occur in some substances such as phosphate rock deposits and minerals such as lignite, and monazite sands in uranium-rich ores (it is recovered commercially from these sources). Uranium has been mined in Canada, the southwest United States, Australia, and parts of Europe, the former Soviet Union, Namibia, South Africa, Niger and elsewhere.

Radon released by radioactive decay of Radium-226 ($T_{1/2} = 1620$ years), Radium-226 is produced through the radioactive decay of Uranium-238 ($T_{1/2} = 4.51$ billion yrs) that comprises 4 ppm of the earth's crust, Radon-222 is a non-reactive noble gas and itself is not a health hazard, Radon is an odorless, tasteless, invisible gas that mixes with air, chemically inert and essentially non-reactive, heaviest noble gas with highest melting and boiling point, highly soluble in non-polar solvents, moderately soluble in cold water, able to diffuse through rock and soil, decays by alpha particle emission ($T_{1/2} = 3.8$ days), decay products are solids and are called daughters or progeny. The ratio of progeny to radon gas ranges from 0.2 - 0.8 (average 0.4), radon progeny are short lived (0.2 milli seconds to 26.8 minutes), seven decay steps from Radon-222 produces stable Lead-206, chemically active and charged radon progeny can attach to air particles. The radon daughters Polonium-218, 214 and 210 are alpha particle emitters, alpha particles, when inspired, can potentially cause physical cellular damage.

Two thirds of the total effective radiation dose to the average humans from all natural sources comes from radon and its progeny. Radon in homes is more concentrated and far more dangerous than outdoors. The National Academy of Sciences estimates that the outdoor radon causes only 800 out of the total of 21,000 lung cancer deaths in the US each year. But radon decay products, radioactive solid particles, much smaller than household dust, float in the air and get trapped in our lungs, trachea, and bronchi. At 4 pCi/L each liter of air contains 70,000 radon atoms. But less than 1% of the inhaled atoms get trapped and we thus accumulate in our airways about 600,000 radioactive particles every hour. They shoot out alpha particles that can pose severe health risk to the people.

The present paper estimates the status and advances in the Radon studies and Estimation procedures, Hydrological applications, possible health risk besides its occurrence as a case study from Bangalore city.

Research in radon

National status

Extensive studies have been conducted on the hydrological behavior and radiological significance of Radon and Radium world over. Radium, radon and thoron are important radionuclides in the uranium and thorium decay series. (Birchard and Libby, 1980; Hermansson et al. 1991) and Sengupta *et al.* (2001) documented radon variation in air to be as low as $2.3 \text{ Bqm}^{-2} \text{ h}^{-1}$ in the vicinity of a shallow, low grade Uranium deposit at Narwapahar to a high of $9.9 \text{ Bqm}^{-2} \text{ h}^{-1}$ close to Jaduguda in Jharkhand India. Several reports on the presence of dissolved radon in groundwater from northern India are also available (Vivek *et al.* 2002).

The study conducted by the Sridhar Babu. *et al.*, 2008 in pockets of Kolar district of Karnataka, the groundwater uranium concentration spanned between 0.3 and $1442.9 \mu\text{g/L}$. According to the World Health Organization 30 ppb is the permissible limit for uranium in drinking water. Computing to this prescribed level, 21.8% samples exceeded the permissible limits. The Uranium concentration in the drinking water samples of Chikmagalur, Karnataka, has been reported to vary from 0.2 to $27.9 \mu\text{g/L}$ (ppb).

Radon concentrations in soil, air and groundwater in Bhilangana Valley, Garhwal Himalaya, by using an LR-115 plastic track detector and radon emanometer, showed measured radon concentrations to vary from 1 KBq/m^3 to 57 KBq/m^3 in soil, 5 Bq/l to 887 Bq/l in water and 95 Bq/m^3 to 208 Bq/m^3 in air. The recorded values are quite high due to associated uranium mineralization in the area. Radon concentration was also found to depend on the tectonic structure and geology of the area (Choubey, 1997).

The gamma radiation level due to the radiological isotopes were checked in the dwelling using a gamma survey meter (Khokhar; 2007) and reported annual average indoor radon concentration in air inside the dwellings varied from 9.91 to 87.84 Bq m^{-3} with overall mean value of 26.48 Bq/m^3 . It was also observed that the radon concentration is relatively higher in the houses where the floor is bare but relatively lower in the tiled or cemented floor.

Relatively higher concentrations of radon (25–92 Bq/l) were reported by Choubey *et al.*, (2003) for groundwater from Quaternary alluvial gravels associated with uranium-rich sediments in the Doon Valley of the outer Himalayas.

The radon concentration recorded in natural Springs of Uttarkhand, West Bengal, Sikkim, and Bhutan, the lowest and highest concentration recorded is 0.1 and 441.2 Bq/l (Swastik Burtu village near Gangtok, Sikkim) respectively. Due to high radon concentration in natural springs, the residents in the city and villages around Gangtok are likely to be exposed to radiation hazards following Consumption of potable spring water (Virk, 2002).

It is well established that some areas of Himachal Pradesh situated in the environs of Himalayan Mountains are relatively rich in uranium-bearing minerals. Some earlier studies have indicated high levels of radon in the dwellings of these zones. An indoor Radon/Thoron survey has been carried out in some villages of four districts in the state of H.P. This survey has been conducted using twin chamber dosimeter cups. The indoor radon levels have been found to be varying from 17.4 Bq/m^3 to 140.3 Bq/m^3 , whereas indoor Thoron levels varied from 5.2 Bq/m^3 to 131.9 Bq/m^3 . The yearly average dose rate for the local population varied

from 0.03 $\mu\text{Sv/h}$ to 0.83 $\mu\text{Sv/h}$. The annual exposure dose to inhabitants in these dwellings lies below the upper limit of 10 mSv (WHO).

Generally, radon concentration have been found to be higher in thermal springs at Kasol with highest value of 792.0 ± 9.0 Bq/l. Radon concentration in the soil-gas has been found to be vary from 1.024 ± 0.27 KBq/m³ to 75.4 ± 2.62 KBq/m³ (Vivek et al., 2000).

Virk *et al.*, (2000) also monitored Radon at Palampur and Dallhousie stations in Kangra and Champa valleys using emanometry for discrete measurement of time series radon data since 1992 under Himalayan seismicity programs of Government of India. The radon data was correlated with micro earthquakes recorded by Indian Meteorological department (IMD) network during 1992- 1997. Radon concentration in Kangra and Champa Valley of N-W Himalayan also suggest that the temperature, rainfall and humidity have positively correlated, whereas wind velocity exhibited negative correlation with radon. Virk *et al.*, (2001) found concentrations of radon in groundwater from tube wells in Bathinda and Gurdaspur districts of Punjab, India in the range 3.0–8.8 Bq/l.

International Status

Lico and Rowee (1991) studied the areal distribution and characteristics of ²²²Rn in the groundwater from the Aquifers of Carson Valley, Nevada USA, to determine the sources of ²²²Rn. Groundwater ²²²Rn concentrations ranged from less than 4 to 400 Bq/l with a median concentration of 18Bq/l. The largest ²²²Rn concentrations were present in the groundwater confined to alluvial deposits on the western side of Carson valley. These large concentrations were attributed to large amount of ²³⁸U present in granitic rocks in the Carson Range (2.9 to 10.1 mg Kg⁻¹). The second factor could be direct flow into the alluvial aquifer from subsurface fractures in the underlying granitic bedrock, rich in dissolved ²²²Rn. A third factor was the gradients that existed along the western side of the valley. At the edge of the valley, the bedrock was closer to the surface. A thinner alluvial at this point caused less dilution of the ²²²Rn coming from the granite. Water quality indicates that the granitic rocks of the Carson Range are the major source of the ²²²Rn in groundwater from the western side of the valley as evidenced by increased inverse relationship of specific conductance and dissolved ²²²Rn concentrations.

Water samples collected in 1995 from 57 monitoring wells (48 shallow and 9 deep) in the fluvial aquifers of the White River Basin were analyzed for radon. Radon concentrations in the shallow wells ranged from 140 to 1,600 pCi/L (picocuries per liter); the median concentration was 420 pCi/L. In comparison, analyses of the samples from the nine deep wells indicated that radon concentrations decrease with depth within the fluvial aquifers; the median concentration was 210 pCi/L. (Joseph and Rhett; 1998).

In the Chickies quartzite of southern Pennsylvania, USA, (Cecil *et al.*, (1991) measured ²²²Rn concentrations ranging from 3.2 to 907 Bq/l and ²²⁶Ra concentrations ranged from less than 0.004 to 4.44 Bq/l in water samples from 103 wells.

Szabo and Zapeza (1991) studied geologic and geochemical factors that controlled radionuclide concentrations in groundwater in the Newark basin, New Jersey, USA. Analysis of 30 groundwater samples showed ²²²Rn concentrations ranging from less than 3 to almost 600 Bq/l, with median concentration of 51.4 Bq/l. Eighty seven percent had concentration greater than 400 Bq/l and were located in three different geologic formations in which

elevated gross alpha particle radioactive series in the water existed. At concentrations less than 400 Bq/l dissolved ^{222}Rn did not correlate with dissolved gross alpha particles or with concentrations of ^{238}U .

The concentrations of both ^{238}U and ^{226}Ra varied with changes in groundwater chemistry, but those of ^{222}Rn did not. Thus, the dissolved concentrations of ^{222}Rn was not controlled by the geochemical composition of the groundwater, but by the ^{238}U and the ^{226}Ra content of the rock and the physical characteristics of the aquifers (Szabo and Rhett, 1998). This is contrary to the report by Torgersen *et al.*, (1992) who opined that the large variability of ^{222}Rn concentrations in groundwater is independent of dissolved ^{226}Ra concentrations, supporting the idea that controls on ^{222}Rn concentrations in a given aquifer are dependent on local aquifer characteristics.

Again in a study of the Kirkwood- Cohansy system in southern New Jersey by Kozin Ki *et al.* (1995) showed that the aquifer materials were the source of the dissolved ^{222}Rn . The majority of the wells (53) contained ^{222}Rn concentrations between 7 and 70 Bq/l with median of 10 Bq/l. Concentration of ^{222}Rn were approximately two orders of magnitude greater than the concentrations of ^{226}Ra in the groundwater samples, indicating that the source of the dissolved ^{222}Rn was not dissolved ^{226}Ra within this aquifer system and the data correlated to the depth and the chemical composition of the water samples. In contrast, the concentration of dissolved ^{222}Rn correlated to the radioactivity of the aquifer sediment adjacent to the well screen, as determined by gamma ray logging.

Recently proposed water quality regulations for ^{222}Rn in ground water is a maximum contaminant level (MCL) of 11.1 kBq m⁻³; 300 pCiL⁻¹ (EPA, 1991)

Sampling and analysis for ^{222}Rn

^{222}Rn in Air: Radon-222 gas is measured by its activity or rate of decay in units called "curies" , One curie equals 3.7×10^7 radioactive disintegrations per second, One pico curie (pCi) equals 3.7×10^{-2} radioactive disintegrations per sec.

The radon concentration measurement techniques fall in either of grab sampling, continuous and active sampling, and integrative sampling. Grab sampling: consist of essentially instantaneous measurements of the radon or radon progeny concentration in air over time intervals that are short (on the order of minutes) compared to the time scale of fluctuations in concentration. The air is collected in a container and brought back to the laboratory for analysis. Typical containers include plastic containers, metal cans and glass containers. The volume of the containers are usually between 5 liters and 20 liters. Continuous sampling involves the automatic taking of measurements at closely spaced time intervals over a long period of time. The result is a series of measurements which can give information on the pattern with which the concentration varied throughout the measurement interval. Integrating Sampling involves integrating devices that collect information on the total number of radiation events which occur throughout some fairly long period of time, usually on the order of several days to months. The result from integrating devices is an estimate of the approximate average concentration in the environment.

Radon analysis in air involves both direct and indirect approaches. Several protocols are employed in the measurement of Indoor Radon Concentrations. Like Continuous Radon Monitors (CR), Alpha Track Detectors (AT or ATD), Activated Charcoal Adsorption Devices (AC), Charcoal Liquid Scintillation (LS) Devices, Grab Radon Sampling (GB, GC, GS),

Pump/Collapsible Bag Devices (PB), Three-Day Integrating Evacuated Scintillation Cells (SC), Unfiltered Track Detectors (UT), Indoor Radon Decay Product Measurement Device Protocols like Radon Progeny Integrating Sampling Units (RPISU or RP), etc.

Water sample and analysis

Concentrations in water typically is reported in disintegration per minute (dpm), picocurie per liter pCiL⁻¹) or Becquerel per liter (BqL⁻¹). One BqL⁻¹ is equal to 60dpm l⁻¹ or 27.03pCiL⁻¹.

Water for ²²²Rn analyses can be collected with the bubbler, liquid scintillation, or field screening methods. These three sampling and associated analytical technique are summarized here.

The liquid scintillation method uses direct liquid scintillation counting. The sampling vial, with 10ml of water sample and 5ml of a mineral oil based liquid scintillation solution, is shaken in the laboratory to mix fluids. This is followed by a wait of at least 3hours to allow measurement the short lived daughters of Radon (²¹⁴Po, ²¹⁸Po) to achieve secular equilibrium measurement of the radioactivity. The detection limit is about 0.04 BqL⁻¹ for 10 ml of sample.

Analyses of water sample in Bubbler method are by direct de emanations and alpha scintillation counting. The de emanation bubbler containing the samples is attached to de emanation system in the laboratory. The de-emanation system consists of following parts 1. Bubbler 2. A glass drying tube packed with anhydrous magnesium per chlorate to remove moisture and sodium hydroxide on asbestos plus soda lime to remove carbon dioxide. 3. A manometer to indicate the pressure inside the system during the transfer of ²²²Rn from the bubbler to the alpha scintillation cell. 4. An alpha scintillation cell, 5. Vacuum pump. The ²²²Rn is purged from the water sample with helium gas into the alpha scintillation cell. The radioactivity of ²²²Rn is determined by the alpha scintillation counter. The detection limit for 60ml sample is 0.01 BqL⁻¹.

The infield analytical instrument is an alpha scintillation meter that contains a phosphor coated cell. These cells should be airtight in order to quantitatively accept a small gas sample from the sample syringe. Such a system has been described by counter for 1 minute. Each analytical system is calibrated and gas extraction efficiency is compared with laboratory standard. For first order approximations of ²²²Rn concentrations, the temperature of the water can be ignored but it should be considered more accurate calculations. The detection limit is about 0.115 BqL⁻¹ for a 100ml gas sample that has been withdrawn from the water sample.

A Lucas cell technique, using a portable device contain 750 ml of water sample is taken in radon-tight reagent bottle of 1 litre capacity connected in a close circuit with a ZnS coated detection chamber through a hand operated rubber pump and a glass bulb containing CaCl₂ to absorb the moisture. Air is then circulated in close circuit for a period of ten minutes till the radon forms a uniform mixture with the air and the resulting alpha activity is recorded. The calibration factor, 1 count/min. = 0.11 Bq/l is used to convert the recorded alpha counts in Bq/l.

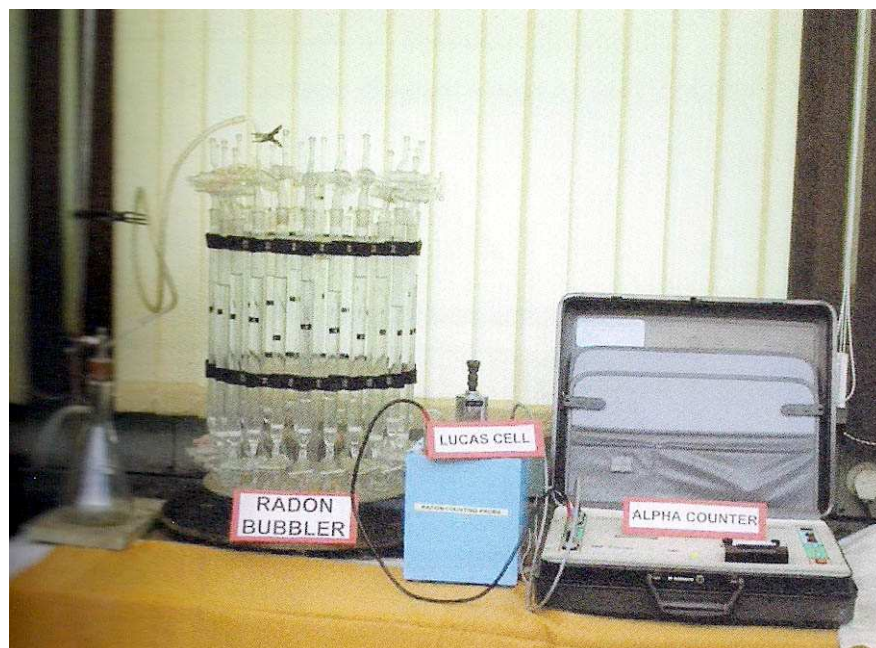


Fig1. A Lucas cell and associated counting device

Radon Monitor (RAD- 7)

The *in situ* field monitor system is similar to the system proposed by Brunett *et al.*, for the radon in air. The radon in the air is continuously pumped through a desiccant. The purpose of desiccant is to remove moisture. In this case the water sample collected in the 250 ml bottle establishes a closed air – water loop to aid the radon to strip in water. The diagrammatic presentation of radon detector is given in fig 1 and 1a and 2.

The RAD monitor uses a high electric field above a silicon semi conductor that detects the ground potential to attract the positively charged polonium daughters, $^{218}\text{Po}^+$ ($t_{1/2}=3.1$ min; alpha energy =6.00 MeV) and $^{214}\text{Po}^+$ ($t_{1/2}= 164$ μs ; alpha energy =7.67 MeV), which are counted as a measure of ^{222}Rn concentration in air. The ions are collected in energy specific windows which eliminate interference and maintain very low backgrounds. ^{222}Rn activities are expressed in Bq/m^3 (disintegration per second per m^3) with 2σ uncertainties. A specially fabricated aerating system is used to strip the radon in water. The system uses the bubbling air in closed loop. This radon gas after passing through the desiccant which will free from moisture is collect through the energy specific windows and counted for the radon concentration. The time elapsed for the sample collection and analysis will corrected with the following equation

$$C = C_0 e^{-\lambda t} \quad (1)$$

Where C= measured concentration, C_0 = initial concentration (to be calculate) after the decay correction, t= time elapsed since collection (days). This instrument is helpful in analysis radon in air and water.

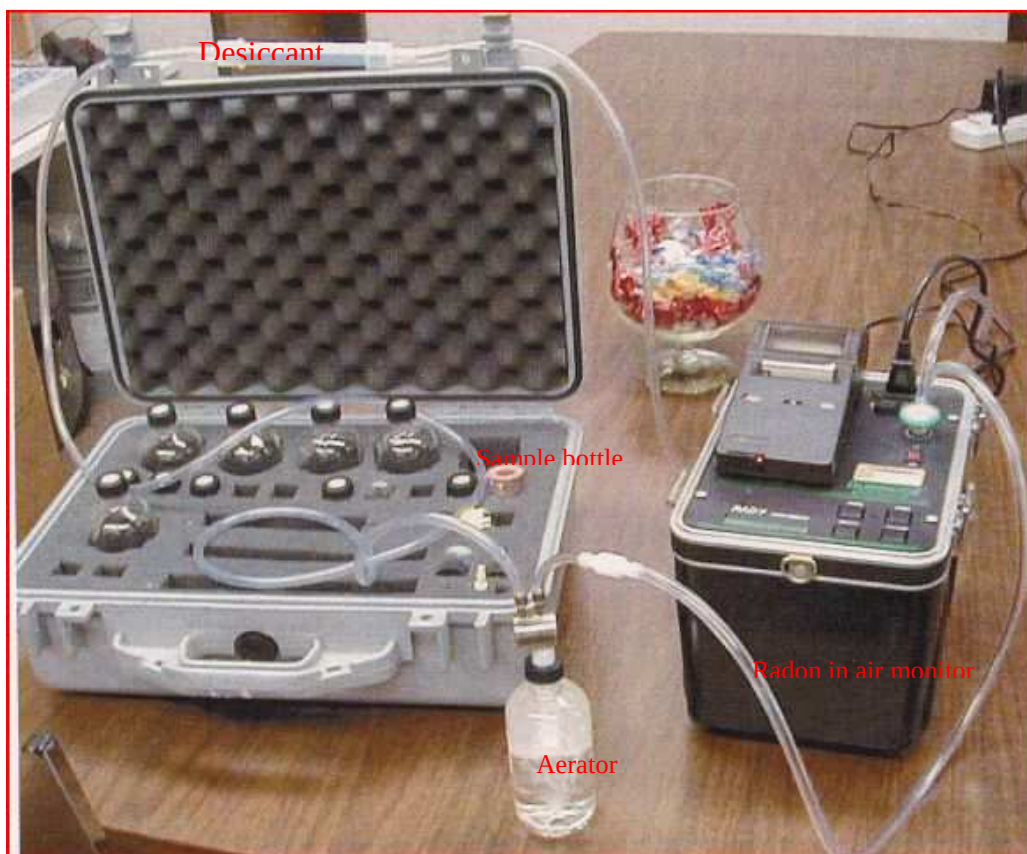


Fig. 1. Radon water monitoring system



Fig. 1a. The aerator of the monitoring system

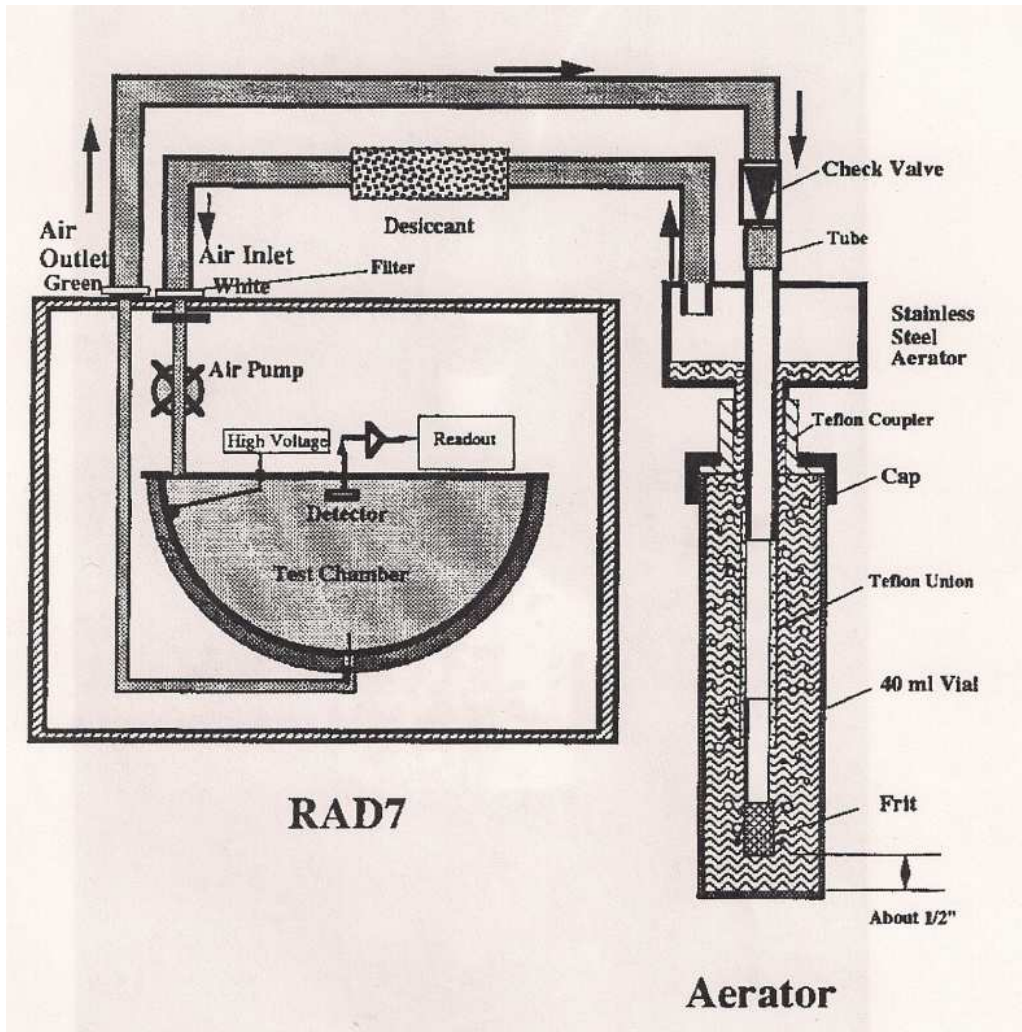


Fig. 2. Diagrammatic view of Radon monitor in water

The *in situ* field monitor system is similar to the system proposed by Brunett *et al.*, for the radon in air. The radon in the air is continuously pumped through a desiccant. The purpose of desiccant is to remove moisture. In this case the water sample collected in the 250 ml bottle establishes a closed air – water loop to aid the radon to strip in water. The diagrammatic presentation of radon detector is given in fig 1 and 1a and 2. The ions are collected in energy specific windows which eliminate interference and maintain very low backgrounds. ^{222}Rn activities are expressed in Bq/m^3 (disintegration per second per m^3) with 2σ uncertainties. A specially fabricated aerating system is used to air the water sample that free the radon in water. This radon gas is collected through the energy specific windows and counted for the radon concentration. The time elapsed for the sample collection and analysis is corrected with the following equation

$$C = C_0 e^{-\lambda t} \quad (1)$$

Where C = measured concentration, C_0 = initial concentration (to be calculate) after the decay correction, t = time elapsed since collection (days). This instrument is helpful in the analysis radon in air and water.

Health risk

An Internationally prescribed radioactivity exposure limit is one msv/year. Radiological effects owing to ingestion of dissolved radon in drinking water are defined in terms of effective radiation dose received by the population during habitual consumption of water. The annual effective dose to an individual consumer due to intake of radon from drinking water is evaluated using the relationship (Alam *et al*, 1999)

$$DW = CwCRwDcw \quad (2)$$

Where Dw is the annual effective dose ($Sv y^{-1}$) due to ingestion of radionuclide from the consumption of water, Cw is the concentration of ^{222}Rn in the ingested drinking water ($Bq l^{-1}$), CRw is the annual intake of drinking water ($l y^{-1}$) and Dcw is the ingested dose conversion factor for ^{222}Rn ($Sv Bq^{-1}$). For calculation of effective dose, a dose conversion factor of $5 \times 10^{-9} Sv Bq^{-1}$ suggested by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) is used. Annual effective dose due to intake of ^{222}Rn from drinking water is calculated considering that an adult (Age > 18 y), on average, takes 730 L water annually (Cevik *et al*, 2006). Following ingestion of ^{222}Rn dissolved in drinking water, mean effective doses per liter ($nSv l^{-1}$) and annual effective doses ($\mu Sv y^{-1}$) are calculated.

In assessing the dose from radon ingestion, it is important that water processing technology that can remove radon be considered before consumption is taken into account. Moreover, the use of radon-containing groundwater supplies not treated for radon removal (usually by aeration) for general domestic purposes will increase the levels of radon in the indoor air, thus increasing the dose from indoor inhalation. UNSCER (2000) reported the “average doses from radon in drinking water to be as low as 0.025mSv/year via inhalation and 0.002mSv/year from ingestion” compared with the inhalation dose of 1.1mSv/year from radon and its decay products in air.

A study conducted in USA estimates that 12% of lung cancer deaths (Grans, 1985) are linked to radon (radon-222 and its short-lived decay products) in indoor air. Erlandsson *et al*. (2001) estimated approximately 100 fold smaller risk from exposure to radon in drinking-water. The recent work assessed that the risk of stomach cancer caused by drinking-water containing dissolved radon is extremely small compared to lung cancer in the cold countries.

Indoor air concentrations vary with underlying or surrounding rock or soil type, occupational radon levels are highest for miners (uranium, iron and fluorospar) , residential radon levels are highest in basements and ground floor rooms, building type, construction, level of repair and ventilation effect levels , average radon level in homes is about 1.25 pCi/L. Radon remediation recommended at residential levels above 4.0 pCi/L. Indoor radon is a significant health hazard (3 - 32,00 lung cancer deaths/ year). Exposure through inhalation virtually occurs in all humans through the respiratory system and ingestion provides for minimal exposure. The delivered human dose from radon exposure cannot be measured directly and radon exposure assessment is modeled beginning with measured air concentration

Potential Dose of Radon-222 decay products are the radon concentration in air and duration of exposure. The potential dose is affected by respiratory rate, lung tidal volume and bronchial

morphology as well as aerosol characteristics. A high percent of airborne radon decay products attach to ambient aerosols. The quantity, size and density of airborne particles affect deposition in respiratory tract, intake rate of media (air) is approximately 0.5 L/Min or 20 m³/day

Internal (Absorbed) dose of Radon-222 decay products are the potential dose multiple with absorption factor. Absorption factor is affected by mucous thickness and clearance rate. Radiation absorbed dose is defined as energy deposited per unit mass of tissue, and is expressed in "rads" or "greys" (Gy) (1 rad = 100 ergs/gram, 1 Gy = 100 rads). The absorbed dose is modified by a qualitative factor related to linear energy transfer and the modified absorbed dose is measured in "rems" (roentgen equivalent man). The average effective dose equivalent exposure of ionizing radiation from all sources to the US population is estimated at 300 mrem / year, radon decay products account for 200 mrem / year of this total solid radon-222 decay products (primarily polonium 218 and 214) ratio of solid radon-222 progeny to radon-222 gas in air is 0.2 - 0.8, solid radon-222 progeny deliver the actual radiation dose to lung tissue. The radiation dose of radon-222 decay products is expressed as "working levels" (WL's). One WL equals a combination of radon decay products which releases 1.3×10^5 MeV of potential alpha energy (equivalent to the decay of 100 pCi/L of radon-222). The cumulative exposure is expressed in WLM (working level months) for exposure to one WL for one working month (170 hours). The risk to the average person of dying of radon-caused lung cancer due to a lifetime exposure to 4 pCi/L radon level at home is 2.3 percent. Radon concentrations in soil gas depends on the concentration of the immediate precursor of Rn-222, Ra-226, in rocks and soils. Rn-222 is the most important source of natural radiation and is responsible for approximately half of the received dose from all the sources. Most of this dose is from inhalation of the Rn-222 progeny, especially in closed atmospheres.

Hydrological applications of radon

²²²Rn occurs naturally in all groundwater systems the concentrations have been used for range of applications. These concentrations may vary considerably between aquifers depending on lithology and geologic structure. Radon concentrations in stream water are usually several orders of magnitude lower than concentrations in groundwater. Radon is easy to sample and analyze. The great potential lies in the study of rapid mixing processes occurring on time scales from hours to days. Over short time scales, increase in radon concentration has been related to aquifer residence time, and used to measure infiltration rates. Comparisons between radon concentrations in groundwater with those in surface waters receiving aquifer discharge have enabled locations groundwater discharge to be identified, and determination of discharge rate. Recently Radon concentration has been used to infer flow rates through fracture rock aquifer and as portioning tracer in the contaminated studies.

The short half life of ²²²Rn limits its applications in most regional flow systems, where residence times exceed a few weeks. The large variability of ²²²Rn concentrations in groundwater, independent of dissolved ²²⁶Ra concentrations, further supports the idea that controls on ²²²Rn concentrations in a given aquifer are dependent on local aquifer characteristics (Krishnaswamy *et al.*, 1982).

²²²Rn is a radioactive noble gas. It is produced from ²²⁶Ra in the radioactive decay. When rainfall or surface water infiltrate into rock or soil, the concentration of ²²²Rn in the groundwater increases due to radioactive decay of ²²⁶Ra in soil or rock. After the rainfall or the surface water infiltrate into rock or soil, about 3 weeks later, the rate of ²²²Rn supply by

radioactive decay of ^{226}Ra will be in a state of balance. At this time, the concentration of ^{222}Rn in the groundwater reaches a stable state. Therefore, the concentration of ^{222}Rn in groundwater is much higher than surface water. The present study shows that based on the knowledge of radon concentration distribution in groundwater and surface water, groundwater discharge points to the surface water can be confirmed. By calculating quantitatively the mass balance equation of ^{222}Rn , the fraction of groundwater discharged to surface water can be assessed. ^{222}Rn in surface flow comes from riverbed sediment or is recharged by groundwater; however, ^{222}Rn in the riverbed sediment is very scarce and can be omitted. Groundwater is the only source of ^{222}Rn in the surface flow. ^{222}Rn diffuses into the river, transfers to the atmosphere due to radioactive decay and gas exchange.

Groundwater dating with the ^{222}Rn

Over short timescales ^{222}Rn can be used to determine the groundwater residences time. Since ^{222}Rn is chemically inert, chemical reactions do not limit the ^{222}Rn input into solution. The growth curve of ^{222}Rn in solution can therefore be used to estimate an apparent age of groundwater. To arrive at an apparent age, the hypothetical steady state ^{222}Rn concentration of water must first be determined. The computation can be done with the following equation

$$^{222}\text{Rn} = 12.38 A\rho U/\phi \text{ Bq/l}^{-1} \quad (3)$$

Where A is the fraction of ^{222}Rn that is generated in the rock that migrates to the groundwater (emanation coefficient), U is the ^{238}U concentration in rock matrix in ppm, ϕ fractional porosity of the rock (unit less)and ρ is bulk density of the rock(g cm^{-3}). Values for the U, ϕ and ρ can be measured for a given rock, but the value of A is difficult to ascertain. If the concentration of dissolved ^{222}Rn is measured instead, then A can be calculated to help understand how ^{222}Rn migrates through the rock. A small value of A indicates that the parent nuclides are tightly bound in mineral phases whereas a value of close unity indicates large degree of ^{222}Rn migration. A high emanation coefficient indicates that the rock has an open texture or that the parent nuclides are present mainly as coatings on the mineral grains or on fracture surfaces. Studies have shown that coarse grained granites may have the emanation factor near to unity. A laboratory study through the sandbox at a constant flow determined the ingrowths ^{222}Rn in a flowing system of water describes radioactive decay equation

$$A_1 + A_e [1 - \exp (-\lambda t)] \quad (4)$$

Where A_t and A_e are radio activities of ^{222}Rn at time t and steady state respectively, and λ is the decay constant of ^{222}Rn . The radon tracing method could possibly apply to aquifers composed of sandy material with inhomogeneous production of ^{222}Rn and flow velocities ≥ 0.2 m/day.

Radon-222 can also be used in conjunction with other tracer like ^4He to determine the apparent age of groundwater. The ^{222}Rn concentration in groundwater is mostly dependent upon the ^{226}Ra content of the rock matrix. On the other hand, the ^4He concentration is direct result of maximum thorium concentration in rock as well as the age of the water. The ratio of ^4He to ^{222}Rn can indicate changes in parent nuclide concentrations as well as in apparent age of the water. The problem in relating the concentration of these inert gases to the apparent age of the water is that an increase in the ^4He : ^{222}Rn ratio might indicate escape of crystal ^4He , or sites where localized diffusion occurs; neither is related to apparent age of the water. Therefore, Changes in ^{222}Rn as a result of variation in ^{238}U and thorium concentration must be eliminated, and fluctuations in the rates at which ^4He and ^{222}Rn escape into the must be taken

to account. The enhancement of ^4He concentrations from the crystal diffusion unusually results in apparent ages that are too young.

Surface water infiltration

^{222}Rn is a natural tracer in river studies. It is documented that in freshly infiltrated groundwater, ^{222}Rn increases with increasing flow distances. Thus the measurement of ^{222}Rn allows the dating of in filtering water to groundwater.

The studies using the ^{222}Rn in alluvial aquifers established that continuous pumping of groundwater causes the river to recharge the aquifer. The distribution of ^{226}Ra in the aquifer and ^{222}Rn losses to the unsaturated zone however was constant with time. Ground water concentrations of dissolved ^{222}Rn increased with distance of the river until a steady state is achieved, at which the point the rate of ^{222}Rn loss from the solution by reactive decay remained balanced by the rate of its input. Therefore, the steady state concentration of ^{222}Rn with respect to conductivity and chloride concentration and the fraction of water coming from river is a function of distance from the river. Despite the mixing of groundwater, away from the river, it is possible to trace the infiltration of river water into the aquifer besides calculating residence time and also estimate the flow velocity of the groundwater.

Groundwater discharge

Radon can also used as a tracer of groundwater discharge to streams and other surface water bodies. The concentration of ^{222}Rn in stream flow is measured to determine the location and magnitude of groundwater seepage. A mass balance approach is used to determine the relation between groundwater and surface water flows for a given reach of stream.

$$Q_s \times A_s + Q_{gw} \times A_{gw} = Q_m \times A_m \quad (5)$$

Where Q_s is the rate of stream flow, A_s is the concentration of ^{222}Rn stream flow at an upstream point, Q_{gw} is the rate of groundwater seepage, A_{gw} is the concentration of ^{222}Rn in groundwater, Q_m is the rate of mixed stream flow and groundwater flow downstream and A_m is the concentration of ^{222}Rn in the mixed water downstream. $Q_s + Q_{gw} = Q_m$ This equation incorporate the rate of stream flow and the rate of groundwater seepage. The ratio of groundwater seepage to the total stream flow at the measured point can be determined using equation.

$$Q_{gw}/Q_m = (A_m - A_s) / (A_{gw} - A_s) \quad (6)$$

The regional maps of radon in surface waters could be used to delineate the major geological structures. Such information is best contoured using the exclusion isolines constructed in a way that they enclose all data points that have concentrations equal to or greater than the concentration of isolines in an area. The high concentration is the indication of ^{222}Rn concentration in groundwater while lower factor may be due to the others, including the turbulent degassing of surface water.

Radon transport in the fractured rock

Aquifers that are composed of fractured crystalline rock can have dissolved ^{222}Rn concentration greater than those expected, based on aquifer mineralogy, when the ^{238}U and ^{226}Ra content of the bedrock concentrated along fracture walls. ^{238}U and ^{226}Ra commonly migrated to sites along fracture surface that are close to rock water interfaces. The migration of ^{238}U and ^{226}Ra enhanced the dissolved ^{222}Rn concentrations in groundwater. A study measured ^{222}Rn emanations rate from fracture surface in Stripe granite to be $1100 \text{ atoms S}^{-1}\text{m}^{-2}$. Comparison of this value with ^{222}Rn concentration measured in mine waters and shallow groundwater allowed estimation of fracture apertures. A fractured granite aquifer aperture affects the ^{222}Rn concentrations. Radon-222 varied by a factor of seven and transmissivity varied by four orders of magnitude within a single rock type. The different hydraulic apertures of water bearing fractures yielded large variations in ^{222}Rn concentrations measured in wells.

The lithologic controls of groundwater and ^{222}Rn concentrations in fractured rock media experimented with 150 samples of groundwater from the wells established primary controls of ^{222}Rn in pore fluid among rock type as the ^{238}U concentrations of the host rock, variations of ^{222}Rn concentrations within the pore fluid in each individual rock unit is controlled by other geologic factors such as the fracture surface area per unit volume of pore fluid and fracture width the fraction. The ^{222}Rn concentration of the single well experiment showed cone of depression is depended and extracted groundwater from the smaller fractures. Another studies found ^{222}Rn concentration increased with the fracture length. Also found the ^{222}Rn concentration independent of the pumping rate and of the hydrodynamic dispersion process.

^{222}Rn in contamination studies

As portioning tracer to determine the amount of non aqueous phase liquid in contaminated aquifers a laboratory found ^{222}Rn as tracer to detect and quantify the amount of diesel fuel in quartz sands. ^{222}Rn concentrations measured at different saturations indicated that saturation increases due to portioning the emanated radon into the organic liquid. The ^{222}Rn concentration decreased by 40 percent when it passed into an area contaminated with diesel fuel. When the water was passed through the contaminated area, the concentration of ^{222}Rn returned to its steady state value. The contamination present was estimated to be 1.5 ± 0.35 per cent which actually represented 1.9 percent of diesel fuel saturation (Hunker *et al.* 1997).

Applications of natural ^{222}Rn hydrological investigations include delineation of groundwater recharge, determination of groundwater flow paths, groundwater and surface water interactions and determining the groundwater apparent ages over short timescales. The short half life of ^{222}Rn limits its applications in most regional flow systems, where residence times exceeds a few weeks. In some cases steady state concentration may be difficult to determine because of local heterogeneity. Thus even short flow path, differentiating between non stay state and steady state concentrations although necessary are difficult to perform.

Occurrence of ^{222}Rn in Bangalore city

Bangalore is one of the fastest growing cities in India with a current estimated population of more than 8.0 million people, spread over an area of about more than 800 Sq.km. and, is situated at an altitude of about 895 m. above MSL. Geologically the area is composed of Younger Granites and Precambrian Gneisses (Fig 3). Water flow is aided through the fractures in the crystalline aquifers. Samples were collected in the sample survey from the Air, Soil, Groundwater (shallow wells and bore wells), surface water and corporation drinking water.

The radon concentrations were measured using the instrument RAD-7, supplied by DurrIDGE Company, USA.

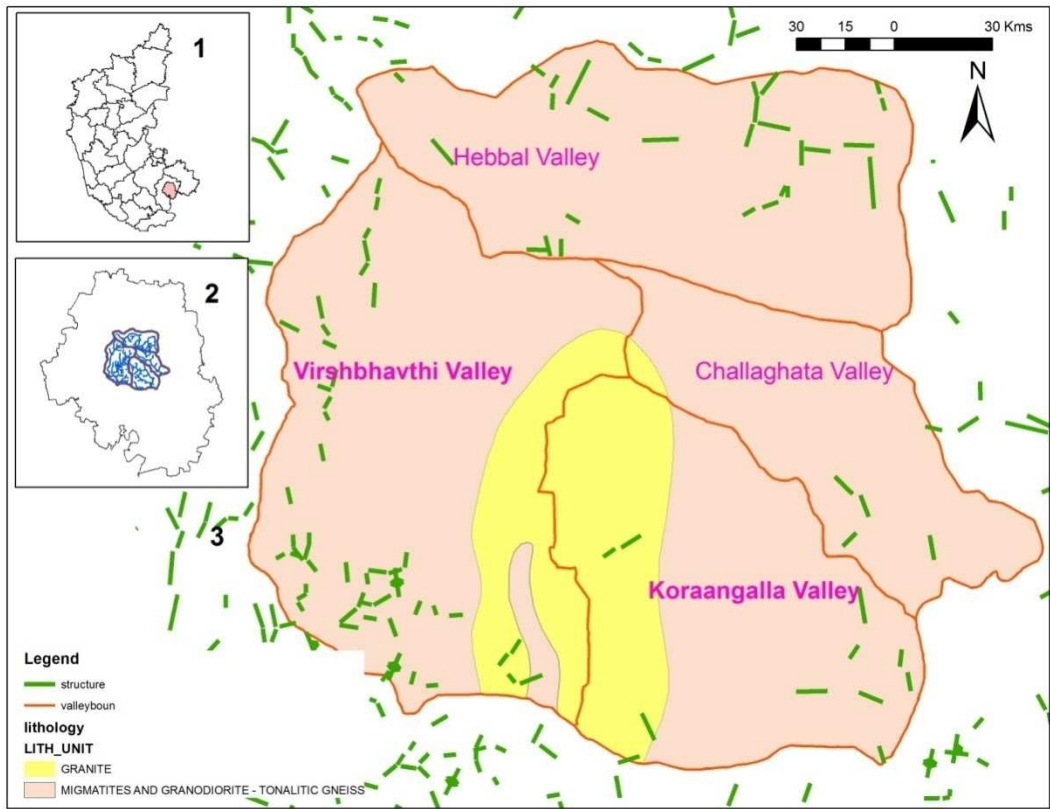


Fig. 3. Lithology and Lineaments in the Bangalore city and adjacent areas

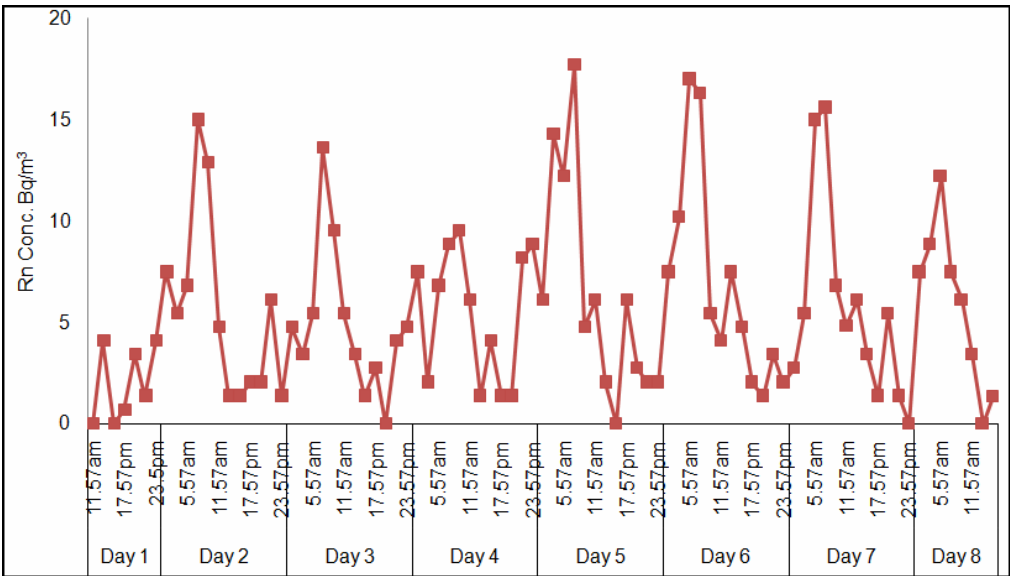


Fig. 4. Rn concentration in air vs Time (weekly)

Outdoor air

The concentration of radon in outdoor was measured through experiments for a day and for a week in the first quarter of April. The experiments are conducted near the Department of Environmental Science, Bangalore University, Jnanabharathi campus, Bangalore. The average outdoor radon concentration is found to be 12.6 Bq/m^3 . The average radon concentration for a week was 5.28 Bq/m^3 (0.142 pci/m^3) per day which is very low compared to the EPA permissible level of 3.7 Bq/m^3 - 14.8 Bq/m^3 and WHO (5 Bq/m^3 and 15 Bq/m^3). The highest value were observed in the mornings and late evenings and lowest during evenings between 3 to 7 pm. Diurnal temperature inversion affects the concentration of radon in the mornings and late nights (Fig.4)

Surface water

Radon in the lake waters of Bangalore city was measured. The highest average concentration was 1.45 Bq/l in Sanky tank while lowest was found in the 0.213 Bq/l in Venkipuram Lake (Fig 5). The overall concentration of radon in the surface waters of Bangalore city is found to be far below the permissible limits. The highest value of Sanky tank indicates the presence of ground water discharge.

Soil

Radon in soil gives an estimate of its distribution in soil. The values ranged between 7670 Bq/m^3 to 9900 Bq/m^3 with a average of 8710 Bq/m^3 (Fig. 6). The radon soil equilibrium was recorded after an hour of the experiment. The wide scale fluctuation can be correlated to the minor trimmers in the earth crust.

Ground water

Radon was measured in 55 samples of ground water collected all over the central core of Bangalore city Radon concentration in the wells varied from 55.96 Bq/l to 1000 Bq/l with an average mean value of 377.448 Bq/l . The open well had the lower concentration than the bore wells. The concentration of radon in the deeper bore wells in Bangalore city is higher, may be due to the presence younger granites and the weaker structures like fractures and liniments. The contour analysis of radon concentration in the bore well waters indicates the background distribution as 200 Bq/L (Fig 7). Higher concentrations were found in some part of the Chikpet and Hebbal which might be due to change in geological regime or exposure of younger granitic rocks associated with high abstraction of ground water. The results of the radon survey vs. the depth confirmed that (Fig.8) radon activity is a function of depth, with higher activities at deeper depths, with some exceptions. Thus, the population of Bangalore City at some locations vulnerable to the health risk because of the higher activities of radon in the drinking water.

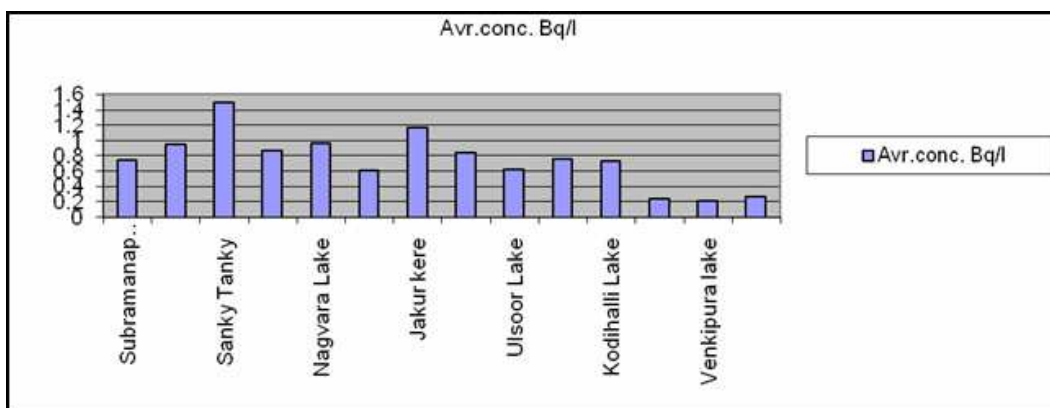


Fig 5. Average Radon concentration in lakes

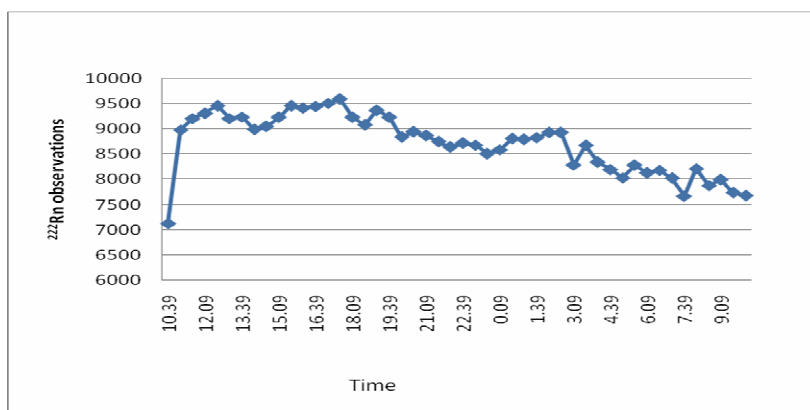


Fig. 6. Radon levels in the Soil

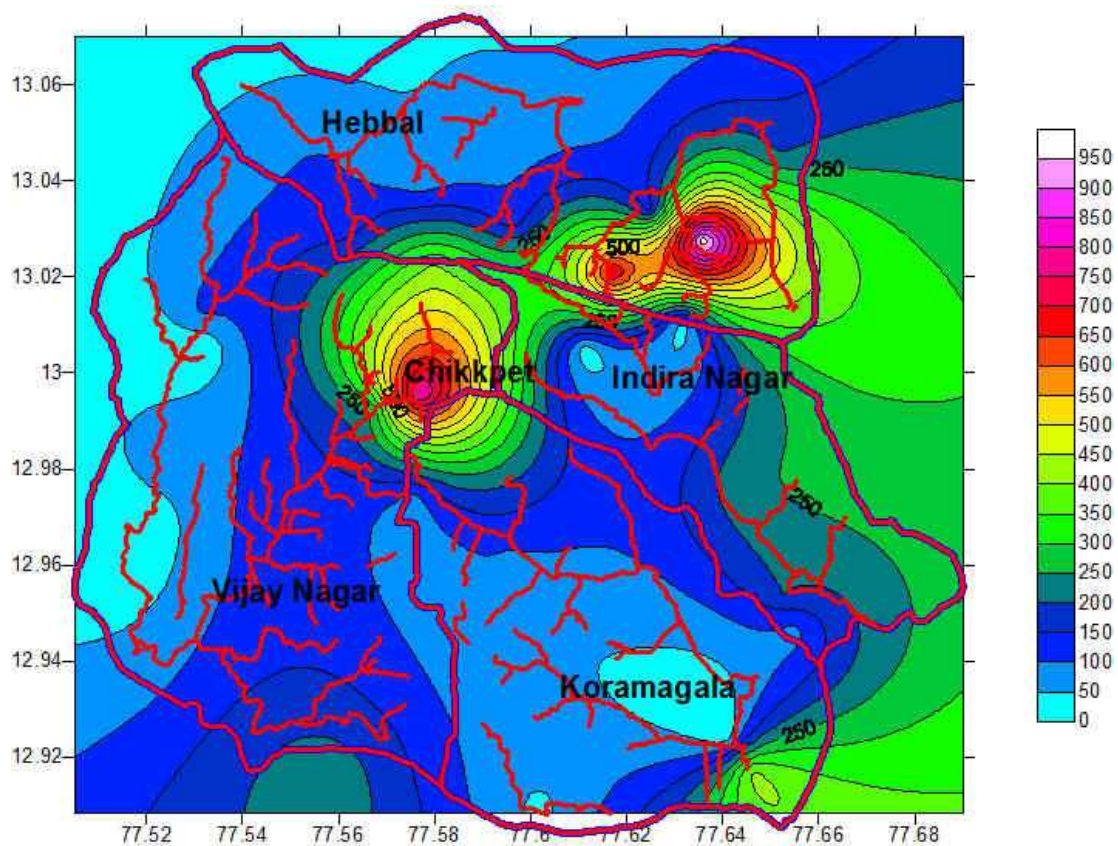


Fig. 7. Spatial distribution of Radon in the bore well waters

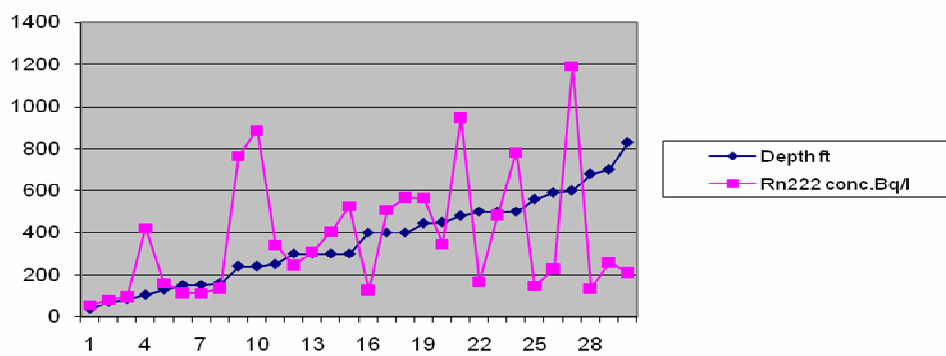


Fig. 8. Radon in bore well waters Vs. total depth

The effective dose per liter and annual effective dose values varied with increase in radon concentration. The effective dose was $1846.9(\text{nSv}^{-1})$ with annual concentration of $1385.2(\mu\text{Sv}^{-1})$. The consumers at locations having greater depth are likely to be exposed to higher radon.

Conclusions

As the climate changes in rapid phase, with the other challenges, the radioactive decay from the nature also carries utmost importance in the present world. Terrestrial radiation together with natural radioactivity and associated health risk therefore assumes great importance in the coming years. Radon is the prominent element that account for 53% natural radiation over the world. Nonetheless, the beneficial use of the radon as natural tracer also carries significant importance in the present day context particularly to understand the regional hydrological regime.

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