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Norms and Associated Health Hazard in Himalayan Water System: A Review

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***Abstract*— *Water is the most important element in our environment. Radionuclides such as Uranium and Radon are soluble in water and can pose a significant health hazard. This review provides a comprehensive analysis of the source, occurrence, impact on inhabitants and affecting factors in Uttarakhand state. As Uttarakhand is a water-rich region known for its abundant rivers, springs and groundwater, monitoring of radionuclide contamination is very crucial from a public health and environmental point of view. Districts Bageshwar and Pauri show the maximum uranium content, and Tehri and Rudraprayag show the maximum concentration of radon in water. Mainly, Geology is the main factor in Uttarakhand for uranium and radon anomalies. The result depicts that there is no significant health risk in Uttarakhand state. All dose rates from the uranium and radon are less than the recommended limit prescribed by UNSCEAR and WHO.*

I. INTRODUCTION

Radiation is a type of energy that is related to wave or particle movement. In our daily lives, we are constantly exposed to this radiation [1]. Various radiations have different properties: 1) Alpha radiations - the alpha particles are taken into the body by inhalation, ingestion or drinking, and they can produce biological effects on the body. 2) Beta radiation- Beta radiation is more penetrating than alpha particles, and it can penetrate easily into 1-2 cm of water. 3) Gamma rays- They are electromagnetic radiation. Uranium is a chemical element symbolized by U and with an atomic number of 92. Uranium is a silvery-grey metal. Uranium has several isotopes, but the isotope of choice in radioactivity and nuclear technology is Uranium-238. Processing and mining of uranium ore is the reason for the introduction of uranium into drinking water [2]. Consumption of uranium ore is the reason for the radiological effect on the kidney liver, and bone [3]. Uranium contains various isotopes. Some of the most prevalent among them include U-238, U-235 and U-234 [4].

Radiation in drinking water can originate from a number of sources, such as industrial processes, naturally occurring minerals in the crust of the earth, and radioactive material contamination [5]. Radium, uranium, and radon are the most frequently occurring radioactive elements in drinking water. From the uranium decay series, 2% of gamma comes from the uranium group, whereas the remaining 98% comes from the radium group [6]. Uranium's oxidation states vary from II to VI in the combined form. The reported divalent uranium compounds are uranium monofluoride and uranium disulfide. There are trivalent uranium compounds, such as hydrides, nitrides, sesquisulfides, halides and borohydrides [7].

Radon is an intermediate element of the Uranium decay series and is placed in the periodic table with the symbol Rn and atomic number 86. It is a colourless, odourless, noble gas and radioactive. Out of the three naturally occurring isotopes of radon, only radon-222 has a half-life long enough (3.82 days) to emanate out of the rock and soil in which it is generated [8]. The initial by-products of the decay of radium isotopes are radon isotopes. Its most stable isotope, radon-222, is not stable, so radon is one of the rarest elements. Though it has a short half-life, radon will remain on Earth for a few billion years because it is constantly being generated as a by-product of the decay of the thorium-232 and uranium-238, two extremely common radionuclides with half-lives of a few billion years. Many other short-lived nuclides, known as "radon daughters", are produced during radon decay and naturally yield stable isotopes [9]. Small amounts of radon-220 are generated as an intermediate step in the decay chain of thorium-232, or the thorium series, which ultimately decays into stable lead-208 [10].

Studies have shown that the second largest cause of Lung cancer is radon, and it was discovered that uranium mines with extremely high radon exposure were at high risk of lung cancer. Chinese, North American, and European studies have also shown that even low levels of radon, such as those occurring indoors, can still be harmful to human health and cause lung cancer globally. The possibility of internal radiation exposure is the main reason why drinking water radioactivity exposure might be harmful to one's health. Over time, eating radioactive materials can cause them to build up in the body and irradiate surrounding tissues, raising the risk of cancer. Depending on the kind and amount of radioactive materials present, drinking water radioactivity can have different health impacts. Limits on permissible levels of radioactivity in drinking water are imposed by regulatory bodies in order to safeguard public health. Filtration, ion exchange, and reverse osmosis are examples of water treatment techniques that can be used to lower radioactivity levels in drinking water [11].

Drinking water contains a low concentration of radon, although the radon emitted during water use contributes slightly to the radon concentration indoors [12]. Research revealed that there is little chance of stomach cancer and other gastrointestinal cancers from radon in drinking water. Research on the cytogenetic and genetic consequences of indoor radon has produced conflicting findings; nonetheless, radon exposure in miners causes chromosomal abnormalities and gene mutations. Several in vitro cytogenetic investigations have shown that radon causes a variety of genetic and cytogenetic damage, which may contribute to the development of radon lung cancer [13].

II. MATERIAL AND METHOD

2.1 Radon in Water

2.1.1 RnDuo

In determining radioactive elements in water, the term RnDuo means that the radon and radium pair is important. Because radium (Ra) and radon (Rn) isotopes are able to cause health hazards, the monitoring of water supplies is common. There are several techniques, such as liquid scintillation counting and alpha spectroscopy are utilized to detect and measure these isotopes in water samples. Sustaining public health and ensuring that water quality standards are met requires continual monitoring of such radioactive elements. In order to test radioactive material in an intelligent manner, the most significant steps to utilise smart RnDuo are sample collection, preparation, instrument set-up, analysis, interpretation and reporting. This instrument detects the emitted alpha particles from Rn-222 and Rn-220 based on the principle of scintillation counting with ZnS (Ag). The device can be used for both short as well as long-term measurements. A pump is attached to the device to take air for the liquid sample pump should be left ON for around 5 min before beginning the sampling [14,15]

2.1.2 RAD7

A commonly employed radon detector for measuring indoor radon gas concentrations is the RAD7. RAD7 is the versatile and advanced method for a complete examination of radon in air, water and soil. RAD7 (DURRIDGE, USA) was used in this study. RAD7 utilised a solid-state alpha particle detector with a silicon ion-implanted detector with a solid-state device. The radioisotope’s daughters form by characteristic radiation such as alpha, beta, and gamma decay. The alpha radiation Rn-222 and thoron were measured by the RAD7 and converted these alpha radiations into electrical signals. The instrument is most suitable for field applications, and it is supplied with a covered, robust carrying case for use in the field. The sample cell of 0.7 litre hemispherical volume in the RAD7. The hemisphere is lined on the inside thereof with an electrical conductor. The inside conductor is charged up to a potential of 2000-2500 V by the high voltage power circuit and makes the positively charged particles come to the detector. Rn-222 decays to the polonium-218 as the positively charged ion, and this short-lived polonium-218, after decay, on the active side of the detector, has a 50% probability of entering the detector and producing an electrical signal of a strength proportioned to the energy of the alpha particle. The signal in the detector is not uniform in strength since different isotopes do not give the same energy. The signal is amplified, filtered and arranged in strength by the instrument. The spectrum of this instrument can allow energies ranging from 0-10 MeV, as most of the decay products of radon and thoron produced alpha particles in the range of 6-9 MeV. The RAD7 operate in the following mode [16]

2.1.3 Uranium in Water

The presence of uranium in water, particularly in excess, may be a causative factor of health harm to human beings. Groundwater is contaminated by naturally occurring uranium in soil and rock [17]. Water contamination by uranium is also brought about by industrial processes like uranium mining and ore treatment. Because uranium is made up of radioactive components, exposure through the ingestion of consumed drinking water is capable of leading to health harm. Damage to the kidney, an increase in the risk of cancer development, and other health complications are linked to long-term uranium ingestion. The risk the radiation poses to the health of individuals is based on the amount of uranium in the water people are exposed to and the duration of exposure [18]. Because of the possible health hazard, uranium in water can be cancerous. Naturally or through man's actions like mining, uranium can find its way into water bodies. Ingestion of contaminated water with high uranium levels will result in some health complications like damage to the kidney as well as a high rate of chances of developing cancer [19].

2.1.4 Inductively Coupled Plasma Mass Spectrometry

Nowadays, one of the most quickly evolving tracer element techniques is inductively coupled plasma mass spectrometry (ICP-MS) [20]. Inductively Coupled Plasma Mass Spectrometry, or ICP-MS is a very effective analytical technique that unites the merits of mass spectrometry and plasma spectroscopy to detect and quantify trace elements and isotopes in different samples. The technique is founded on the introduction of a sample into an ICP torch, which atomizes, ionizes, and transforms it into a plasma state. The ions produced in the plasma are drawn and separated in the mass spectrometer according to their mass-to-charge ratio. Its advantages are low detection limits, high analysis speed, and the ability to analyze multiple isotopes. Scientists are employing ICP-MS for the analysis of U-238 in seawater increasingly since ICP-MS equipment became available [21].

2.1.5 Atomic Absorption Spectroscopy

Atomic Absorption Spectroscopy, abbreviated as AAS, is another intriguing technique for analyzing the elements present in a sample [22]. It quantifies the light absorbed by elements present in a sample by the transmission of light through it. The absorbed light quantifies the varying concentration levels of elements present in the sample. AAS is commonly applied in a laboratory to quantify metals in various materials, such as biological samples, environmental samples, and even food and drinks [23]. Because of its specificity and sensitivity, AAS (Atomic Absorption Spectroscopy) is one technique of uranium detection in water [24].

2.1.6 Assessment of Effective Dose

A useful method of estimating possible radiation exposure risk is effective dose assessment. In addition to the parts of the body that are exposed, it considers the nature of the radiation and the sensitivity of each body part to radiation. An effective dose is quantified in terms of a measurement called a sievert (Sv). For the protection of human beings from harmful doses of radiation, it is used to quantify the risk of health effects resulting from radiation exposure and in the establishment of safety standards [25].

The International Commission on Radiological Protection (ICRP) developed the effective dose as a risk-based hazard to human beings. It is the quantification of the radiation hazards of whole-body exposure to a non-uniform dose of radiation. The effective dose in radiation protection is a quantification that considers the varying radiation sensitivity levels of the body's tissues and organs [26]. Tissue weighting factors and radiation weighting factors are used in its calculation. The International Commission on Radiological Protection (ICRP) has established guidelines for the calculation of the effective dose. The dose absorbed in an organ or tissue times the radiation weighting factor is referred to as the organ equivalent dose. The ICRP offers the most common radiation and tissue weighting parameters in its publication, ICRP 103. These elements are required for accurately determining the effective dose.

III. RESULT AND DISCUSSION

2.2 Uranium and Radon in water

Table 1: Uranium and Radon concentrations in districts of Uttarakhand.

SN	Location	Uranium (ppb)			Radon (Bq/L)			Reference
		Min	Max	AM	Min	Max	AM	
1	**Tehri**	0.001	7.41	0.89	29.0	192.0	70	[27]
2	**Dehradun**	0.02	4.97	0.97	3.35	99.25	33.97	[28,29]
3	**Almora**	0.1	23.1	4.3				[30]
4	**Pithoragarh**	0.10	1.12	0.37	0.60	81.90	17.80	[31,15]
5	**Nainital**	0.10	27.40	4.40				[30]
6	**Chamoli**				2	47	11	[32]
7	**Champawat**	0.09	9.01	4.55				[31]
8	**Bageshwar**	0.10	28.40	14.25	3.40	101.30	34.80	[33]
9	**Haridwar**	0.35	27.53	7.14	0.36	2.64	1.5	[28,34]
10	**Uttarkashi**	0.01	21.57	2.86	1.11	183.86	19.67	[27,35]
11	**Rudraprayag**	0.001	6.03	0.71	1.7	400	67	[27,32]
12	**Pauri Garhwal**	0.01	67.45	5.78	0.43	0.73	0.68	[36]
13	**Udham Singh Nagar**	0.01	26.98	3.43				[37]

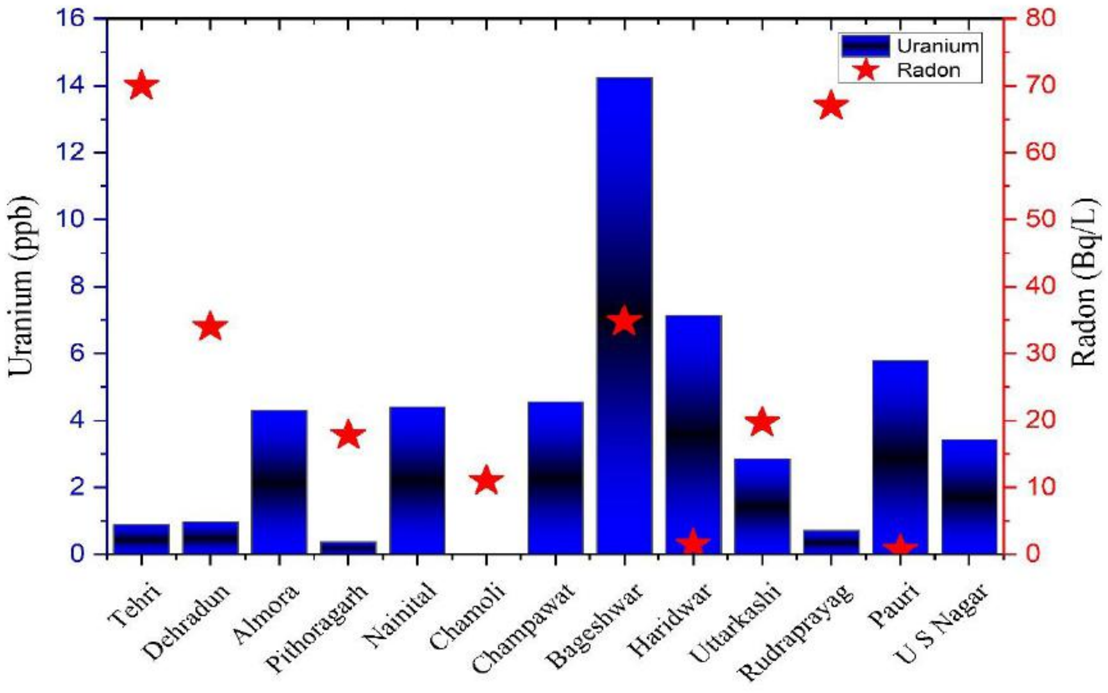

Fig 1. (A) Spatial Distribution of Uranium (B) Uranium and Radon levels in districts of Uttarakhand

The Uttarakhand state is rich in water resources. Table 1. depicts that the uranium concentration is evaluated from the water samples of all the districts of Uttarakhand. Pauri Garhwal, Haridwar, Bageshwar, and Nainital have relatively high average uranium levels. These regions are known to contain granitic rocks**,** metamorphic formations**,** and uranium-bearing minerals**.** When groundwater percolates through these rocks, uranium leaches into the water. Uranium content in the water system in Uttarakhand varies from 0.37 ppb (Pithoragarh) to 14.25 ppb (Bageshwar), whereas radon values range from 0.68 Bq/L (Pauri) to 70.00 Bq/L (Tehri). Their elevation in that area is due to groundwater flowing through mineral-rich rocks, which raises uranium concentrations. The high uranium level in Bageshwar (up to 28.4 ppb, AM = 14.25 ppb) may be due to the area's underlying granitic and metamorphic rocks, which naturally contain higher uranium content. Weathering and leaching processes likely mobilize uranium into groundwater [33] noted such geogenic factors in their hydrogeochemical assessment of the region. Additionally, as uranium decays, radon gas is produced and can build up in buildings. Water in these areas might have an alkaline pH and oxidizing conditions, which enhance uranium solubility, leading to elevated concentrations. Districts like Dehradun**,** Tehri**,** Pithoragarh**,** and Rudraprayag show low uranium averages (<1 ppb)**.** These areas may be dominated by sedimentary deposits, which contain less uranium than igneous or metamorphic rocks. High rainfall and surface water influence in areas like Tehri and Dehradun can dilute uranium concentrations. Groundwater in these regions might flow through less mineralized zones, meaning fewer uranium sources are present in the aquifer. The Uranium content in all districts is well below the recommended level of 30 ppb and 60 ppb recommended by WHO and AERB, respectively.

Table 1 also presents radon concentration data (in Bq/L) in groundwater samples from various districts of Uttarakhand. The values show significant variability across the region, influenced by geological and environmental factors. Among the districts with reported radon data, Tehri stands out with the highest maximum value of 192.0 Bq/L and an average concentration of 70 Bq/L, followed closely by Rudrapryag (Max: 400 Bq/L, Avg: 67 Bq/L), These elevated levels are primarily due to the presence of uranium-rich rocks and geothermal activity common in Himalayan terrains, where radon gas accumulates in deep aquifers. In contrast, some regions like Haridwar report very low radon values (AM 1.5 Bq/L), as do Pauri Garhwal (Max: 0.73 Bq/L, Avg: 0.68 Bq/L). These areas lie in the foothills and plains, dominated by sedimentary formations and alluvial soils, which naturally contain less uranium and allow radon to escape more easily before entering water supplies. Additionally, water sources in these areas are typically shallower, reducing the contact time with radon-emitting rocks.

Comparing these values to the World Health Organization (WHO) guideline of 100 Bq/L, only Tehri and Bageshwar have reported maximum radon levels that exceed this limit. However, when compared to the much stricter USEPA proposed limit of 11 Bq/L, several districts, including Tehri, Bageshwar, Pithoragarh, and Uttarkashi, exceed safe levels, especially in terms of average concentration.

2.3 Water Quality Parameters

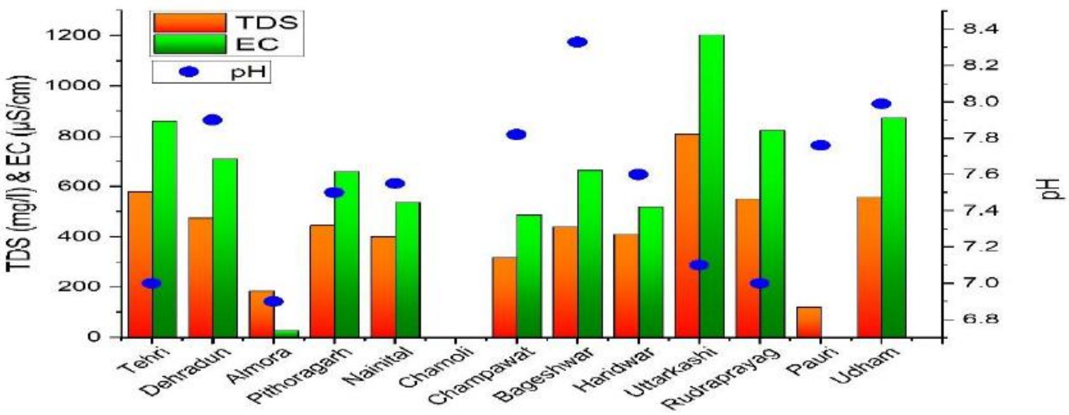

Fig 2. pH, TDS, EC level in Uttarakhand.

Table 2: Water Quality parameters in districts of Uttarakhand.

SN	District	pH	TDS (mg/l)	EC (µS/cm)	Reference
1	Tehri	7.0	578.1	859.0	[27]
2	Dehradun	7.9	475.24	709.24	[38]
3	Almora	6.9	183	26	[30]
4	Pithoragarh	7.5	444	657.6	[39]
5	Nainital	7.55	400	536.00	[40]
6	Chamoli				
7	Champawat	7.5	317.5	486	[31]
8	Bageshwar	8.33	438	663	[41]
9	Haridwar	7.6	408.3	518	[34]
10	Uttarkashi	7.1	807.2	1201.1	[27]
11	Rudraprayag	7.0	550.9	822.2	[27]
12	Pauri Garhwal	7.76	119		[42]
13	Udham Singh Nagar	7.99	558.4	872.5	[15]

Table 2 provides a comparative analysis of groundwater quality across various districts of Uttarakhand, focusing on physicochemical parameters like pH**,** Total Dissolved Solids (TDS), and Electrical Conductivity (EC) with the permissible limits of WHO. The pH levels in the districts vary from 6.9 to 8.33, which is predominantly in the WHO guideline range of 6.5 to 8.5 for potable water. The districts of Bageshwar, Dehradun, and Udham Singh Nagar have a pH that is slightly above 7 and hence are more susceptible to mobilization by uranium. This is due to the fact that uranium prefers to precipitate as soluble carbonate complexes in basic conditions, hence promoting an increased concentration of uranium in the water. However, some areas, such as Almora (with an average pH of 6.9) have slightly acidic water, which tends to favour radon solubility. As a gas, radon is easily dissolved in slightly acidic water, particularly where there are high granite contents that are prevalent in such regions.

The TDS values in the districts vary widely, with values ranging from 119 mg/L (in Pauri) to a striking 807.2 mg/L (in Uttarkashi). WHO suggests a desirable limit of 500 mg/L, with an upper permissible limit of 1000 mg/L. Districts like Tehri, Udham Singh Nagar, and Uttarkashi have higher TDS, indicating mineral-rich groundwater. Such high mineralization suggests that geochemical weathering is likely occurring in the area, which may lead to increased uranium mobilization from rocks into the groundwater. In regions with higher TDS, uranium can become more soluble, posing potential health risks. On the other hand, Almora, with a low TDS (183 mg/L), and Pauri Garhwal (with 119 mg/L), have low mineral content, meaning the groundwater has lower ionic strength. However, low TDS doesn't rule out the possibility of radon presence, especially if the geology is favourable (such as granite formations, which are common in Almora).

EC is a good indicator of the water's ionic content. WHO does not set a strict EC limit, but values above 750 µS/cm are considered high. The average EC ranges from 26 µS/cm in Almora to 1201.1 µS/cm in Uttarkashi. High EC values like those in Uttarkashi and Udham Singh Nagar suggest high mineralization of water, which might be related to geothermal activity or metamorphic rock interactions, which can increase the likelihood of uranium contamination. The high EC reflects the presence of dissolved salts and ions, which can carry uranium and other trace elements. Low EC values, as seen in Almora and Pauri Garhwal, suggest low ionic content and generally indicate a lower concentration of dissolved minerals. However, this does not completely eliminate the possibility of radon contamination, as radon can still be found in areas with low mineralization, particularly if the geology is conducive to radon release (e.g., granite).

2.4 Chemical Parameters in Water

Table 3: Statistical analysis of chemical parameters.

SN	Location	F^-	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	Reference
1	**Tehri**		19.65	0.72	28.2	0.58	39.5	26.95	13.95	9.25	[43]
2	**Dehradun**	1.58	10.07	3.46	132.77	1.03	85.22	37.01	1.71	10.24	[38]
3	**Almora**										
4	**Pithoragarh**	0.2	97.7	4.8	11.3	0.4	20.1	60.2	15.77	14.49	[39,44]
5	**Nainital**	0.06	5.2	4.6	39	0.12	57	21	1.8	6.6	[45]
6	**Chamoli**										
7	**Champawat**	0.19	113.44	21.05	13	1.30	27.57	25.06			[31]
8	**Bageshwar**	0.56	22.01	2.62	32.71		31	31.75	2.5	8	[41,46]
9	**Haridwar**	0.15	29.34	12.15	36.22		59.23	30.65	5.38	39.21	[35]
10	**Uttarkashi**						27.57	25.06			[30]
11	**Rudraprayag**		4.48	0.6	0.31	0.53	17.8	8.85			[47]
12	**Pauri Garhwal**	0.40	15	1.4	6		18	7.30	1.17	3.22	[42]
13	**Udham Singh Nagar**	0.79	81.05	4.26	48.4		66	46	6.5	58.35	[48]
14	**Permissible limits**	1.5	250	45	200	1	75	30	25	200	[49,50]

The table presents the concentration ranges of fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), and phosphate (PO_4^{3-}) across various districts of Uttarakhand, and when analyzed against recommended values from WHO and BIS, it highlights potential geochemical environments that could influence the behaviour of uranium and radon in groundwater. For instance, the BIS permissible limit for fluoride is 1.5 mg/L, but Dehradun shows concentrations as high as 1.58 mg/L, and other regions also exceed safe levels—suggesting strong fluoride-bearing mineral interactions, which can also mobilize uranium through the formation of soluble UO_2F^+ complexes. Nitrate concentrations, which can accelerate the oxidation of U(IV) to the more soluble U(VI) form, are notably high in Champawat (up to 21.05 mg/L), pointing to both anthropogenic input and an environment conducive to uranium migration. Sulfate and phosphate also affect uranium mobility: extremely high sulfate values may contribute to complexation, while phosphate levels—like the 39 mg/L in Nainital—may lead to precipitation of low-solubility uranium-phosphate minerals. These areas also lie within or near regions of high uranium-bearing bedrock, like granites and metamorphic, which are sources of radon gas. Since radon is a decay product of uranium, its concentration in groundwater and indoor air is strongly influenced by uranium content and the permeability of the host rocks. Thus, districts such as Nainital, Dehradun, Pithoragarh, and Haridwar not only exhibit chemical signatures favourable for uranium mobility but are also geologically predisposed to elevated radon risk, warranting detailed hydrogeochemical and radiological assessments to ensure safe water quality and public health protection.

The presence of calcium is higher than the recommended values in Dehradun. The maximum value of calcium in water samples of different localities of Uttarakhand state ranges from 17.8-85.22 mg/l and the permissible limit is 75 mg/l. The values of magnesium ion are higher in some places like Dehradun (37.01mg/l), Pithoragarh (60.2mg/l), and Udham Singh Nagar (46mg/l) than the safety guidelines is 30mg/l in all the investigated areas of Uttarakhand except Rudraprayag (0.53mg/l), the values of magnesium ion in Rudraprayag are under the permissible limit.

The presence of potassium in the water samples of different districts of Uttarakhand varies from district to district. The value of potassium ions ranges from 1.17 - 15.77 a with a permissible limit of 25 mg/l. The value of Sodium metal ranges from 3.22-58.35 mg/l in the water samples of different districts of Uttarakhand that are under the permissible limits (200).

2.5 Associated Health risk in Uttarakhand by radioactive elements

According to the World Health Organization, the recommended annual effective dose for radon exposure should not exceed 1 mSv (1000 µSv/year), while the United Nations Scientific Committee on the Effects of Atomic

Radiation suggests that ingestion of uranium should remain below 100 µSv/y. Among the surveyed regions, Bageshwar and Haridwar are getting the highest value. In Bageshwar, the Excess Cancer Risk (ECR) value varied between 3×10^{-8} and 894×10^{-8} with a mean value of $50.0 \pm 21 \times 10^{-8}$. The computed values of ECR were well within the safe limit for radiological risk. The concentration of uranium in drinking water was less than the reference limit suggested by USEPA and WHO but in 20% of samples the concentration of uranium was greater than the limits suggested by ICRP [33]. Also, in the Haridwar district the Hazard Quotient was observed with the value of 0.093 and the lifetime average daily dose was found 0.056 µg/kg/d which is less than the reference dose of 0.6 µg/kg/d and 4.4 µg/kg/d prescribed by WHO, 2004 and AERB, 2004. The observed annual effective dose by radon inhalation in Rudraprayag district was a mean value of 100 µSv/y, which is less than the recommended reference limit of 1 mSv/year prescribed by UNSCEAR and WHO.

IV. CONCLUSION

Water is a very important element of life and radioactive contaminated water can pose significant health hazards to inhabitants. The present result shows that Bageshwar and Haridwar show high levels of Uranium content that are largely below the recommended levels set by several regulatory bodies, including the USEPA, WHO, and AERB. Likewise, the use of groundwater as drinking water in many parts of Uttarakhand contributes to the slightly elevated radon consumption in drinking water samples in some areas, which is over the recommended levels. To protect against the health risks that radon poses, it is critical to look into the presence of radon in groundwater. Moreover, the majority of these sources with elevated radon and uranium concentrations come from groundwater sources. The concentration of uranium also varies with the water quality parameters found in the Uttarakhand areas under investigation. This is because uranium tends to be more soluble in areas with low pH levels, while high pH levels in water samples cause uranium to form insoluble precipitates like uranium hydroxides. The geology of Uttarakhand is varied, with some regions naturally having significant uranium and radon concentrations. In some areas, this may be a contributing factor to increased natural radioactivity. In Uttarakhand, water from public supply sources is generally treated and closely monitored to guarantee that it satisfies safety standards, especially those pertaining to radiological safety. Nonetheless, it is advised to have water tested frequently in regions with high levels of naturally occurring radioactivity or where private wells are utilized. Thus, in the future, a thorough investigation from the perspective of health risks will be needed to lower the dose of radon and uranium in water so that residents of these places do not become increasingly exposed to health risks.

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