OPERATIONS AND PRINCIPLES OF LOW LEVEL LIQUID SCINTILLATION COUNTERS AND APPLICATION IN WATER RESOURCE MANAGEMENT

Summer Internship Training Report

Submitted by

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DECLARATION

I hereby declare that this internship report, entitled **"OPERATIONS AND PRINCIPLES OF LOW LEVEL LIQUID SCINTILLATION COUNTERS AND APPLICATION IN WATER RESOURCE MANAGEMENT"** is an original work I carried out in partial fulfillment of the requirements for the degree of Master of Science in Applied Geology at Anna University. The work was conducted under the supervision and guidance of Dr. Gopal Krishan, Scientist 'E', Hydrological Investigations Division, National Institute of Hydrology, Roorkee for the duration of Six weeks (01.06.2025-10.07.2025).

I further declare that neither this report nor any part of it has been the basis for the ward of any previous degree or diploma. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented, fabricated, or falsified any idea, data, fact, or source in my submission.

DATE:

AARON ALEXANDER RONALD BS
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CERTIFICATE

This is to certify that the internship report entitled "**OPERATIONS AND PRINCIPLES OF LOW LEVEL LIQUID SCINTILLATION COUNTERS AND APPLICATION IN WATER RESOURCE MANAGEMENT"** submitted by **AARON ALEXANDER RONALD. BS** as partial fulfillment for the award of the degree of Master of Science in Applied Geology at ANNA UNIVERSITY is a record of the candidate's own work carried out by her under my supervision and guidance for the duration of Six weeks (01.06.2025-10.07.2025).

The matter embodied in this report has not been submitted for the award of any other degree.

Dr. Gopal Krishan
Scientist 'E',
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National Institute of Hydrology,
Roorkee.

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AARON ALEXANDER RONALD BS

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ABSTRACT

Tritium (^3H), a radioactive isotope of hydrogen with a half-life of 12.32 years, serves as a vital tracer for determining the age and recharge characteristics of groundwater. Naturally produced through cosmic ray interactions and historically elevated by mid-20th century nuclear testing, tritium integrates into the hydrological cycle primarily as tritiated water (HTO). This applies tritium dating to groundwater samples from eight locations in Punjab, India, using measured tritium units (TU) and liquid scintillation counting (LSC) to infer residence times.

Groundwater samples underwent pre-treatment, electrolytic enrichment, and final tritium activity measurement using an ultra-low-level liquid scintillation spectrometer. Tritium concentrations were converted to TU, and water ages were estimated using the radioactive decay formula, assuming a modern recharge level of 10 TU. The results reveal a spatial gradient in groundwater age.

This regional tritium distribution suggests groundwater flow from northwest to southeast and highlights variations in recharge conditions driven by topography, aquifer type, and anthropogenic influences. This report also explains the utility of tritium as a tracer for delineating recharge zones, estimating flow velocities, and guiding sustainable groundwater management. Future integration of stable isotope analysis ($\delta^{18}O$, $\delta^{2}H$) and hydrogeological modeling is recommended to enhance understanding of recharge sources and aquifer connectivity.

CHAPTER – 1

1.1 INTRODUCTION

Tritium (^{3}H or T) is a radioactive isotope of hydrogen, consisting of one proton and two neutrons in its nucleus, giving it a mass number of 3. It is naturally rare and emits low-energy beta radiation with a half-life of about 12.32 years, decaying into helium-3. Because of its weak radioactivity and chemical behavior similar to ordinary hydrogen, tritium poses minimal external risk but can become hazardous when inhaled, ingested, or absorbed as tritiated water (HTO) or organically bound tritium (OBT). Tritium is produced both naturally in the upper atmosphere through cosmic ray interactions and artificially via nuclear reactions, especially through neutron bombardment of lithium-6 or heavy water in nuclear reactors. Tritium (^{3}H) is continuously generated in the upper atmosphere when galactic cosmic rays strike nitrogen atoms, liberating fast neutrons that convert nitrogen-14 into tritium via spallation.

$$^{14}\mathrm{N(in\ atmosphere)} + n \rightarrow {}^{3}\mathrm{H} + {}^{12}\mathrm{C}$$

This newly formed tritium quickly oxidizes to tritiated water vapour (HTO), which accumulates in the stratosphere—about half of natural production occurs there, with an atmospheric inventory stabilized at roughly 2,590 PBq and a global production rate near 148 PBq Circulation by the Brewer–Dobson mechanism transports HTO poleward and downward from tropical stratospheric regions into the troposphere. Within the lower atmosphere, tritiated vapour mixes into clouds and precipitation, and typically returns to Earth in weeks, integrating into surface and groundwater systems.

A major increase in tritium levels occurred during the mid-20th century, particularly in the 1950s and early 1960s, due to atmospheric testing of thermonuclear (hydrogen) bombs. These tests released massive quantities of tritium into the atmosphere, peaking around 1963 before the Limited Test Ban Treaty curtailed such activities. The tritium released during this period rapidly entered the hydrological cycle, making its way into rainwater, rivers, and groundwater. This atmospheric pulse has since been used as a valuable tracer in hydrology to estimate groundwater residence times and flow pathways.

1.2 GROUNDWATER AGE CLASSIFICATION USING TRITIUM (^3H) CONCENTRATION

Modern Groundwater (>7 TU): This type of groundwater was recharged after around 1952, during or after the rise in atmospheric tritium from nuclear testing. The high tritium levels indicate recent infiltration, short residence time, and active recharge—typically found in shallow, unconfined aquifers or regions with high permeability.

Mixed Modern and Sub-modern Groundwater (4–7 TU): Water in this range reflects a combination of modern and older recharge events. It suggests partial infiltration after 1952 mixed with pre-modern water, likely due to natural mixing or layered aquifer structures. This indicates moderately active recharge and transitional flow conditions.

Sub-modern Groundwater (2–4 TU): This groundwater likely recharged between the early 1950s and before the 1963 "bomb peak." Lower tritium levels point to longer residence times and slower infiltration, often found in semi-confined or deeper aquifers with limited recent recharge.

Old Groundwater (<1 TU): Characterized by little or no detectable tritium, this water recharged well before the nuclear era—possibly hundreds or thousands of years ago. Found in deep or confined aquifers, it indicates very slow or no modern recharge and represents a non-renewable water source.

S.No	Classification	Tritium Units (TU)
1.	Modern Groundwater	>7 TU
2.	Mixture of Modern & Sub-modern Groundwater	4-7 TU
3.	Sub-modern Groundwater	2-4 TU
4.	Old Groundwater	<1 TU

1.3 TRITIUM DATING PRINCIPLE

Tritium dating is a radiometric technique used to determine the age of relatively recent water sources—particularly groundwater and precipitation—based on the concentration of the radioactive hydrogen isotope tritium (^3H). Tritium has a half-life of approximately 12.32 years and decays into helium-3 (^3He) by beta decay. Since tritium behaves like water in the environment, it enters the hydrological cycle through rainfall and becomes part of surface water and aquifers. A unique advantage of tritium dating is its ability to trace water that has infiltrated into the subsurface within the last 70 years, making it a vital tool in hydrogeology and environmental science. Tritium was naturally present in small amounts due to cosmic ray interactions in the atmosphere, but its levels spiked dramatically during the mid-20th century due to atmospheric nuclear weapons testing—especially around 1963. This sharp increase, known as the "bomb peak," provides a chronological marker that allows scientists to determine whether water was recharged before or after nuclear testing.

1.3.1 LIQUID SCINTILLATION COUNTING1 (LSC)

The process of tritium dating involves the **collection and preparation of water samples**, followed by **enrichment** to concentrate the low levels of tritium, especially in older or deeper groundwater. Tritium enrichment methods aim to increase the concentration of tritium in water samples for detection and analysis. The most common approach is electrolytic enrichment, where lighter hydrogen isotopes are preferentially removed during electrolysis, leaving behind concentrated tritiated water. Distillation enrichment uses the slight boiling point difference between tritiated and regular water but is less efficient and slower. Isotopic exchange involves chemical reactions to transfer tritium between substances, often used in industrial or labeling applications. Thermal diffusion separates isotopes using temperature gradients but is slow and mainly experimental, while cryogenic distillation offers high-purity separation for specialized uses like nuclear fusion. Additionally, tritium spiking, which involves adding a known amount of tritiated water to samples, is widely used as a tracer for calibration and hydrological studies rather than for enrichment itself.

After enrichment, the tritium activity is measured, where the enriched water sample is mixed with scintillators like **Organic scintillators**, including plastics and liquids, are carbon-based and known for their fast response, commonly used in beta and gamma detection. **Inorganic scintillators**, made from crystalline solids like **sodium iodide** and **cesium iodide**, offer higher density and light output, making them ideal for gamma spectroscopy and medical imaging. **Plastic scintillators** are cost-effective and versatile, while **liquid scintillators** are useful for detecting low-energy beta particles such as tritium. **Gas scintillators**, though

less common, are used in specialized detectors. Each type serves different applications based on its properties like response time, light yield, and form factor, and the resulting light flashes from beta decay are counted by a **spectrometer.**

1.3.2 $^{3}H/^{3}He$ DATING

In advanced groundwater dating techniques, the decay product of tritium—helium-3 (^{3}He)—is also measured alongside tritium itself, in what is known as **$^{3}H/^{3}He$ dating**. This method provides a more refined and precise estimate of groundwater age, especially for samples recharged within the last 30 to 50 years. The underlying principle involves detecting the amount of ^{3}He that has accumulated as a direct result of tritium decay. Since the decay rate of tritium is well-known (with a half-life of 12.32 years), the ratio of tritium to its daughter product helium-3 can be used to calculate the exact time since the water was last in contact with the atmosphere.

To carry out this method, highly sensitive instrumentation such as **noble gas mass spectrometers** or **high-vacuum mass spectrometry systems** is required. These instruments are capable of detecting extremely low concentrations of helium isotopes, even in the presence of other gases. Unlike standard tritium dating, which relies solely on the decay signal of beta particles, this method allows for the dating of water that has very low or near-background levels of tritium—thereby extending the usable dating range and improving accuracy in older or more dilute samples.

Moreover, with the growing need for field-based applications, **portable liquid scintillation systems** have been developed for in situ tritium measurements. These mobile units are especially valuable in remote or logistically challenging areas where transporting samples back to a laboratory may be impractical or where rapid, on-site analysis is required.

Together, these advanced tools and methodologies enable researchers to trace groundwater movement, determine recharge timing with high resolution, and improve understanding of subsurface hydrology.

CHAPTER-2

2. INSTRUMENTS (LSC)

2.1 TRITIUM ENRICHMENT UNIT

The **tritium enrichment unit** is a specialized device used to concentrate tritium in water samples via controlled **electrolysis**.

Tritium Enrichment Unit Exterior and Interior

It consists of a sealed, corrosion-resistant metal box containing a network of **copper tubes** that circulate coolant to maintain a low temperature—crucial for minimizing tritium loss and isotopic fractionation.

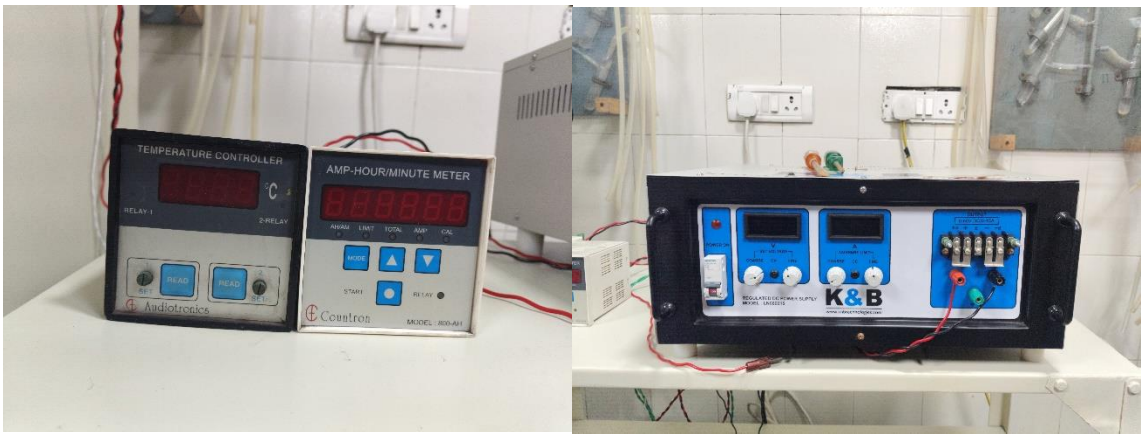
Tritium Enrichment Cells

Inside the chamber, **electrolytic cells** with **platinum or stainless steel electrodes** hold the sample water. A **direct current** supplied to these cells breaks down H_2O molecules, releasing hydrogen and oxygen gases and reducing the sample volume, which increases tritium concentration.A **tube assemblage panel** with

vacuum lines removes the evolved gases, maintaining pressure stability and preventing interference.

Gas Outlet Tubes

Thermostats and temperature regulators control the cooling system, while **current controllers, timers**, and **safety interlocks** ensure stable and safe operation.



Circuit Control Units

Advanced systems may include **degassing units, water level sensors**, and **automated data loggers** for real-time monitoring, enhancing precision and reproducibility in tritium analysis.

2.2 ULTRA LOW LIQUID SCINTILLATION SPECTROMETER

The liquid scintillation counting system comprises several specialized components designed for ultra-sensitive detection of low-energy beta emitters

like tritium. At the center is the **detection chamber**, where a **sample vial** containing the water sample mixed with a **liquid scintillation cocktail** is placed between two **photomultiplier tubes (PMTs)**.

These PMTs are highly sensitive light detectors that convert scintillation light into electrical signals. Surrounding the detection setup is a **dual-layered shielding system**: an inner layer of **copper shielding** that reduces X-rays and secondary emissions, and an outer layer of **lead shielding** that absorbs gamma radiation and cosmic rays, minimizing background interference. The PMTs are connected to **coincidence units**, which verify simultaneous signal detection from both tubes to distinguish true decay events from noise.

ULLSS Interior

Valid signals are sent to a **summing amplifier**, which combines them to estimate the beta particle's energy, and then to an **analog-to-digital (AD) converter** that digitizes the information. The system also includes **Trigger and Inhibit circuits**—the Trigger initiates the data logging when a valid event occurs, while the Inhibit prevents overlapping or invalid signals from being recorded. Finally, the digitized signals are directed to **Multi-Channel Analyzers (MCAs)**, which sort the signals into energy channels for spectral analysis. Together, these components form a highly sensitive and accurate system for detecting and analyzing tritium decay events.

CHAPTER-3

3. OPERATIONS

3.1 TRITIUM ENRICHMENT UNIT OPERARTIONS

The operation of a **tritium enrichment unit** involves concentrating tritium in water samples by gradually reducing the water volume through **controlled electrolysis**. Before the electrolysis the sample water is distilled and then, the process begins by placing the sample water into **electrolytic cells**, typically made of glass or plastic and fitted with **platinum or stainless steel electrodes**.

Enrichment Cells Pluged with wires for Hydrolysis

A **direct current (DC)** is supplied from a power unit to initiate electrolysis, during which **hydrogen and oxygen gases** are released from the water molecules. As these gases are evolved, the total water volume in the cell decreases, thereby **increasing the concentration of tritium** in the residual liquid. To prevent the loss of tritiated water through evaporation and to avoid isotopic fractionation, the entire unit is kept at a **low and stable temperature** using a **network of copper cooling tubes** that circulate chilled fluid throughout the enclosure. The **tube assemblage panel**, equipped with vacuum lines or suction outlets, removes the released gases from each cell, either venting them safely or trapping them depending on safety protocols. The unit also contains **thermostats** and **temperature regulators** to monitor and maintain optimal cooling conditions. Additional components such as **current controllers**, **timers**, and **safety interlocks** are used to ensure consistent current flow, prevent overheating, and protect the integrity of the samples. Advanced units may also feature **degassing chambers**, **water level sensors**, **interchangeable cell holders**, and **automated monitoring systems** that log real-time data on temperature, voltage, and current—enhancing both **safety** and **reproducibility** throughout the enrichment process

3.2 ULTRA LOW LIQUID SCINTILLATION SPECTROMETER OPERATIONS

The operation of a **liquid scintillation counting (LSC) system** is centered around the precise detection of low-energy beta emitters such as tritium. The process begins with a **sample vial** containing water mixed with a **liquid scintillation cocktail**, which is placed between two **photomultiplier tubes (PMTs)** in the **detection chamber**. When a tritium atom decays, it emits a beta particle that interacts with the scintillation cocktail, producing a flash of light. This light is detected by both PMTs, which convert it into electrical pulses.

These signals are sent to **coincidence units**, which confirm that both PMTs detected the event simultaneously—ensuring it is a genuine decay and not background noise. If validated, the signals are forwarded to a **summing amplifier** to calculate the energy of the beta particle, and then passed through an **analog-to-digital (AD) converter** for digitization. **Trigger and Inhibit circuits** control the data flow—Trigger initiates data logging when a valid event occurs, while Inhibit blocks false or overlapping signals. The digital signals are then analyzed by **Multi-Channel Analyzers (MCAs)**, which sort the pulses into discrete energy levels, producing a beta spectrum. Throughout this process, **dual-layer shielding**—**copper** on the inside and **lead** on the outside—surrounds the detection system to minimize interference from ambient radiation, ensuring highly sensitive and accurate tritium detection.

CHAPTER-4

4. SAMPLE PREPARATION AND ANALYSIS FOR TRITIUM MEASUREMENT

To begin the tritium analysis, 500 mL of water sample is first distilled to remove any organic or inorganic impurities that might interfere with subsequent steps.

$$\text{Impure } H_2O\ (l) \xrightarrow{\text{boil}\rightarrow\text{condense}} \text{Pure } H_2O\ (l) + \text{Impurities (residue)}$$

Pre-enrichment Distillation Unit

Following distillation, 2 grams of sodium peroxide (Na_2O_2) are added to the sample to initiate chemical enrichment.

$$Na_2O_2 + 2H_2O \rightarrow 2NaOH + H_2O_2$$

The treated sample is then transferred into electrolysis cells within the tritium enrichment unit.

Electrolysis is carried out at low temperatures, controlled by a cooling system that circulates coolant through copper tubing around the cells. During electrolysis, water is gradually decomposed, concentrating tritium in the residual fraction.

$$2H_2O_2 \xrightarrow{\text{electricity}} 2H_2O + O_2$$

At Cathode (Reduction):

$$2H_2O\ (l) + 2e^- \rightarrow H_2(g) + 2OH^-$$

At Anode (Oxidation):

$$4OH^- \rightarrow O_2(g) + 2H_2O\ (l) + 4e^-$$

Net Ionic Equation:

$$2H_2O\ (l) \rightarrow 2H_2(g) + O_2(g)$$

Post Enrichment Distillation Unit

After enrichment, the samples are treated with lead chloride ($PbCl_2$) to neutralize the residual Na_2O_2, ensuring the pH is brought to neutral

$$PbCl_2 + 2NaOH \rightarrow Pb(OH)_2 \downarrow + 2NaCl$$

and then the sample is distilled, where the salts are precipitated and the vapour is condensed and collected separately

$$PbCl_2 + 2NaOH + H_2O \xrightarrow{\text{reaction + distillation}} \text{Pure } H_2O + Pb(OH)_2 \downarrow + 2NaCl$$

.

Ultima Gold Scintillation cocktail and samples mixed with it.

A portion of the enriched sample (typically 8 g) is then mixed with 13 grams of Ultima Gold™ scintillation cocktail, which enables effective detection of low-energy beta particles through phosphorescence. The prepared vials are placed in a tray and loaded into an ultra-low-level liquid scintillation spectrometer (ULLSSM) for final tritium counting.

4.1 DATA ANALYSIS

In tritium dating, data analysis is central to estimating the age and origin of groundwater. After sample collection and preparation, the tritium content is typically measured using **Liquid Scintillation Counting (LSC)**, which detects beta radiation emitted during tritium decay. The raw count rate (in counts per minute or disintegrations per minute) is corrected for background radiation and quenching effects using internal standards. The corrected activity is then converted into **Tritium Units (TU)**, where **1 TU = 1 tritium atom per 10^{18} hydrogen atoms**, or approximately **0.118 Bq/L** at 20°C. This unit standardizes tritium concentration across different samples and regions. For precise age determination, it is essential to understand both the measured tritium level and the historical input of tritium in rainfall, which varies over time due to natural and anthropogenic influences, particularly atmospheric nuclear testing in the 1950s–60s, which caused a global spike in tritium levels.

To determine the groundwater age, tritium decay is modeled using the exponential decay law:

$$N = N_0 e^{-\lambda t} \quad \text{or} \quad t = \frac{1}{\lambda} \ln\left(\frac{N_0}{N}\right)$$

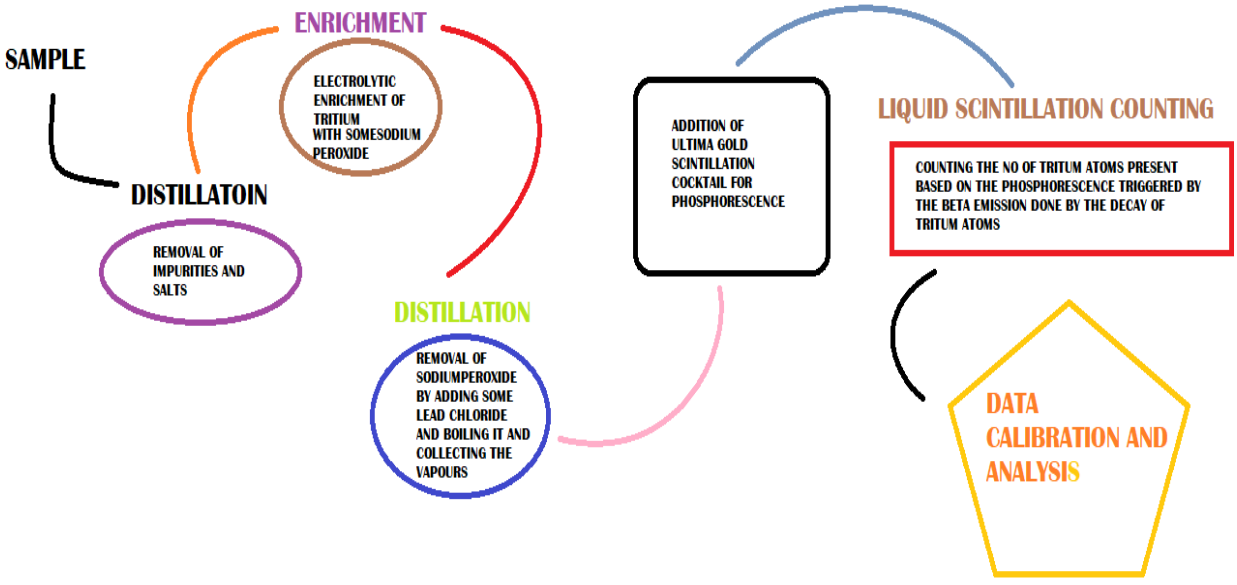
Where:

N is the current tritium concentration

N_0 is the initial tritium concentration (based on historical records or modelsλ is the decay constant, calculated from $\lambda = In_2 / T_{1/2}$

t is the age of the water

4.1.1 FLOW CHART



CHAPTER-5

5. APPLICATIONS

5.1 GROUNDWATER AGE DATING AND RECHARGE ESTIMATION

Tritium is most commonly used to determine the **residence time** of groundwater—how long it has been underground since infiltration. Measured tritium levels are compared with historical atmospheric records to assess recharge timing. Waters with >5 TU are typically **modern recharge** (post-1960s), while those with <1 TU are considered **pre-bomb**, or older than 70 years. This helps in managing aquifer sustainability, estimating recharge rates, and developing water resource models

5.2ESTIMATING GROUNDWATER FLOW VELOCITY

Tritium data can be used to estimate **groundwater flow velocity** by determining the time taken for tritium-bearing water to travel a known distance between recharge and sampling points. Once the **age (t)** is estimated using decay calculations, and the **flow path length (L)** is known (e.g., from geological mapping or well spacing), the **velocity (v)** can be calculated by the formula:

$V = L/t$

This velocity reflects the **average linear velocity** of groundwater movement and is essential for modeling aquifer dynamics, contaminant transport, and wellhead protection zones. Tritium dating is especially useful for velocities in the range of **0.1–10 meters/year**, making it suitable for regional hydrogeologic studies.

5.3 IDENTIFICATION OF MIXING ZONES IN AQUIFERS

Intermediate tritium levels often suggest **mixing between older and younger waters**. Such mixing zones can affect water quality and complicate interpretations of contamination sources. Tritium data, in combination with mixing models, can estimate the proportions of different-aged waters, helping to delineate aquifer layering and hydraulic connections between zones.

5.4 DELINEATION OF RECHARGE AREAS AND FLOW PATHS

Since tritium enters aquifers only through surface infiltration, it helps map **recharge zones** and trace **flow paths**. If tritium-rich water is found deep

underground, it confirms that surface recharge is occurring and that the aquifer is active. This has implications for protecting recharge areas and managing land use near aquifers.

5.5 SURFACE WATER–GROUNDWATER INTERACTION

Tritium levels help identify **gaining and losing streams**, by showing whether groundwater is entering the stream (low TU) or the stream is recharging the aquifer (high TU). This application supports integrated management of water resources in basins with complex surface–subsurface interactions.

5.6 ENVIRONMENTAL AND CLIMATE STUDIES

Tritium data is useful in identifying **paleowater** (ancient water stored underground since wetter climatic periods) versus modern water. This helps in reconstructing past environmental and climate conditions, particularly in arid and semi-arid regions where present-day recharge is minimal.

CHAPTER-6

6. INTERPRETATION OF GROUNDWATER AGES AND RESIDENCE TIME FROM THE PROVIDED TRITIUM UNITS DATA

Tritium (^3H) is a radioactive isotope of hydrogen used to determine the relative age of groundwater. This evaluates groundwater samples from eight locations in Punjab, India, using tritium data and an assumed modern recharge level of **10 TU**. The ages are calculated using the radioactive decay formula. Locations with negative or negligible TU values are interpreted as having groundwater that is older than the detection range of tritium (~>100 years). Spatially, the tritium distribution and corresponding groundwater age patterns provide insight into recharge dynamics, aquifer isolation, and potential flow directions.

6.1 STUDY AREA:

6.1.1 Geographic Setting of the Study Area

The samples were collected in Punjab, a northwestern state of India located within the Indo-Gangetic Plain. This region is known for its flat topography, fertile alluvial soils, and intensive agricultural practices. The climate is subtropical, featuring hot summers, cold winters, and concentrated monsoonal rainfall between June and September. The groundwater samples were collected from eight locations: Phagwara, Bholath, Gondpur, Adampur, Bussowal, Phillaur, Mallian Kallan, and Jalandhar. These towns are distributed from the central to the northwestern parts of the state. Notably, Jalandhar and Mallian Kallan lie in the northwest, whereas Bussowal and Phillaur are situated further southeast. This spatial arrangement coincides with a gradient in groundwater age, suggesting a directional trend in recharge and subsurface flow from the northwest toward the southeast.

6.1.2 Groundwater Characteristics and Recharge Conditions

Punjab's groundwater occurs primarily in unconfined to semi-confined alluvial aquifers composed of sand, silt, and clay. Recharge is mainly derived from monsoon rainfall, seepage from irrigation canals, and return flow from agricultural fields. However, the recharge rate and water age vary by location due to differences in aquifer confinement, permeability, and land use. In the present study, groundwater in Jalandhar and Mallian Kallan exhibited undetectable tritium concentrations, indicating that the water is over a century old and likely stored in confined or poorly recharged aquifers. In contrast, Phagwara, Bholath, and Gondpur showed moderately low tritium levels, signifying sub-modern

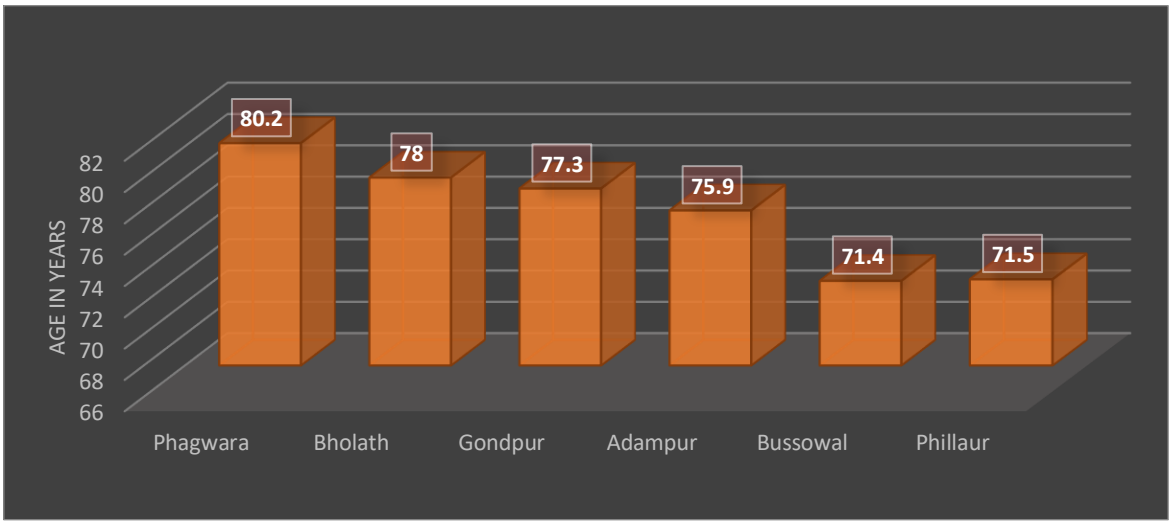
groundwater likely recharged during the 1950s or early 1960s. Bussowal and Phillaur displayed relatively higher tritium content, pointing to more recent recharge from surface sources such as canal seepage or irrigation return. Punjab faces increasing groundwater stress due to intensive irrigation and over-reliance on tube wells, especially in the central and southwestern regions, which has led to falling water tables and long-term aquifer depletion.

6.1.3 LOCATIONS

Location	Lat	Long
Phagwara	31.183	75.401
Bholath	31.334	75.559
Gondpur	31.222	75.757
Adampur	31.548	75.513
Bussowal	31.724	75.766
Phillaur	31.43	75.72
Mallian Kallan	31.214	75.155
Jalandhar	31.024	75.788

6.2 GROUNDWATER AGE SUMMARY

Location	TU (Measured)	Age (years)
Phagwara	0.110	80.2
Bholath	0.124	78.0
Gondpur	0.130	77.3
Adampur	0.140	75.9
Bussowal	0.180	71.4
Phillaur	0.179	71.5
Mallian Kallan	-0.340	Below detection
Jalandhar	-0.290	Below detection



Histogram representation of the Ages of the Samples

6.2.1 Comparatively older groundwater in northwestern sites

Mallian Kallan and Jalandhar show negative tritium values, indicating that groundwater is significantly aged, likely older than 100 years. These values suggest the groundwater in these areas has undergone little or no recharge in recent decades. This may be due to the presence of confined aquifers, deeper groundwater systems, or aquifer zones with inherently low recharge potential. From the map, these locations lie in relatively low-relief areas, which could further limit infiltration. They also appear to be positioned away from prominent recharge sources such as rivers or irrigation canals, supporting the interpretation of older, isolated groundwater.

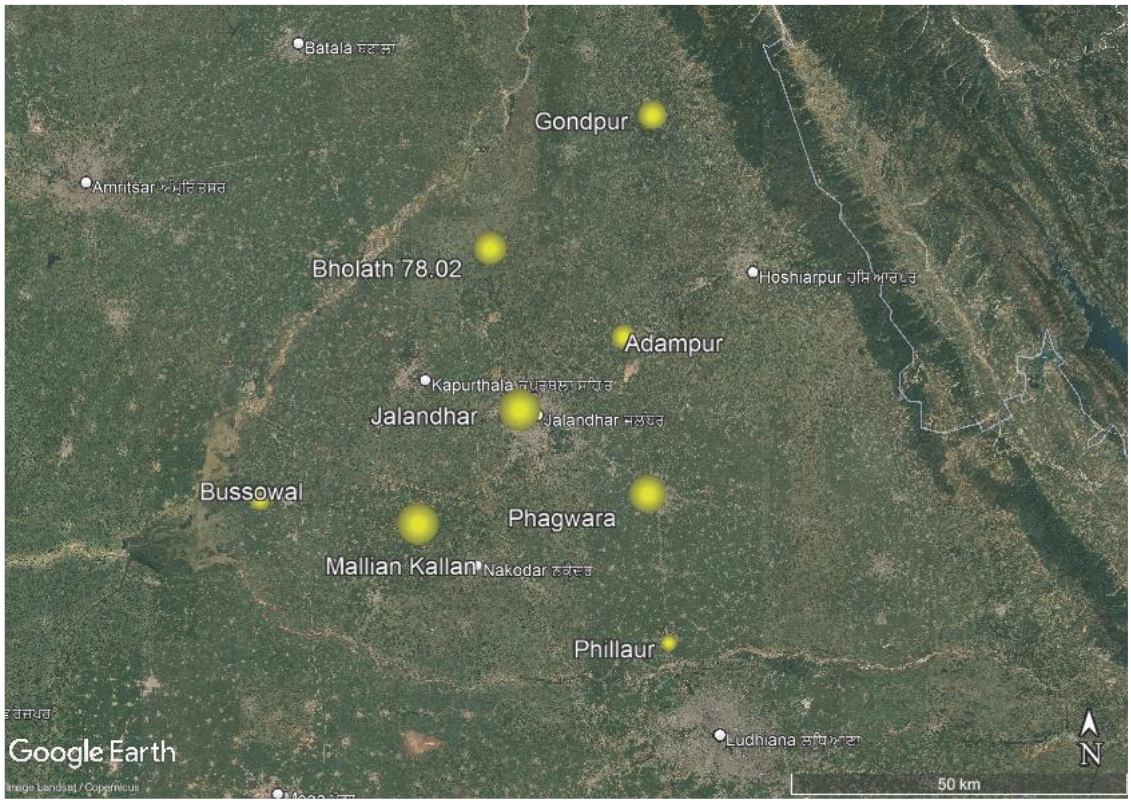
6.2.2 Progressively Younger Water Eastward

Sites such as Phagwara, Bholath, and Gondpur show moderately aged groundwater, with estimated residence times ranging from approximately 77 to 80 years. These intermediate-age waters suggest that recharge may still occur in these areas, though infrequently. Their position on the map indicates a slight elevation gradient, which may contribute to increased runoff and infiltration potential. These locations appear closer to possible recharge zones such as agricultural fields, small streams, or areas where seasonal rainfall percolates into the subsurface. The moderately high tritium content indicates that while recharge is not recent, it has occurred within the last century.

6.2.3 Comparatively Younger Groundwater in the Southeast

Bussowal and Phillaur show the youngest groundwater in the dataset, with estimated ages around 71 years. These towns are located on the southeastern portion of the map, likely in areas where recharge from monsoonal rain or canal seepage is more active. The elevated tritium concentrations in these samples suggest more recent interaction with the surface hydrological cycle. This is consistent with a relatively an open aquifer system but not frequently recharged. These areas may also benefit from anthropogenic recharge due to irrigation practices, further contributing to thisgroundwater signature.

6.3 SPATIAL IMPLICATIONS FROM THE MAP



Tritium Sampling Locations.

The satellite map of Punjab clearly illustrates the spatial distribution of tritium sampling points, revealing notable geographic patterns in groundwater age across the region. The northeastern and southeastern parts, particularly around locations such as Bussowal and Phillaur, exhibit relatively **higher tritium concentrations**, indicating the presence of **younger groundwater**. This suggests that these areas benefit from **active recharge mechanisms**, including seepage from an extensive canal irrigation network, surface runoff from monsoonal rains, and possibly agricultural return flow. The combination of permeable alluvial soils, shallow unconfined aquifers, and proximity to irrigation infrastructure appears to enhance infiltration rates, promoting quicker interaction between surface water and groundwater systems.

In contrast, the **northwestern part of Punjab**, where towns like Jalandhar and Mallian Kallan are located, is characterized by **very low or undetectable tritium levels**, signaling the presence of **older groundwater**, likely more than 100 years in age. These areas are interpreted to lie within **confined or semi-confined aquifer systems**, where natural recharge is restricted due to finer sediments, greater aquifer depth, or low vertical permeability. The extended residence time and lack of recent tritium input in these zones support the inference of isolated groundwater bodies with minimal connection to surface hydrology. This spatial

contrast strongly indicates that **aquifer conditions vary significantly across Punjab**, with **comparatively open and dynamic systems dominating the southeastern areas**, and **confined, low-recharge systems** prevalent in the northwest.

The tritium data suggests a **regional groundwater flow direction** trending from **northwest to southeast** or **west to east**, aligning with the observed increase in tritium concentrations and corresponding decrease in water age along this axis. This interpretation is consistent with the natural slope of the land and the distribution of recharge zones, including river networks and canal systems, which are more prominent in the central and eastern parts of the state. Moreover, locations farther from major surface water sources or elevated terrain—typically in the northwest—tend to show signs of reduced recharge potential and older water ages.

These findings underscore the critical influence of both **natural topography** and **human land use** on groundwater dynamics. Areas under intense irrigation, with accessible recharge sources and permeable soils, exhibit significantly younger groundwater signatures. Conversely, locations distant from recharge zones or with subsurface geological constraints tend to retain older water, indicative of long-term storage and limited renewal. Overall, this spatial trend not only highlights the **variability in groundwater availability and vulnerability** across Punjab, but also emphasizes the importance of incorporating hydrogeological and isotopic data into **sustainable water resource management and aquifer protection strategies**.

CHAPTER-7

7. CONCLUSION

This report demonstrates the effectiveness of tritium (^{3}H) as a tracer for estimating groundwater age and understanding aquifer dynamics in the Punjab region of India. By applying tritium dating techniques—including sample enrichment, liquid scintillation counting, and data interpretation using historical tritium inputs—groundwater samples from eight locations were analyzed to assess their residence times and recharge characteristics. The classification of groundwater based on tritium content allowed for the differentiation between modern, sub-modern, and old groundwater, revealing significant spatial variation in recharge activity across the region.

The results indicate that southeastern locations such as Bussowal and Phillaur contain comparatively younger groundwater, suggesting recharge influenced by monsoonal rainfall, canal seepage, and irrigation return flow. In contrast, northwestern sites like Jalandhar and Mallian Kallan exhibited tritium levels below detection, reflecting older, possibly fossil groundwater stored in confined aquifers with minimal modern recharge. This spatial trend aligns with the region's topographic gradient and human land-use patterns and suggests a general groundwater flow direction from northwest to southeast.

The integration of isotope data with hydrogeological interpretation not only improves our understanding of aquifer behavior but also highlights areas of potential concern where recharge is limited and groundwater is effectively non-renewable. These insights are crucial for sustainable groundwater management in Punjab, where over-extraction and declining water tables pose a serious threat to long-term water security. Future studies combining stable isotope analysis (e.g., $\delta^{18}O$ and $\delta^{2}H$), numerical modeling, and land use assessment will further enhance the understanding of recharge processes and support evidence-based groundwater governance in the region.

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