INTEGRATION OF RIVERBANK FILTRATION WITH MULTISTAGE FILTRATION FOR SUSTAINABLE WATER SUPPLY IN RURAL AREAS OF WEST BENGAL

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of my **Master of Engineering** in **Water Resources & Hydraulic Engineering** in the Faculty of Interdisciplinary Studies, Jadavpur University during academic session 2022-2024.

All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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Abstract:

This study assesses the effectiveness and sustainability of combining riverbank filtration (RBF) with multistage filtration techniques, including roughing filters, slow sand filters, and activated carbon, to address the challenge of removing emerging contaminants in rural areas of West Bengal, India. Through a comprehensive approach, the research evaluates the sustainable withdrawal quantity of sub-surface water in the riverbank via pumping tests and well field design, assesses the effectiveness of RBF and multistage filtration systems individually and in combination, and investigates novel methods to enhance water quality and mitigate emerging contaminants. Pumping tests and well field design indicated a sustainable withdrawal quantity with transmissivity measurements averaging 1956 m^2/day, ensuring long-term water availability and minimal ecological disruption. The proposed well field design, comprising seven wells spaced 52 meters apart and each pumping 800 m^3/day, maintained drawdown within acceptable limits. Mechanical sieve analysis guided the selection of appropriate gravel pack materials, ensuring optimal filtration efficiency. The combined use of RBF with multistage filtration techniques demonstrated superior effectiveness in removing emerging contaminants from raw water sources, surpassing performance expectations with significant contaminant removal rates and minimal fouling. Chemical tests confirmed compliance with permissible limits for parameters such as pH, TDS, nitrate, sulphate, iron, and ammonia, while bacteriological tests highlighted the necessity for continuous monitoring due to fluctuating contamination levels. The multistage filtration system notably reduced endosulfan concentration from river water to well water, achieving substantial percentage removal and enhancing water safety, thus validating the integrated approach as a viable solution for sustainable water supply in rural West Bengal.

Key words: Subsurface water Sustainable Yield, Well Field, River Bank Filtration (RBF), Multistage Filtration,

ABBREVIATION:

RBF- River Bank Filtration

MSF-Multi-Stage Filtration

MDGs- Millennium Development Goals

SSF-slow sand filtration

TDS-Total dissolved solids

GAC-granular activated carbon

NTU- Nephelometric turbidity unit

SS- Suspended Solids

BAC- Biological Activated Carbon

BF- Biofiltration

MF- Microfiltration

UF- Ultra filtration

NF- Nano-filtration

BDOC- Biodegradable Dissolved Organic Carbon

EBCT- Empty-Bed Contact Time

MCL- Maximum Contaminant Level

THMFP –Trihalomethanes Formation Potential

ASSF – Aerated Slow Sand Filter

GCMS- Gas Chromatograph-Mass Spectrometer

SYMBOLS

º: Degrees

ºC: Celsius degrees

cm: centimetre

d_{10}: 10% effective size diameter

d_{60}: 60% passing diameter

dc: collector size or grain diameter, grain size

log: logarithm

m: meter

Re: Reynolds number

Uc: uniformity coefficient

Eps: Emerging Pollutant

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1. **INTRODUCTION**:

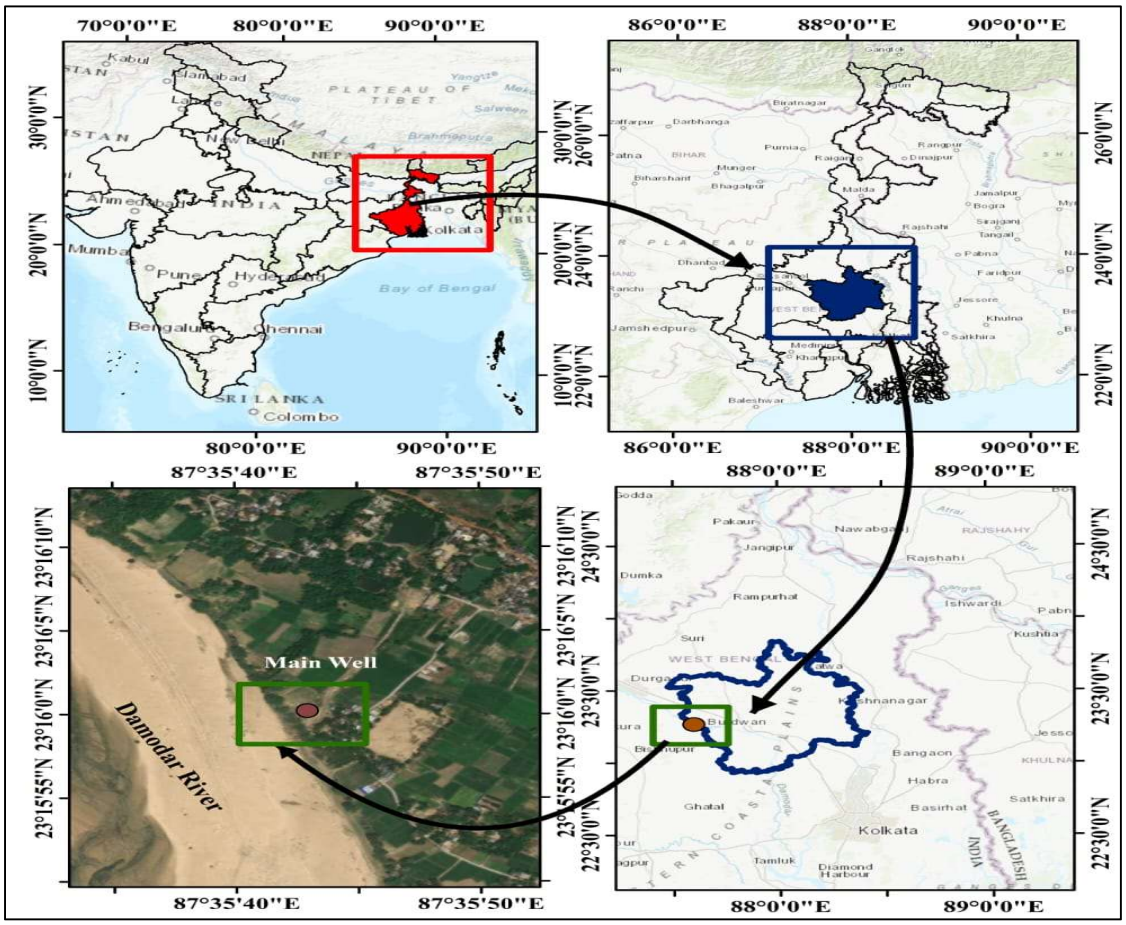
1.1 Background of the Study:

More than one billion people in the world - 18% of the global population - do not have access to safe drinking water (UN, 2006). India is included in the group of countries with the maximum percentage of citizens who experience health problems due to unsafe water Figure1.1 (Nature,2000). The pivotal role of clean water in public health cannot be overstated, particularly in regions like rural India, where access to safe drinking water remains a significant challenge. With more than one billion people lacking this essential resource, the need for effective and affordable water treatment solutions is urgent. Riverbank filtration (RBF) presents a promising approach, harnessing natural processes to purify water extracted from wells adjacent to surface water sources. However, while RBF offers potential, its efficacy in removing emerging contaminants remains unclear, necessitating further exploration and refinement. As a result of unsafe drinking water, the World Health Organization reports that 4,000 children under the age of five die daily from diarrheal diseases worldwide. This is 90% of the total deaths due to diarrhea in the developing world (WHO, 2005; WHO, 2010) The CIA World Factbook ranks India 51st out of 224 countries for infant mortality rate, with 51 infants dying by their first year of age per 1,000 live births. This is more than eight times the reported rate in the United States (CIA, 2009). Some common water-related diseases are those caused by infection from hepatitis A, typhoid, giardia 3 lamblia, cryptosporidiosis, poliomyelitis, cholera, amebic dysentery, cyclosporiasis, and Escherichia coli (E. coli) (Centers for Disease Control and Prevention, 2003). These diseases can cause gastro-intestinal infections, which in weak populations, such as the very young, can lead to death. Additionally, repeated diarrheal episodes can impair health by causing chronic malnutrition, increased infections, and reduced growth and development (Ejemot et al, 2009). Many of India's perennial rivers are heavily polluted by the discharge of untreated sewage and effluents from industrial facilities. This water should not be used without treatment, even for irrigation. However, due to lack of other options and weak enforcement of existing water quality regulations, contaminated surface water serves many uses, including drinking. Access to improved drinking water is estimated to reduce the occurrence of diarrhea by 25% (WHO, 2005). Others, when reviewing 38 studies on the topic, have found a 15 - 43% reduction in diarrheal diseases due to hygiene, sanitation, water supply, and water quality interventions (Fewtrell et al, 2005). Therefore, the reduction of diarrheal diseases in the developing world requires a multi-pronged approach including availability of sanitary toilet facilities, access to safe drinking water, handwashing education, and safe storage of water (WHO, 2005). Low cost treatment such as RBF can be a part of this effort as it can potentially provide a clean and affordable source of drinking water to thousands of people in rural India. Total coliforms are a group of bacteria that can survive and grow in both aerobic and anaerobic settings in warm-blooded hosts as well as in water and soil (WHO, 2006). Presence of total coliform indicates incomplete treatment or potential 4 contamination of drinking water (Feng, Weagant and Grant, 1998). E. coli is a subset of total coliforms that are adapted to the higher temperatures of human and animals' intestines (WHO, 2006). Therefore, E. coli are used as indicators of recent fecal contamination because they are unable to grow and reproduce outside of their host. In temperate environments their survival half-life

outside of their hosts ranges from 1 day (in water) to 3 days (in soil). But in moist, warm, high-nutrient settings in tropical environments, E. coli can maintain free-living populations (Winfield and Groisman, 2003). The RBF field site is in a moist, warm tropical environment, but highly leached soils such as laterites have naturally low fertility (Baligar et al, 2004). For this reason, E. coli is used as an indicator of recent fecal contamination at the RBF field site. Fecal contamination is a concern in drinking water supplies because it can carry pathogens causing diarrhea, meningitis, and other health problems (WHO, 2006). This study embarks on a crucial investigation into the combination of RBF with multistage filtration techniques, specifically integrating roughing filter, slow sand filter, and activated carbon, to address the challenge of emerging contaminant removal. Situated along the banks of the Damodar River, demonstration sites were established to evaluate the effectiveness and sustainability of this combined approach. Notably, while multistage filtration is recognized as an efficient treatment technology capable of removing chemical parameters and emerging contaminants, its widespread adoption is hindered by large scale implementation compared to conventional methods. The research seeks to bridge this gap by assessing the economic and energetic operation factors of a combined RBF and multistage filtration system. By studying an out/in ultrafiltration treatment plant for river water and bank filtrate, the study aims to elucidate the fouling potential of raw water sources and the resulting water quality. Moreover, it explores novel methods, such as natural filtration and pesticide removal, to enhance water quality and mitigate fouling potential. The significance of this study is underscored by the pressing public health challenges posed by unsafe drinking water in India. With a substantial portion of the population vulnerable to waterborne diseases, including diarrheal illnesses responsible for thousands of deaths annually, the need for accessible and reliable water treatment solutions is paramount. By elucidating the potential of combined RBF and multistage filtration, this research endeavors to offer a pathway towards scalable, cost-effective, and sustainable water treatment solutions, thereby mitigating the burden of water-related diseases and improving public health outcomes in rural India. This study focuses on integrating multistage filtration techniques with RBF to address emerging contaminant removal challenges. Demonstration sites along the Damodar River banks evaluate the effectiveness and sustainability of this combined approach. Despite its efficiency, multistage filtration's widespread adoption is hindered by limited large-scale implementation compared to conventional methods. This research aims to assess the economic and energetic factors of a combined RBF and multistage filtration system, focusing on an ultrafiltration treatment plant for river water and bank filtrate.

1.2. DESCRIPTION OF THE STUDY AREA:

Bardhhaman is the westernmost district of West Bengal. The study area is situated between 23°16′0.2” N and 87°35′43” E as shown in 1.2**.** It comprises 20 community development blocks administrative units with a total area of 5433 km2 Government of West Bengal, 2011.



1.2 Location map of the study area.

1.3 Research Gap:

Despite the recognized efficiency of multistage filtration techniques in removing chemical parameters and emerging contaminants, their widespread adoption is hindered by limited large-scale implementation compared to conventional methods. This research seeks to bridge this gap by evaluating the economic and energetic factors of a combined RBF and multistage filtration system. It focuses on the system's effectiveness in removing emerging contaminants from raw water sources in geogenically contaminated areas of West Bengal. The study also aims to explore novel methods to enhance water quality and mitigate fouling potential, offering scalable, cost-effective, and sustainable water treatment solutions to improve public health outcomes in rural India.

1.4 Research Objectives:

This study aims to assess the effectiveness and sustainability of combining riverbank filtration (RBF) with multistage filtration techniques, including roughing filter, slow sand filter, and activated carbon, to address the challenge of removing emerging contaminants in rural areas of West Bengal, India. The research intends to achieve the following objectives:

- Evaluate the sustainable withdrawal quantity of sub-surface water in the riverbank through pumping tests and well field design.
- Assess the effectiveness of RBF and multistage filtration systems individually and in combination in removing emerging contaminants from raw water sources.
- Compare the removal efficacy of the integrated system to conventional treatment methods.
- Investigate novel methods, such as natural filtration, to enhance water quality and mitigate emerging contaminant**.**

1.5. Methodology Adopted for the Research:

The integration of Riverbank Filtration (RBF) and MSF for sustainable water supply in rural West Bengal involves a multi-faceted research methodology encompassing field studies, laboratory experiments, and modeling techniques. Field studies commence with the identification of suitable sites along riverbanks through pumping tests and well field design to evaluate the sustainable withdrawal quantity of sub-surface water. Continuous monitoring of water quality parameters at various filtration stages, alongside hydrogeological characterization of riverbank or sand filter bed properties, guides understanding of filtration efficiency. Laboratory experiments entail the replication of SSF conditions in controlled setups, facilitating the investigation of flow rates, media properties, and water quality impacts on filtration. Batch studies further delve into specific processes like microbial inactivation and chemical transformations. Advanced analytical techniques are employed for microbial and chemical analysis, utilizing methods such as chromatography and spectroscopy. This integrated approach synergizes field data, laboratory findings, and modeling insights, enabling a comprehensive comprehension of RBF and MSF processes, crucial for treating Bacteriological Quality water in geogenic regions like Bardhhaman, West Bengal. Additionally, the methodology assesses the effectiveness of RBF and multistage filtration systems individually and in combination in removing emerging contaminants from raw water sources, compares the removal efficacy of the integrated system to conventional treatment methods, and investigates novel methods such as natural filtration to enhance water quality and mitigate fouling potential.

1.6 Research Outcomes:

The research project aims to evaluate the sustainable withdrawal quantity of sub-surface water in the riverbank through pumping tests and well field design. It also seeks to assess the effectiveness of Riverbank Filtration (RBF) and multistage filtration systems individually and in combination in removing emerging contaminants from raw water sources. Additionally, the project aims to compare the removal efficacy of the integrated system to conventional treatment methods. Furthermore, the research investigates novel methods, such as natural filtration, to enhance water quality and mitigate fouling potential.

- Evaluate the sustainable withdrawal quantity of sub-surface water in the riverbank through pumping tests and well field design.
- Assess the effectiveness of RBF and multistage filtration systems individually and in combination in removing emerging contaminants from raw water sources.
- Compare the removal efficacy of the integrated system to conventional treatment methods.
- Investigate novel methods, such as natural filtration, to enhance water quality and mitigate fouling potential.

1.7 Outline of The Thesis:

Drinking water facility, condition, pollution status, economical background of villagers, cause of water pollution etc. assessment done in this study and a sustainable RBF and SSF unit developed. This research work consists of seven chapters. Chapter 2 contains literature review of different similar nature of national and international scenarios of RBF and SSF units. Chapter 3 presents the description of study area. Chapter 4 discuss about theoretical concept on water treatment technology and ground water hydrology Chapter 5 consist of methodology and experimental design of different filtration techniques. Chapter 6 contains results and discussion part. Chapter 7 ends with conclusions and recommendations.

2.0 LITERATURE REVIEW:

The integration of well field design and multistage filtration with riverbank filtration (RBF) for sustainable water supply in rural areas of West Bengal is a crucial area of research that can significantly impact public health and environmental sustainability. By reviewing 29 journal papers, the research aims to identify gaps in existing knowledge and improve the understanding of this integrated approach. RBF, a natural water-treatment process, leverages surface water infiltration into groundwater through riverbeds or banks, effectively removing microbial pathogens and contaminants. However, the efficiency of RBF depends on aquifer characteristics and groundwater flow rate. Slow sand filtration, on the other hand, is a cost-effective method for rural water treatment, removing microbial contamination without chemical additives. Integrating these methods can enhance water quality and sustainability in rural areas. Identifying research gaps through a literature review is crucial for advancing this field, ensuring that the integrated approach is optimized for maximum effectiveness and sustainability, ultimately benefiting rural communities in West Bengal.

2.1 Research Review of International and National scale on River Bank filtration, Pumping test and Aerated Slow Sand Filter in a Lab-Scale Model for water Treatment Method.

Jaramillo (2010) stated riverbank filtration (RBF) is a water treatment method that involves extracting water from rivers through wells located in adjacent alluvial aquifers. As the water travels through the underground aquifer, it undergoes various physical, chemical, and biological processes. These processes help improve the quality of the surface water, often to a degree that conventional drinking water treatment methods may be reduced or replaced. Although RBF has been widely utilized in Europe and is gaining attention in the United States, there's a lack of scientific literature on its application in Colombia, despite promising conditions. The primary objective of this paper is to provide a concise overview of the theoretical principles behind RBF, its advantages, and its limitations. In essence, RBF offers a natural and effective means of enhancing water quality by leveraging the filtration capabilities of alluvial aquifers. However, its implementation may face challenges such as site-specific geological conditions, potential contamination risks, and the need for careful monitoring and management. Nonetheless, RBF holds significant potential for sustainable water resource management and warrants further exploration, particularly in regions like Colombia where it has yet to be extensively studied or implemented.

Dalai et.al (2014) discussed water treatment encompasses the selection of sampling sites and frequencies to assess the physical, chemical, and biological properties of water. Two primary approaches to water treatment have been identified: hydrogeologic and statistical. Various methods from hydrologic literature have been evaluated based on factors such as spatial scale, sampling objectives, data requirements, temporal effects, and applicability range. Significant progress has been achieved over the past two decades, enabling the application of systematic and testable approaches to water quality monitoring and riverbank filtration design. While these approaches mainly serve for preliminary analysis and design, they contribute to understanding the efficacy of riverbank filtration as a cost-effective pretreatment for filter media technologies. Research indicates that implementing riverbank filtration can potentially reduce membrane treatment costs by 10-20%. Furthermore, recommendations have been formulated to aid utilities in evaluating riverbank filtration as a lower-cost alternative to minimize treatment expenses. Regarding Ground-Water Quality Monitoring Network Design, advancements in hydro `geochemistry, groundwater hydrology, and risk and geostatistical analysis are anticipated to enhance and refine methods for designing groundwater quality monitoring networks. These advancements will play a crucial role in improving water treatment processes, ensuring the effective management of water resources.

Ronghang et.al (2018) described the study assesses the feasibility and potential of implementing riverbank filtration (RBF) schemes for drinking water supply in the lower Himalayan region. Unlike plains where RBF has been successfully implemented, the mountainous regions have narrower alluvial aquifers confined to riverbanks. Production wells, ranging from 18 to 30 meters deep, were installed along rivers in Uttarakhand, India, at various elevations. Water samples from rivers, production wells, and hand pumps were analyzed for major ions, coliforms, and stable isotopes (δ18O and δ2H). The results revealed that the production wells consistently delivered coliform- and turbidity-free water, even during the monsoon season. However, the proportion of bank filtrate varied among sites and seasons. The Satpuli scheme predominantly drew bank filtrate throughout the year, while the other schemes relied more on groundwater, especially during the monsoon. In Srinagar, although the well water had similar chemical properties to groundwater, its isotopic composition resembled that of river water. The study highlighted the region's complex hydrology, where river water containing coliforms and suspended silt can infiltrate up to approximately 0.5 kilometers inland. Additionally, severe flooding events during the study period affected RBF sites in Srinagar and Kaleshwar, underscoring the need for flood-proofing RBF wells. Overall, the study demonstrates that RBF can be an effective and sustainable option for providing drinking water in certain regions of the lower Himalayas, despite challenges such as complex hydrology and vulnerability to flooding.

Rajendiran et.al (2022) Stated the study aimed to identify ideal locations for bank filtration wells by assessing the efficiency of riverbank filtration around a check dam in a non-perennial river in southern India. The methodology involved water sampling, water level measurements from existing wells, analysis of geochemical and biological parameters, pumping tests, and borehole drilling. Results indicated that production wells could be positioned up to 300 meters from the check dam along the groundwater flow direction, as indicated by conservative chloride and water level measurements. It was recommended that if wells do not receive at least 50% surface water contribution, they should be positioned within 110 meters. The effectiveness of riverbank filtration in improving water quality was evaluated by examining hydraulic conductivity (estimated at 20 to 50 m/day), travel time, and various water quality parameters. Even with a short travel time of 46 days, a significant reduction in microbiological load from surface water was observed. Wells located within production zones showed substantial reductions in turbidity and improved geochemical characteristics, supported by Schoeller plots. The study concluded that to maximize the benefits of bank filtration in a non-perennial river, the same well cannot be used as a production well indefinitely. Based on factors such as water level in the check dam, groundwater flow direction, and percentage contribution of the river, it may be necessary to periodically shift the location of production wells.

Knabe (2020) examined Managed aquifer recharge through bank filtration is an important method for producing sustainable drinking water, but concerns arise regarding the transport of pathogens such as bacteria and viruses from surface waters into groundwater systems, particularly in urbanized areas. A 1-year monitoring campaign was conducted at a riverbank filtration site in Germany, and a reactive transport model for bacteria transport was developed based on the collected data. The model simulates advective-dispersive transport and incorporates colloid filtration theory to mimic the attachment and detachment of bacteria to and from sediment, as well as processes like inactivation, straining, and blocking of bacteria. Due to the complexity of these processes, the model requires a high level of parameterization, covering flow, solute, and colloid transport parameters. A global sensitivity analysis was performed to identify the most relevant model parameters concerning piezometric pressure heads, groundwater temperature, and concentrations of chloride, oxygen, coliforms, and Escherichia coli. The model was calibrated within a stochastic framework to estimate model parameters and quantify their uncertainty. The results indicate that bacteria transport models are highly sensitive to parameters such as inactivation coefficients, straining coefficients, and bacteria size. The permeability of the colmation layer at the riverbank significantly influences bacteria transport by affecting residence times. Seasonal variability in boundary conditions, particularly anoxic aquifer conditions in summer and high

groundwater flow velocities during flooding periods, led to reduced inactivation and increased bacteria concentrations at observation wells.

Tyag et.al (2013) studied In the Himalayan region of India, poor water quality, bacterial contamination, seasonal variation, uncertainty during the monsoon, and sustainability issues pose significant challenges to the water sector. To address these challenges, River Bank Filtration (RBF) has been implemented in Uttarakhand as a domestic water pre-treatment technology. This technique has proven effective in removing turbidity and bacterial contamination from the surface water of four rivers in Uttarakhand: Alaknanda, Mandakini, East Nayar, and Pinder. The study reveals that RBF improves water quality sustainably compared to untreated surface river water used for drinking purposes. The classification of water quality, conducted using Pearson correlation, Piper trilinear, and Chadha's diagrams, provides further evidence of the enhanced water quality achieved through RBF. Additionally, Water Quality Index (WQI) results indicate that water samples obtained after RBF treatment consistently achieve an 'A-Grade,' signifying excellent water quality, compared to untreated river water samples that typically receive a 'B-Grade.' However, it's noted that at the Srinagar site, untreated river water was deemed unsuitable for drinking ('E-Grade'). The presence of alluvial deposits at RBF sites along the banks of the four rivers suggests the potential for replicating RBF on a larger scale in the hilly state of Uttarakhand. Overall, the study highlights the effectiveness of RBF in improving water quality and its potential for widespread implementation in the region to address water quality challenges sustainably.

Doussan et. al (1996) described that the Bank-filtrated water plays a crucial role in the production of drinking water in many countries, but the changes in water chemistry during its transfer from the river to the aquifer significantly affect the quality of the produced water. This paper focuses on an experimental site situated along the Seine River in France, where bank-filtration results in highly reducing conditions in the aquifer. The paper begins by describing the evolution of water chemistry during bank-filtration at this experimental site. A conceptual and numerical macroscopic model, particularly focusing on nitrogen compounds, is then introduced. This model is designed to simulate organic matter mineralization and redox reactions catalyzed by bacteria in the riverbed sediments where water infiltrates. It explicitly considers the growth and decay of bacteria and employs a numerical solution using an operator splitting technique. The model successfully replicates column experiments conducted by von Gunten and Zohrist in 1993, which simulated the infiltration of organically polluted river water into an aquifer. Additionally, the model is applied to the characteristics of the experimental site, highlighting the importance of two factors in particular: the flow rate of water infiltrating riverbed sediments and the organic carbon content of these sediments, for the evolution of water quality during transfer from the river to the aquifer. Overall, the study provides valuable insights into the complex processes involved in bank-filtration and underscores the significance of factors such as flow rate and organic carbon content in determining water quality during this transfer process.

Mustafa et.al (2019) describe in cases where the efficiency of riverbank filtration systems is crucial due to high pollution of river water and increasing water demand, designing pumping wells adjacent to river banks is a significant practical task. This ensures the provision of acceptable amounts of river water with minimum contaminant concentrations, thereby guaranteeing the quality and safety of drinking water supplies. This article presents an analytical solution based on the Green’s function approach to solve an inverse problem: determining the shortest distance to the riverbank that maximizes the percentage of river water based on the required level of contaminant concentration and planned pumping time period. The model is developed for a confined and homogeneous aquifer partially penetrated by the stream due to the presence of clogging layers. Initially, the analytical results obtained for various pumping times, rates, and initial concentration values are validated numerically using MODFLOW software. The distance results obtained from the proposed model are generally acceptable. Subsequently, the model is validated using data from two pumping wells located at the first riverbank filtration pilot project conducted in Malaysia. Overall, the developed analytical solution provides a practical tool for designing pumping wells near riverbanks to ensure the efficient operation of riverbank

filtration systems, especially in scenarios with high pollution levels and increasing water demand. The validation using real-world data further strengthens the reliability and applicability of the model.

Jeyakumar et. al (2017) described River Bank Filtration, a method of Managed Aquifer Recharge, involves the natural treatment of surface water as it flows through the aquifer medium. This study aims to review research conducted on River Bank Filtration in India, focusing on geological conditions, well types, and the impact of bank filtration on water quality. The review highlights that bank filtration effectively serves as a natural treatment method in India. It discusses in detail how this technique positively influences the physical, chemical, and biological quality of water. The findings suggest that River Bank Filtration can be a viable solution to partly meet the current water demand in India Overall, the study indicates that River Bank Filtration holds promise as a sustainable water treatment method in India and could be replicated in other locations after thorough examination and study.

Purandara (2015) studied in fast-developing countries like India, providing safe drinking water is a major challenge due to growing population and difficulties implementing new technologies. Increasing waste generation and lack of proper dumping sites in many cities has led to unscientific disposal of solid and liquid wastes into major rivers, turning them into wastewater streams. This trend threatens the ability to supply good quality water to the public in cities. The research studied the impact of sewage and industrial wastewater draining into freshwater streams in Belgaum city, Karnataka, and explored using riverbank filtration to overcome this. Water samples from the polluted stream and adjoining groundwater wells were analyzed. The stream water quality was significantly deteriorated, but groundwater in riparian zones was good without external treatment. Modeling showed large seepage of stream water into the groundwater aquifer. However, the groundwater quality did not degrade significantly, likely because contaminants were absorbed as water passed through thick black clayey soils before entering aquifers. This natural bank filtration process can purify polluted surface water for agriculture and domestic use. The recommendation is to construct open wells to draw good quality water from the stream filtered by this process rather than using polluted stream water directly.

Hoang (2022) investigated the Riverbank filtration (RBF) is a simple and inexpensive pretreatment technology, but its cost-effectiveness depends on complex hydrogeological and hydrochemical variables. Optimal site selection is one of the most important issues for decision makers regarding RBF implementation. The proposed methodology serves as a pre-screening method over a wide area and can also guide evaluation of individual RBF sites. It involves three sequential steps: 1) Establishing river-aquifer connectivity (essential criterion), 2) Assessing aquifer capacity and extractable bank filtrate amount (quantity criteria), 3) Evaluating surface and groundwater quality (quality criteria). The quantity and quality criteria results are combined into a site suitability index (SSI) ranging from 0 to 1, with higher scores indicating greater suitability. The methodology's reasoning and weight for each relevant factor is presented to facilitate discussion on improvements. It is applied to evaluate existing large-scale RBF sites as a demonstration, comparing their success to the calculated SSI values. In essence, it provides a multicriteria framework to systematically evaluate potential sites for implementing large-scale riverbank filtration based on key hydrogeological and water quality factors.

Zhang et.al (2023) examined the study investigated the characteristics and origins of water composition during reservoir water recharge into groundwater via river bank filtration (RBF) over four periods: before recharge, early, intermediate, and late recharge stages. Hydrogeochemical methods like Piper diagrams, chlor-alkali indices, ion correlations, and principal component analysis were used to analyze the chemical evolution of groundwater. Total dissolved solids (TDS) concentration tended to increase in later stages due to enhanced carbonate rock dissolution and cation exchange adsorption. The groundwater remained categorized as Ca-Mg-HCO3-SO4 and Ca-Mg-SO4-HCO3 type before and after recharge, indicating a small temporary influence of reservoir water. Mineral dissolution from water-rock interactions was the primary control on groundwater composition during recharge, promoting dissolution and potentially increasing nitrate levels - a risk impact. As

the recharge process continued, it further promoted mineral dissolution and water-rock reactions, altering the groundwater chemistry over time.

Boving et.al (2018) investigated on Riverbank filtration (RBF) systems which were installed in four rural villages along a 64 km stretch of the upper Krishna River in southern India, each designed to supply around 2,500 people. Site selection considered hydrogeological suitability, land availability, proximity to villages, population sizes, and power supply. Water samples from the river, RBF wells, and shallow groundwater were collected over more than a year (Nov 2015 - Dec 2017) and analyzed for E. coli, major ions, and other physico-chemical parameters. The hydrogeology of the four RBF systems was characterized using borehole logs, mixing calculations, pumping tests, and vertical profiling. Greater than 99.9% removal of E. coli was observed, especially before and during monsoon when river concentrations were highest. Results show RBF installations are challenging but possible in this region, requiring balancing well depth, setback distance from the river, and limited alluvial deposits. Viability is also influenced by surface/groundwater salinity, surrounding agricultural practices, and reliability of the power grid, factors not limited to southern India.

Gorski et.al (2021) stated in the present work measurements of chloride concentrations were used to assess the variability of infiltration conditions and contributions of surface water and local groundwater to the discharge of wells at Krajkowo riverbank filtration site (western Poland). Tests were performed on samples from 26 wells located in a well gallery close to the River Warta. Due to higher chloride concentrations in river water in comparison with local groundwater, significant differences in concentrations in samples from individual wells were noted. In particular, lower chloride concentrations in 11 wells were recorded, which can be linked to the local occurrence of low-permeability deposits in the superficial zone; a locally higher degree of riverbed sediment clogging in the highly convex meandering zone, where strong erosion of the riverbed occurred, which in turn led to increased clogging; the occurrence of a more intensive groundwater inflow into the river valley due to water infiltration from a smaller river entering the River Warta valley, as well as unfavourable conditions for the infiltration of surface water to the lower part of the aquifer with a greater thickness. Differences in chloride concentrations observed were also used to quantify approximately river water contribution to the well production. The average contribution of the River Warta to the recharge of the entire well gallery was estimated at 59.8%.

Dillon et.al (2001) examined the compatibility of using riverbank filtration for town water supplies in semi-arid areas, considering two constraints: 1) adequate removal of cyanobacterial toxins like microcystin, and 2) acceptable salinity levels for drinking water. Experiments quantified the adsorption and biodegradation of microcystin in porous media. The analysis found riverbank filtration could meet both criteria for toxin removal and salinity in a limited range of conditions, excluding locations where saline groundwater discharges to the river. For a river meander that had been flushed by a hydraulic gradient from a lock, the study compared feasible positions for bank filtration wells. It identified the best location meeting salinity and microcystin criteria while minimizing pumping energy costs. The simple approach aimed to assess the feasibility of riverbank filtration designs in semi-arid areas before conducting field studies, considering both cyanotoxin removal and salinity constraints.

Ramji et.al (2023) implemented an RBF production well in a complex hydrogeological setting under the ephemeral Varaha River in Visakhapatnam district, India to provide drinking water to nearby rural areas without piped water supply. Groundwater modeling using MODFLOW and particle tracking with MODPATH was conducted to understand the river-aquifer interactions and determine the capture zones, travel times, and proportions of river water and groundwater captured by the RBF well. two-dimensional, two-layer unconfined aquifer model with a partially penetrating well was developed to simulate the river-aquifer-well field interactions. The modeling results showed the RBF well could yield about 61% of its water from bank filtration of the river and 39% from groundwater. The modeling was used to optimize the pumping duration from the

RBF well to 5 hours per day at 31.2 m3/hr without compromising bank filtrate quality, especially during the monsoon season. The study demonstrated that RBF can be a viable approach to provide safe drinking water supply in rural areas from an ephemeral river system influenced by a saline coastal aquifer through proper design and controlled operation

Mamdouh et.al (2022) aimed to facilitate the application of riverbank filtration (RBF), an affordable drinking water treatment technique, in Egypt using numerical modeling. A groundwater model (GMS) was constructed to study the effect of four design parameters on RBF performance metrics like river filtrate portion and travel time. The four design parameters examined were: 1) pumping rates of RBF wells, 2) number of operating wells, 3) distance between wells and river, and 4) spacing between wells. The results showed that the river filtrate portion exceeded 75% regardless of design conditions. RBF hydraulic performance was highly controlled by the production capacity of wells and their positions relative to surface water, while well spacing had minimal effect. Two equations were developed to estimate the river filtrate portion and minimum travel time as functions of pumping rate and distance between the well and river. The study focused solely on the hydraulic aspects of the RBF technique.

Zahra Dashti et.al (2022) emphasized the accurate determination of hydrodynamic parameters like transmissivity, hydraulic conductivity, and storage coefficient through pumping tests is critically important for groundwater modeling and management. Two main methods are used for parameter estimation: Analytical solutions with curve matching of time-drawdown data, which is widely used but can be time-consuming and approximate Numerical modeling approaches. The study reviews the application of graphical type-curve methods, which are commonly used in water resources but relatively new for pumping test analysis. It categorizes literature from 2000-2022 into graphical, modeling, and hybrid approaches for estimating key aquifer parameters. The focus is on estimating specific capacity (C), transmissivity (T), and Storativity (S) - fundamental parameters indicating groundwater availability and flow - through aquifer performance tests (APTs). The review aims to guide researchers by examining the characteristics and capabilities of different methodologies for effective pumping test analysis, which is crucial for understanding groundwater dynamics.

Kumbhar et.al (2019) conducted 10 aquifer performance tests (APTs) across different locations within shallow basaltic aquifers. During the 3-hour tests, water was continuously pumped out, and changes in water levels were observed for drawdown and recuperation phases. The dugwell depths ranged from 11 to 18.2 meters. The results showed a wide range of specific capacity values (16 to 583.36 liters per minute per meter), Storativity values (1.8 to 13.7 meters per day), and transmissivity values (40.67 to 211.87 meters per day). These findings provide insights into the characteristics of the studied aquifers and contribute to understanding groundwater behavior in the area.

Zahid et al (2008) studied that in the deltaic and flood plain regions of Bangladesh, shallow groundwater (5-50m depth) is contaminated with high levels of arsenic, posing a major challenge for accessing safe drinking water. In Madaripur town, the municipal water supply is facing quality degradation due to high arsenic, iron, chloride, and salinity levels in the shallow and deeper aquifers. The study identified a 30-meter thick clay layer between 130-160m below the land surface, acting as a confining unit that separates the deep aquifer from the contaminated shallow aquifer. The deep aquifer below the clay layer generally contains minimal arsenic concentrations, suggesting it could be a potential source of safe drinking water if properly tapped. Utilizing aquifer-test data collected from a deep borehole, the study applies the Hantush-Jacob solution (1955) for a leaky confined aquifer. The analysis reveals that this solution provides the best fit to the data. The resulting curve matches observations from two wells, yielding key parameters: an average aquifer storage ranging from 0.0003 to 0.006, aquifer transmissivity of 4500 m^2/day, a vertical to lateral aquifer hydraulic conductivity ratio of 1.0, and a confining unit vertical hydraulic conductivity ranging from 0.044 to 0.93 m/day. This analysis confirms that the deep aquifer can supply significant quantities of water to wells with minimal drawdown, reducing the

risk of drawing potentially contaminated water from the shallow aquifer. This characterization of the deep aquifer is crucial for sustainable drinking water use in Madaripur town and similar areas facing groundwater quality challenges.

Amah et.al (2016) stated Pumping tests were conducted on 5 boreholes in Akpabuyo Local Government Area, Cross River State to assess hydraulic parameters. The results showed a range of transmissivity (T) from 485.0 m^2/d to 1346.0 m^2/d, hydraulic conductivity (k) from 9.7 m/d to 27.9 m/d, and specific capacity (SC) from 0.02 $m^3/d/m$ to 346.0 $m^3/d/m$. The mean static water level (SWL) was 30.29 m, the saturated aquifer thickness (b) was 48.0 m, and the borehole drilled depths (BDD) averaged at 64.8 m. The litho-logs confirmed that these parameters were derived from unconfined gravelly sandy aquifers underlain by sandy clay (aquitard). Suggestions for future research include incorporating observation wells for Storativity (S) computation and considering electrical resistivity techniques as a cost-effective alternative to pumping tests for estimating hydraulic parameters in the area.

Dillon et al. (2001) investigated that in semi-arid regions, using alluvial aquifers adjacent to streams for pumping town water supplies instead of directly extracting from the stream itself has shown potential for improving water quality by reducing turbidity and potentially removing blue-green algal toxins like microcystin. This method, known as riverbank filtration, involves water passing through soil and sediment layers, which can naturally filter contaminants. For the River Murray in South Eastern Australia, a significant challenge is that the ambient groundwater in unconfined aquifers along some parts of the river is saline. This poses a dual challenge for water quality: ensuring that cyanobacterial toxins are adequately removed while maintaining salinity levels that are acceptable for drinking water. Research has been conducted to quantify the adsorption and biodegradation properties of microcystin in porous media, which are crucial for understanding how effectively these toxins can be removed through riverbank filtration. The findings suggest that riverbank filtration can meet both the toxin removal and salinity criteria under specific conditions. However, locations where saline groundwater naturally discharges into the river are unsuitable for this method. In particular, a hydraulic gradient induced by a lock on a river meander was studied to identify the best positions for bank filtration wells. Several potential well locations were evaluated to find one that met both the salinity and microcystin removal requirements while also being energy efficient in terms of pumping costs. This research highlights the importance of site-specific assessments when designing riverbank filtration systems in semi-arid areas. The simple approach developed in this study aims to provide a preliminary feasibility assessment of different riverbank filtration designs before conducting detailed field studies

Fildebrandt et al. (2003) used a similar analytical approach to arrive at the appropriate separation distances between injection and recovery wells in the Bandung Basin in Indonesia, taking account of the travel time needed to achieve a given level of pathogen attenuation. A nomogram was developed that allowed prediction of the number of pathogen log removals from any set of design parameters. Miller et al., (2002) developed the ASR Risk Index (ASRRI), a computer program that evaluates the risk of contamination from trace organic or microbial contaminants based on the formulations.

SJ. Haig et.al (2011) studied on SSF has been an effective water treatment method for over 200 years, capable of removing microbiological contaminants from both small and large community water supplies. Despite its effectiveness, SSF lost popularity compared to rapid sand filters due to smaller land requirements and less sensitivity to water quality variations for the latter. SSF is still an attractive process as it does not require chemicals or electricity for operation. The high treatment level achieved by SSF is mainly attributed to naturally-occurring biochemical processes in the filter biofilm. Several microbiologically-mediated purification mechanisms (predation, scavenging, adsorption, and bio-oxidation) are hypothesized or assumed to occur in the biofilm, but these have not been comprehensively verified. Due to knowledge gaps in understanding the underlying ecology and ecophysiology of SSF, it is currently operated as a "black box," limiting the design and

optimization of the technology. Recent developments in molecular microbial ecology can help outline the biological aspects of SSF and address the existing knowledge gaps.

Abdiyev et.al (2023) examined the Providing safe drinking water to people in developing countries is a major worldwide challenge and part of the UN Sustainable Development Goals. Slow sand filters (SSF) are an efficient and inexpensive method to achieve this goal, particularly in rural areas without centralized water supply. The main advantage of SSFs in developing countries is their ability to function as biological filters, removing viruses, bacteria, and parasites from polluted surface and groundwater. However, factors like low temperature, high/intermittent flow rates, reduced sand depth, filter immaturity, and filter amendments can adversely affect the microbiological removal efficiency of SSFs. Further research is needed, specifically for developing countries, to address these issues and optimize the performance of slow sand filters in providing safe drinking water.

Ankidawa et.al (2017) The research involved designing a slow sand filtration system for treating water in rural areas, with the goals of making water treatment easy and producing high quality treated water. The system consisted of three main components: tanks to hold the raw water, filter beds containing layers of different sand particle sizes to filter the raw water, and filtrate tanks to collect the filtered water. After initial filtration through the sand beds, the water passed through a filter media containing diatomite to provide further filtering before entering the final filtrate tanks. Testing showed that this slow sand filtration system with the added diatomite filter was moderately efficient for treating raw water in rural areas. The design utilized appropriate technology principles, allowing for simple operation while still improving the taste and odor of the treated water compared to the raw water source. Key advantages were the low operational complexity and the effective removal of contaminants to produce cleaner, better tasting water for rural domestic use through this multi-stage filtration process.

Thomas et.al (2016) examined Slow sand filtration is a simple water treatment technology suitable for small, rural communities as it does not require high operator skill or constant attention. It operates at very slow filtration rates, at least 50 times slower than rapid rate filtration, necessitating large land areas for the filter basins. No chemical addition is required as particle removal occurs primarily through biological processes in the top layer called the "Schmutzdecke" as well as potentially throughout the filter bed depth. A ripening period of several weeks to months is needed for the biological organisms to mature in a new slow sand filter. Instead of backwashing, the filter beds are periodically scraped or harrowed when head loss builds up to 3-4 feet to remove accumulated particles. The slow rate and biological treatment mechanism make it a low-maintenance and chemical-free water filtration option, especially suitable for small community water supplies.

Maiyo et.al (2022) analyzed Safe drinking water remains a major global challenge, especially in rural areas of developing nations. Slow sand filters (SSFs) or biological sand filters are ideal low-cost water treatment solutions for these regions. SSFs remove suspended particles, organic compounds, turbidity, and contaminants, enabling low-cost disinfection methods. While the core principles remain the same, SSF designs and sizes have been customized over time. This review covers recent adaptations and performance reports, focusing on turbidity and microbial contaminant removal - critical issues for rural populations in developing countries. Addressing unsafe water through appropriate technologies like SSFs can reduce disease burden and economic impacts in these areas.

Bhutiani et.al (2018) realized that Sand intermittent filtration was studied for industrial wastewater treatment. Beds with sand/gravel mixtures performed better than 100% sand beds. The 2:1 sand:gravel ratio yielded the best overall results. Maximum reductions were observed for parameters like BOD (94%), COD (59.65%), TSS (46.26%). Other parameters like pH, TDS, chlorides and hardness also showed good reductions. Reductions were highest at 30 cm bed width across all setups. Sand/gravel beds are a promising low-cost option for

industrial wastewater treatment. This technology can be suitable for developing countries with limited resources.

3.DESCRIPTION OF THE STUDY AREA

3.1 Location:

Bardhhaman is the westernmost district of West Bengal. The study area is situated between 23°16′0.2” N and 87°35′43” E as shown in Figure3.1**.** It comprises 20 community development blocks administrative units with a total area of 5433 km2 Government of West Bengal, 2011.

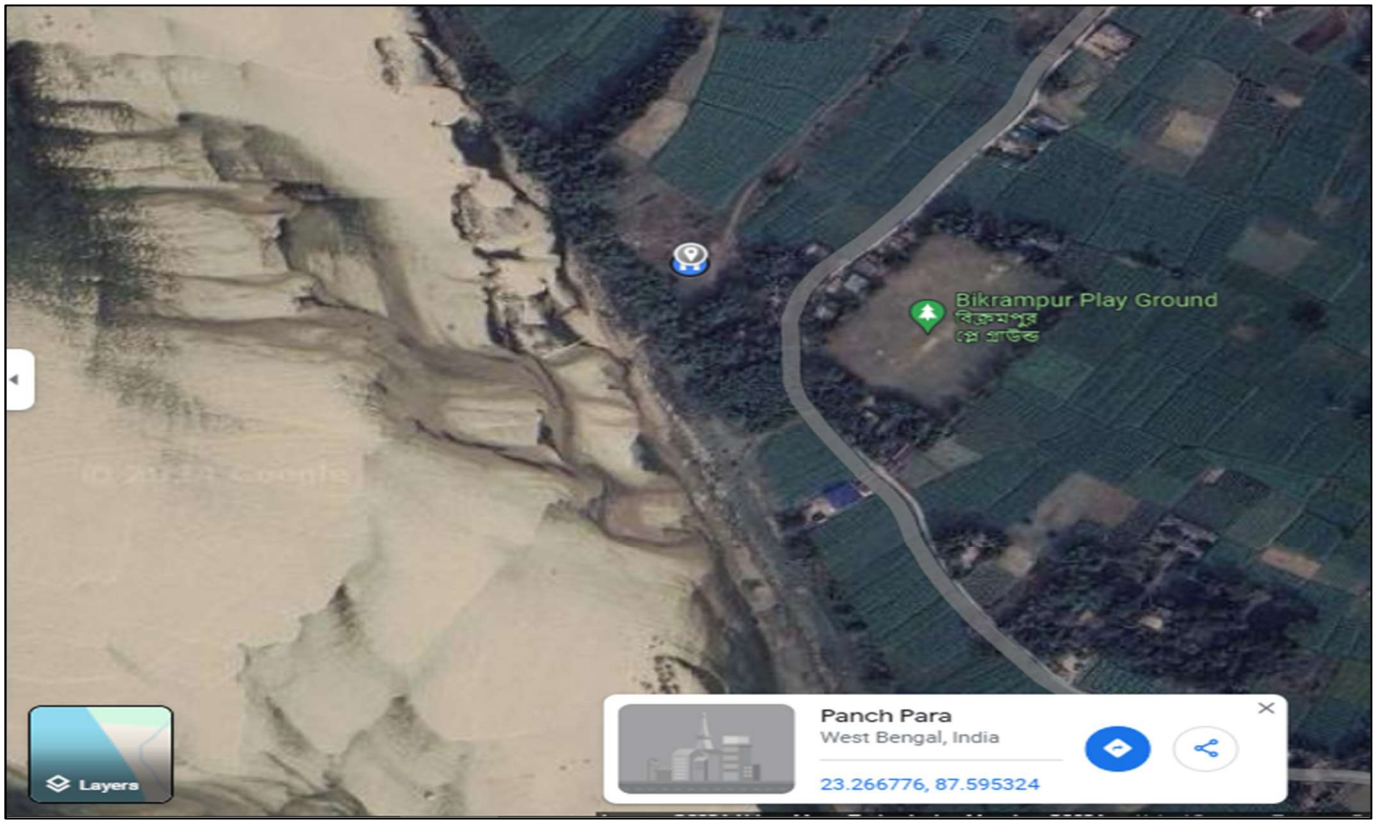


Figure 3.1 : Study Area of The Map

he focused ADI region has occupying an area of 5433 km^2 in the Bhagirathi-Hooghly catchment with an approx. look like a hammer. Administratively, the region is placed on the Bardhhaman District of West Bengal in eastern India. The study area is bounded by the Ajay River on the north, Barakar River and Maithan Dam on the west, girdled by Damodar River on the south and the Bhagirathi-Hooghly River on the east. District boundary of Bardhhaman has been taken as the limit of study area in the southeast corner.

The study area lies in the north-eastern part of the ‘*Rarh* Bengal’ (Bagchi and Mukherjee, 1979) and is divided into three distinct geomorphic units by the contour lines . On the basis of pedo-geomorphological classification (Singh et al., 1998), the western part of the region lies under the ‘Old Fluvial or Deltaic Plains’, whereas eastern part lies on the ‘Young Fluvial Plains’. Geologically, the area is characterized by Quaternary sediments on the east and by Gondwana Super Group with some lateritic patches on the western part (GSI, 2001); it is also overlain by Vindhyan Alluvium (Agricultural Finance Corporation Ltd., 2013). Elevation of the region ranges from 2 to 221 m (as per ASTER data, 2009), where a majority portion of land (40.32%) comes under Plateau Fringe.

3.2 Population of Rural and Urban:

As per 2011 census, 60.11 % population of Bardhhaman districts lives in rural areas of villages. The total Bardhhaman district population living in rural areas is 4,639,264 of which males and females are 2,373,787 and 2,265,477 respectively. In rural areas of Bardhhaman district, sex ratio is 954 females per 1000 males. If child sex ratio data of Bardhhaman district is considered, figure is 962 girls per 1000 boys. Child population in the age 0-6 is 511,969 in rural areas of which males were 260,995 and females were 250,974. The child population comprises 10.99 % of total rural population of Bardhhaman district. Literacy rate in rural areas of Bardhhaman district is 72.65 % as per census data 2011. Gender wise, male and female literacy stood at 79.12 and 65.86 percent respectively. In total, 2,998,277 people were literate of which males and females were 1,671,556 and 1,326,721 respectively.

Table 3.2: Population Census Data of Bardhhaman district, West Bengal:

Village	Population	Area (km2)	Pop. Density	Sex-ratio
Jamalpur	266338	267.39	996	980
Mangolkote	263240	390.73	674	954
Bhatar	263064	430.38	611	962
Manteswar	237398	321.30	739	963
Memari - I	218425	186.43	1172	973
Burdwan - I	215943	247.64	872	966
Purbasthali - II	212355	203.98	1041	940
Purbasthali - I	206977	154.99	1335	934
Kalna - I	206945	177.07	1169	958
Khandaghosh	189336	275.13	688	950
Galsi - I	187588	263.57	712	939
Ondal	186915	78.14	2392	904
Raina - I	180952	272.62	664	959
Kanksa	178125	288.07	618	950
Katwa - I	173087	178.72	968	943
Kalna - II	167335	181.51	922	976
Ketugram - I	165408	202.75	816	947
Salanpur	163057	47.39	3441	946
Pandabeswar	161891	114.53	1413	912
Burdwan - II	152939	188.26	812	979
Raina - II	151401	230.28	657	953
Ausgram - II	150896	358.13	421	955
Memari - II	150252	201.07	747	964
Galsi - II	147177	223.46	659	969
Katwa - II	136708	154.78	883	937
Barabani	123598	43.04	2872	933
Jamuria	123176	133.86	920	907

3.3 Climate and Temperature:

The hot season lasts for 2.8 months, from March 25 to June 17, with an average daily high temperature above 94°F. The hottest month of the year in Bardhamān is May, with an average high of 98°F and low of 80°F.The cool season lasts for 2.0 months, from December 5 to February 6, with an average daily high temperature below 80°F. The coldest month of the year in Bardhhaman is January, with an average low of 55°F and high of 76°F

3.4 Rainfall:

Average annual rainfall is 1417 mm. The winter season starts from about the middle of November and continues till the end of February. March to May is dry summer intervened by tropical cyclones and storms which although infrequent. June to September is wet summer while October and November is autumn.Fig.2.4 depicted the average rainfall of the district. The district's southern region experiences the most rainfall, while the western and central regions have the least. However, due to the harsh, rocky terrain, most of the water evaporates as surface runoff, thus this little fluctuation in precipitation has little bearing on the existence and accessibility of groundwater.

3.5. Slope and Elevation:

- **Slope**: The district has a gentle slope, with a gradual elevation change from north to south. The northern part of the district is slightly higher in elevation compared to the southern part. However, the overall slope is not steep, and the terrain is generally suitable for agriculture and human settlement.
- **Elevation**: The average elevation of the Bardhhaman district ranges from approximately 20 meters (65 feet) above mean sea level in the southern parts to around 50 meters (164 feet) in the northern areas. The highest point in the district is located near the town of Galsi, with an elevation of around 80 meters (262 feet) above mean sea level. The district's flat terrain is due to its location in the lower Gangetic plain, which is a vast alluvial plain formed by the deposition of sediments from the Ganges River and its tributaries over thousands of years. The soil in the region is generally fertile, making it suitable for cultivation of crops like rice, wheat, potatoes, and vegetables. It's important to note that while the overall topography of the Bardhhaman district is relatively flat, there may be some local variations in elevation and slope, especially in areas near rivers or other water bodies. Additionally, human activities such as construction, mining, and agricultural practices can also influence the local topography to some extent

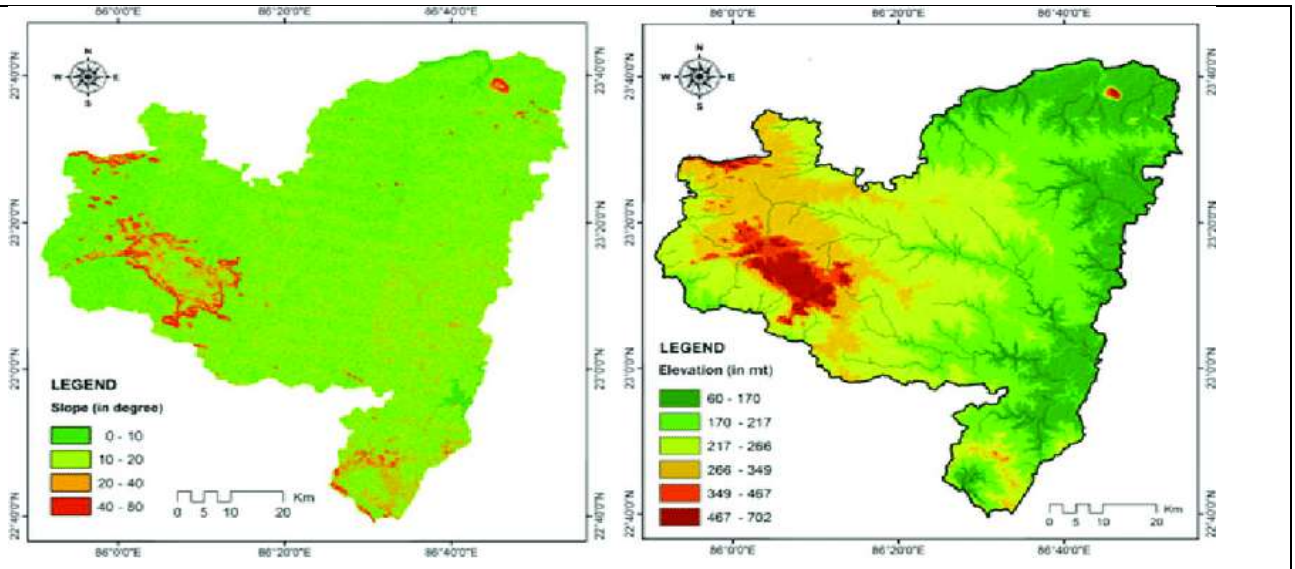


Figure 3.5: Slope and Elevation map of Bardhhaman District

3.6. Natural Vegetation & Forest Cover:

The natural vegetation in the Purba Bardhhaman district is primarily tropical in nature, encompassing deciduous forests, scrub forests, and grasslands. Common tree species found in the region include Sal (Shorea robusta), Mahua (Madhuca longifolia), Neem (Azadirachta indica), and various species of Acacia. The district also features riverine vegetation along the banks of the Damodar River and its tributaries.According to the India

State of Forest Report (ISFR) 2021, the total forest cover in Purba Bardhhaman district is approximately 289.66 square kilometers, accounting for around 6.59% of the district's total geographical area. The district hosts several protected areas and reserved forests, including Baikunthapur Forest Division, Ambika Tiger Reserve (partially located in the district), Chhatna Reserve Forest, Patiraj Reserve Forest, and Ranibandh Reserve Forest. The forests in the district are predominantly dry deciduous and mixed dry deciduous types, serving as habitats for various flora and fauna species, including endangered species such as the Indian Elephant and the Indian Leopard.

3.7. Geology & Minerals:

- Geological Formation: Purba Bardhhaman is situated in the Damodar Valley region, which is a part of the lower Gondwana basin. The geological formation in this area primarily consists of sedimentary rocks like sandstone, shale, and coal seams belonging to the Permian-Triassic age.
- Coal Resources: The Raniganj Coalfield, which is a part of the Damodar Valley Coalfields, extends into the Purba Bardhhaman district. This coalfield is known for its high-quality coal reserves, which have been extensively mined for several decades.
- Fire Clay: Purba Bardhhaman is renowned for its fire clay deposits, which are found in association with the coal seams. Fire clay is an important raw material for the manufacturing of refractory bricks, which are used in furnaces and kilns.
- Building Materials: The district is also known for its reserves of building materials like stone, gravel, and sand, which are extracted from various quarries and riverbeds in the region.
- Mineral Exploration: There have been ongoing efforts by the Geological Survey of India (GSI) and other agencies to explore and map the mineral resources in Purba Bardhamān and the surrounding areas.

The geological and mineral resources of Purba Bardhamān have played a crucial role in the economic development of the region, particularly in the mining and manufacturing industries. However, it is important to strike a balance between resource extraction and environmental conservation for sustainable development

3.8. Soil Type:

- Alluvial Soils: A large portion of the district is covered by alluvial soils, which are formed by the deposition of sediments carried by the Bhagirathi River (a distributary of the Ganges River) and its tributaries. These soils are generally fertile and suitable for agriculture.
- Red and Lateritic Soils: In the western and southwestern parts of the district, red and lateritic soils are found. These soils are formed under conditions of high temperature and heavy rainfall, leading to the leaching of silica and the accumulation of iron and aluminum oxides.
- Coastal Alluvial Soils: In the eastern part of the district, near the confluence of the Bhagirathi River with the Hooghly River, coastal alluvial soils are found. These soils are influenced by tidal action and are often saline in nature.
- Terai Soils: In the northern part of the district, near the foothills of the Himalayas, terai soils are found. These soils are formed by the deposition of sediments carried by streams originating from the Himalayan ranges. The alluvial soils and coastal alluvial soils are generally fertile and suitable for agriculture, particularly for the cultivation of paddy, jute, and vegetables. The red and lateritic soils, on the other hand, are less fertile and require appropriate soil management practices for agriculture.

3.9. Geomorphology and Hydrogeology:

Purba Bardhhaman district is predominantly flat and plain, featuring a gentle slope towards the east and southeast, characteristic of the Lower Gangetic Plain. The district is divided into two main physiographic units: The Older Alluvial Plain, which covers the western part of the district and is characterized by older

alluvial deposits from the Ganga River system, and the Newer Alluvial Plain, which covers the eastern part of the district and consists of newer alluvial deposits from the Ganga and its tributaries. The soil in the district is predominantly alluvial, ranging from sandy loam to clay loam, with texture and composition varying depending on the physiographic unit.

Hydrogeologically, the district is underlain by a multi-layered aquifer system, consisting of both confined and unconfined aquifers. Groundwater occurs under semi-confined to confined conditions in the deeper aquifers, while it is mostly unconfined in the shallow aquifers. The depth to the water table varies from a few meters to about 20 meters below ground level, depending on location and season. Generally, the groundwater quality is good and suitable for drinking and agricultural purposes, though localized pockets of high iron, arsenic, and salinity concentrations have been reported. The district is drained by the Ganga River and its tributaries, such as the Damodar, Ajay, and Kunur rivers, which play significant roles in the recharge and discharge of groundwater in the region**.**

3.10. Water Quality Scenario of Study Area

- Water Sampling:

- Groundwater and surface water samples were collected from different sources within the Bardhhaman circle, at the block level.
- Sampling was done during both the pre-monsoon and post-monsoon seasons.

- **Water Quality Parameters**:

- Different water quality parameters were analyzed, both on-site and in the laboratory.
- These parameters were used to assess the suitability of the water for various applications, such as drinking, domestic use, irrigation, bathing, or sustaining aquatic life.

- **Conductivity and Total Dissolved Solids (TDS**):

- The conductivity and TDS data suggested that surface water is a better choice over groundwater for agricultural applications.
- Higher conductivity and TDS levels in groundwater could indicate the presence of dissolved salts or other substances, which may not be favourable for irrigation purposes.

- **Arsenic:** Contamination in Purbasthali Block, Burdwan District:

- In the Purbasthali block of Burdwan district, water from a deeper tube well was found to be more suitable for drinking purposes compared to a shallow tube well.
- This assessment was based on the arsenic contamination levels, which were lower in the deeper tube well water.

3.11. Water Resources Problem of the Study Area:

• Groundwater depletion: Excessive extraction of groundwater for agricultural and domestic purposes has led to a significant decline in groundwater levels in the district. This has resulted in the drying up of many shallow and deep tube wells, particularly during the summer months.

• Arsenic contamination: The presence of arsenic in groundwater is a severe problem in several blocks of the Bardhhaman district. Prolonged consumption of arsenic-contaminated water can lead to various health issues, including skin lesions, cancer, and neurological disorders.

• Salinity ingress: In the coastal areas of the district, saltwater intrusion into groundwater aquifers has been observed due to excessive groundwater extraction and sea-level rise. This has rendered the groundwater unsuitable for drinking and irrigation purposes.

• Flooding: The district is prone to frequent floods, particularly during the monsoon season, due to its proximity to the Damodar River and its tributaries. Floods can contaminate water sources and disrupt water supply systems.

• Water quality issues: Apart from arsenic and salinity, the water resources in the district may also be affected by other contaminants, such as fluoride, iron, and microbial pollutants, which can pose health risks and make the water unsuitable for consumption.

4. **THEORETICAL CONCEPTS OF DIFFERENT TOPICS**:

THEORETICAL CONCEPTS OF TWO TYPES WATER TREATMENT TECHNOLOGY

4.1. RIVER BANK FILTRATION 4.2. SLOW SAND FILTER

4.1. RIVER BANK FILTRATION:

Riverbank Filtration (RBF) is a technology that operates by pumping out water from borewells drilled along the banks of a river. During the pumping process, river water infiltrates into and passes through the riverbed sediments. As the raw surface water travels towards the RBF well, dissolved and suspended contaminants, as well as pathogens are potentially removed or significantly reduced in numbers resulting from a combination of the physical, chemical and biological processes. When wells are placed sufficiently close to rivers or other surface water bodies, a part of the surface water is induced to flow toward the cone of depression caused by the pumping wells. The pumped water, thus, is a mixture of groundwater and surface water. The early emphasis of RBF was on the enhancement of well yields, whereas the later emphasis has been on the improvement of water quality. Most RBF wells are typically located in alluvial aquifers along riverbanks or in the unconsolidated sand and gravel along lakeshores or storage reservoirs. The alluvial aquifers along riverbanks can store and release river water, depending upon the river stage. When a river floods, part of the water gets stored in the adjacent aquifers. As the river stage drops below that in the adjacent aquifers, the stored water drains to the river. This exchange process, known as "bank storage," can take place without pumping stresses. Bank-stored water can contain the contaminants normally found in river waters. Although there is some similarity between RBF and bank storage, readers should realize the primary difference between the two processes stated above. In the early years of RBF construction, enhanced well yield through induced infiltration was the primary goal. More recently, improvements in water quality have become equally important. Rivers, reservoirs, and lakes experience seasonal fluctuations in water quality. For example, rivers and lakes near cities in combe It states experience peak concentrations of agricultural chemicals in late spring and early summer when the runoff from farm fields contributes to stream flow. Similarly, most rivers and lakes in temperate climates experience high concentrations of dissolved organic carbon in late fall when decomposed leaf litter finds its way to streams and rivers. Utilities that directly use surface water not only have to deal with these seasonal variations in chemical concentrations, but if they are located on the banks of navigable waters, they also have to deal with minor to massive chemical spills. RBF systems moderate the concentration peaks in the event of a spill and attenuate most contaminants found in river waters. Particulates and pathogens can be filtered out by the porous media to a significant extent. Many chemicals from surface water are also attenuated by sorption, microbial decay, and other chemical reactions. Pathogens such as bacteria and viruses can be removed due to a combination of sorption and death. If the background groundwater contains relatively low concentrations of chemicals compared to the concentrations in surface water, this means dilution has taken place and chemicals from surface water have dispersed during the travel toward the pumping wells.

Design Considerations:

The main design considerations when using Riverbank Filtration are water quantity and quality, and any system will require a balance of the two. The intake needs to produce sufficient quantity for the intended purpose at an acceptable quality. Both will be determined by the type of sediments between the surface water source and the intake as well as the distance between the water source and abstraction point.

In most long-term set-ups, the abstraction rate will decrease due to clogging of the interface between the surface and groundwater. Where bank sediments are not permeable enough to allow the required volume to be abstracted from the intake, various improvements can be made. These include creating an artificial channel of permeable sediments between the water source and intake, which is then backfilled above the channel, or using an infiltration gallery, which consists of a horizontal 75–300 mm jointed or slotted pipe laid beneath the riverbed or in the banks. Infiltration galleries should have a graded gravel filter installed around the pipe, which should be at least 1metre below the dry-season saturated zone and deep enough to not be affected by river scour (at least 1.5metres). For infiltration galleries, clogging can still occur with time, so they are best suited to river sections where there is no deposition (i.e. choosing riverbeds with medium to coarse sand and avoiding the inside of river bends where deposition occurs). It is also best to avoid having any gravel bed in direct contact with the river water, as clogging may increase compared with a sand surface (as fine particles tend to penetrate the bed deeper, preventing their subsequent resuspension through scour). The construction of both of these systems is usually more difficult than for other intakes and requires a significant amount of excavation and de-watering. Various other intakes can be used in conjunction with Riverbank Filtration, such as Protected Boreholes or jetted wells and Protected Dug Wells or riverbed wells. These can be constructed within/under the riverbed itself (e.g. jetted or riverbed wells with off-set suction pump) or in the riverbanks. Water quantity for all types of Riverbank Filtration intakes can also be increased through managed aquifer recharge methods, such as gully plugs, check dams, leaky dams and groundwater dams in seasonal rivers. The microbiological, chemical and physical water quality of surface water will be much improved through Riverbank Filtration due to the combination of natural treatment processes, though a final treatment may still be needed. Alternatives to Riverbank Filtration include treating surface water through Roughing Filtration. Rapid Sand Filtration and Slow Sand Filtration on the riverbanks or in the home.

Materials

Riverbank Filtration can be a good option for using local materials and skills, depending on the type of intake (e.g. PVC pipes, locally available gravel, concrete).

Applicability

Riverbank Filtration is a good option for the acute response phase, as long as the intake can be created quickly (e.g. jetted well). Other intakes will probably be more suited to the recovery and stabilization phases due to the time taken for excavation and construction (e.g. infiltration gallery or Protected Dug Well, I.7). Its main use is to improve water quality to reduce subsequent treatment needs (e.g. to allow for chlorination only).

Health and Safety

Water may still need treatment or may be a risk to health, particularly from the microbiological contamination that is more likely to be an issue in populated areas or where there are a lot of animals. Other health risks are

associated with excavation and will vary according to the type of intake. For infiltration galleries or where channels of permeable material are installed between the source and intake, a risk of collapse in the saturated zone combined with the required deep trench excavation pose a health risk where construction/shuttering procedures are not adequate.

RBF Performance Assessment:

WELL TYPES IN RBF SYSTEMS

1. **Vertical Wells**

Description: Vertical wells are the most common type of wells used in RBF systems. These wells are drilled vertically into the ground to reach the aquifer from which water will be extracted.

Advantages:

Deep Penetration: They can reach deeper aquifers, which may be more protected from surface contamination.

High Yield: Capable of providing substantial amounts of water, depending on the aquifer's characteristics.

Ease of Maintenance: Easier to maintain and monitor compared to other well types.

Disadvantages:

Higher Costs: Drilling deep vertical wells can be more expensive.

Limited to Specific Geological Conditions: They may not be suitable in areas with thick layers of impermeable material above the aquifer.

Applications:

Commonly used in various geological settings, especially where deep aquifers with high yield are present.

2. Horizontal Collector Wells (Ranney Wells)

Description: Horizontal collector wells, also known as Ranney wells, consist of a central vertical shaft with horizontal laterals (screens) extending radially into the aquifer. These laterals are perforated pipes that collect water horizontally.

Advantages:

Large Area Coverage: They cover a larger area of the aquifer, increasing water collection efficiency.

High Volume Extraction: Suitable for extracting large volumes of water.

Effective Filtration: Enhanced filtration due to the extended contact with the aquifer material.

Disadvantages:

Complex Installation: More complex and expensive to install compared to vertical wells.

Maintenance Challenges: More challenging to maintain, especially the horizontal laterals.

Applications:

Ideal for sites where extensive horizontal aquifer exposure is needed, such as in large river valleys with extensive alluvial deposits.

3. Infiltration Galleries

Description: Infiltration galleries consist of horizontal perforated or slotted pipes buried beneath the riverbed or bank. These pipes collect water that infiltrates from the surface water body into the subsurface.

Advantages:

Shallow Installation: Can be installed at shallow depths, making them less expensive to construct.

Uniform Water Quality: Provide more uniform water quality as the water passes through the same filtration media.

Low Maintenance: Easier to maintain compared to deep wells.

Disadvantages:

Limited to Shallow Aquifers: Suitable only for shallow aquifers.

Lower Yield: Typically have lower yields compared to vertical and horizontal wells.

Susceptible to Surface Contamination: More susceptible to contamination from surface activities.

Applications:

Often used in small-scale RBF systems or in areas where shallow aquifers are sufficient to meet water demand.

4. Caisson Wells

Description: Caisson wells are large-diameter wells constructed by sinking a pre-fabricated caisson (a watertight structure) into the ground. These wells are typically used where the aquifer is shallow and has a high yield.

Advantages:

High Capacity: Capable of yielding large volumes of water.

Durability: Robust construction suitable for long-term use.

Ease of Access: Easier to access for maintenance and repairs.

Disadvantages:

High Initial Cost: Expensive to construct due to the size and materials required.

Geological Limitations: Not suitable for deep aquifers or areas with complex geology.

Applications:

Best suited for areas with high-yield, shallow aquifers, such as in large river plains.

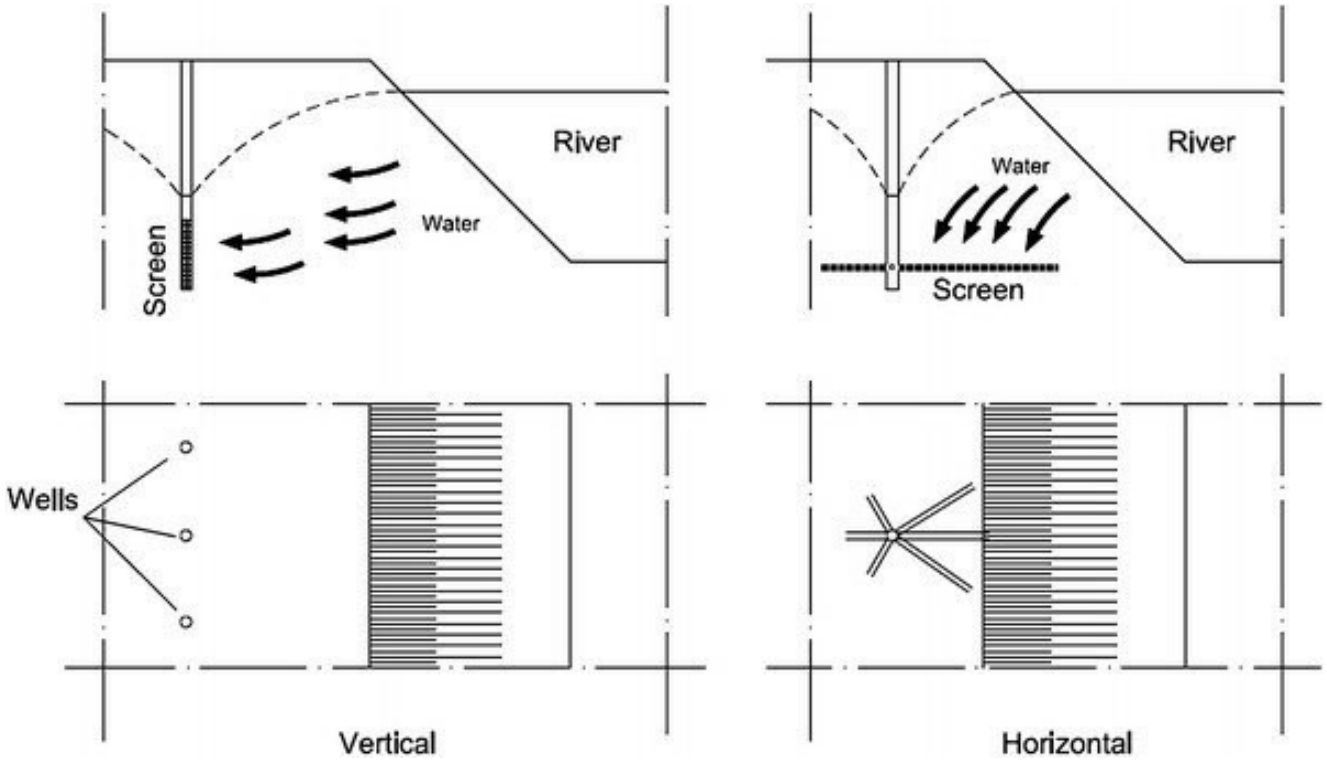


Figure. 4.1: Well Types in RBF Systems

- **. WATER QUALITY IMPROVEMENTS WITH RBF**

Mechanisms of Water Quality Improvement

1. **Physical Filtration**:
    - **Particulate Removal**: As surface water infiltrates through the riverbank and aquifer materials, particulates, including suspended solids and sediments, are trapped in the porous media. This physical filtration process significantly reduces turbidity and particulate content in the water.
2. **Biological Processes**:
    - **Microbial Pathogen Removal**: RBF is effective in removing microbial pathogens, including bacteria, viruses, and protozoa. The slow movement of water through the porous media increases contact time between the water and microorganisms present in the soil, enhancing the removal of pathogens through biological processes such as predation, competition, and natural die-off.
    - **Biofilm Formation**: Aquifer materials support the formation of biofilms on their surfaces. These biofilms consist of microorganisms that can degrade organic matter and reduce the concentration of contaminants in the water.
3. **Chemical Processes**:
    - **Adsorption**: Contaminants such as heavy metals and organic pollutants can be adsorbed onto the surfaces of aquifer materials. This process reduces the concentration of these harmful substances in the water.

- **Redox Reactions**: RBF environments often facilitate redox reactions that can transform contaminants into less harmful forms. For example, nitrate can be reduced to nitrogen gas through denitrification, thereby removing nitrogen-based pollutants from the water.

4. **Hydraulic Gradient Enhancement**:
    - The hydraulic gradient imposed by nearby pumping wells enhances the infiltration rate of surface water into the aquifer. This increased infiltration can improve the efficiency of the RBF process by increasing the volume of water treated and enhancing the contact time between water and aquifer materials.

Factors Influencing RBF Efficiency

1. **Aquifer Characteristics**:
    - **Granular Porous Media**: Aquifers composed of granular materials with open pore spaces are most effective for RBF. The tortuous flow paths in these media provide ample opportunity for contaminants to come into contact with and attach to grain surfaces.
    - **Permeability and Porosity**: High permeability and porosity enhance the infiltration and flow of water, improving the efficiency of contaminant removal.
2. **Groundwater Velocity**:
    - **Slow Flow Rates**: Slow groundwater velocities increase the contact time between water and aquifer materials, enhancing the removal processes. In slow-flow conditions, the likelihood of contaminant detachment is reduced, and microorganisms are more likely to become inactivated before reaching the pumping well.
3. **Hydraulic Loading Rates**:
    - Appropriate hydraulic loading rates are critical for maintaining the efficiency of the RBF process. Overloading can reduce the contact time and filtration capacity, while underloading may not effectively utilize the filtration potential of the aquifer.

➢ Physical, chemical and biological characteristics and fate during bank filtration Physical water-quality parameters:

Turbidity:

In place of direct measurement of SS of natural surface waters or drinking waters, a test for turbidity is used. Turbidity is a measure of the extent to which light is either absorbed or scattered by material present in water. Because absorption and scattering are influenced by both size and surface characteristics of the SS, turbidity is not a direct quantitative measurement of SS. In almost all studies on RBF, the turbidity of filtrate has been found to be very low (< 0.3 NTU). It is one of those characteristics of surface waters, which is altered very easily as river water flows towards an RBF well. Turbidity is retained on the interface and in the adjacent layers of the aquifer material. Inert material builds up while organic one undergoes changes. During high flow, it is washed off, and a fresh filtering layer is laid.

Color: Pure water is colourless, but surface waters are often coloured due to the presence of foreign substances. Water may have true or apparent colour. Color contributed by the dissolved

material is defined as true while that partly due to SS is classified as apparent. In RBF, apparent colour is removed while true colour is not eliminated in many cases requiring post-treatment of filtrate.

Taste and odor: Substances that produce an odour in water will almost invariably impart a taste as well. The reverse is not true, as there are many mineral substances that produce taste but no odour. A comprehensive study regarding the attenuation of taste and odour during RBF is not reported.

Temperature: Temperature is not used to evaluate the potable waters directly. Surface waters experience large fluctuations in temperatures. In the case of the filtrate, wide variations have not been reported

Chemical water-quality parameters: Water is a universal solvent. Total dissolved solids, alkalinity, hardness, metals, organics, and nutrients are some of the chemical parameters of concern.

Total dissolved solids: Dissolved solids (DSs) enter in natural waters due to solvent action of water on solids, liquids, and gases. Like SSs, DSs are also inorganic and organic in nature. Examples of inorganic DSs are minerals, metals, and gases while common organic DSs are materials from the decay products of vegetation, from organic chemicals, and from the organic gases. Water comes in contact with these materials in the atmosphere, on surfaces, and within the soil. During RBF, DSs increase mainly due to the dissolution of aquifer material and mixing with groundwater. In general, at particular place groundwater has more DSs compared to surface waters. Accordingly, bank filtrate has been found to contain more DSs than the corresponding surface source

Alkalinity: Alkalinity causing compounds result from the dissolution of mineral substances present in the soil and atmosphere. Wastewater discharges, fertilizers and microbial decomposition of organic material also contribute. By far the most common constituents of alkalinity are bicarbonate, carbonate, and hydroxide. In addition to their mineral origin, these substances also originate from carbon dioxide, a constituent of atmosphere and a product of microbial decomposition of organic material in the aquifer adjacent to the interface. As water travels from the surface source to the well its alkalinity increases. Bank filtrates have been found to have greater alkalinity than corresponding natural surface waters.

Hardness : Hardness is defined as the concentration of multivalent metallic cations in solution. Calcium and magnesium are the most abundant ones, and for all practical purposes, hardness is represented by the sum of the calcium and magnesium ions. During RBF, hardness has been found to increase. The increase depends on the proportion of groundwater in the pumped water, time surface water takes to reach the well and distance it travels, and geology/ aquifer characteristics. As long as hardness remains within prescribed desirable/ permissible limits, no post-treatment of filtrate is required. In most of the studies, increase in hardness has been reported to be within limits as specified in the Indian Standard for Drinking Water.

Metals: All metals are soluble to some extent in water. An excessive amount of any metal may present health hazards. However, only those metals that are harmful in relatively small amounts are commonly labelled toxic; others fall into the nontoxic group. Sources include dissolution from natural deposits and discharges of domestic, industrial, or agricultural wastewaters. In the case of RBF, it is essential to know the geology of the well surroundings.

Organics: Many organic materials are soluble in water. In natural waters, organics come from either natural sources or result from human activities. Most of the natural organics are the result of the decay of organic solids. Synthetic organics are due to discharges of wastewaters or runoff from agricultural lands. Organics are classified as biodegradable/ non-biodegradable (refractory). In studies related to RBF, the important parameter is total/ dissolved organic carbon (TOC/ DOC), which includes both biodegradable and non-biodegradable fractions. Presence of organics is also related to disinfection by-products. A filtrate having DOC < 2 mg/L is considered to be safe for further chlorination. In some of the studies on RBF, it has been found that if the source water is polluted, bank filtrate had unacceptable DOC and post-treatment for the removal of organics was unavoidable.

Nutrients: A wide variety of minerals and trace elements can be classified as nutrients. Those required in most abundance by aquatic species are carbon, nitrogen, and phosphorus. In most cases, nitrogen and phosphorus are the nutrients that are limiting factors. Nutrients are of more relevance in the case of lakes/ reservoirs rather than rivers. As lake bank filtration sites are limited, the fate of nutrients during RBF is not studied much.

Biological water-quality parameters

Water serves as a medium in which literally thousands of biological species spend part of their life cycles. Aquatic organisms' range in size and complexity from the smallest single-cell microorganism to the largest fish. Pathogens/ pathogen indicators Pathogens are the most important biological organisms in water from the perspective of human use and consumption as they are capable of infecting, or of transmitting diseases to humans. These organisms are not native to aquatic systems and usually require an animal host for growth and reproduction. They are only temporary members of the system and can survive and maintain their infectious capabilities for significant periods of time. These waterborne pathogens include species of bacteria, viruses, protozoa, and helminths.

- **Advantages of RBF:**

•**Natural Process**: Utilizes natural geological and biological processes, minimizing the need for chemical additives.

•**Cost-Effective**: generally, less expensive than conventional water treatment methods, particularly in areas with suitable geological conditions.

•**Sustainable**: Provides a sustainable water treatment solution with low operational and maintenance costs.

•**High-Quality Water**: Produces water with improved physical, chemical, and microbiological quality.

4.2. The different of treatment unit:

- **Aeration:**

It is generally used for groundwater and removes undesirable gases. It can also remove volatile illiquid like phenols & humic acids. It removes iron and manganese & it also increases the acidity of water. There is a different process which is used for aeration are discussed below:

- **Spray nozzle:** Very costly and high efficiency.
- **Cascade aerator:** In the aeration process, the cheapest method is the cascade method.
- **Diffused air aerator:** Water absorbs oxygen from compressed air and Colour, odour and taste are removed.
- **Trickling bed or tray tower aerator:** It is used in small-scale industries where discharge is less.

- **Sedimentation**

It is used to removed suspended solids. It is two types:

- **Plain sedimentation:** Discrete particles will remove here.
- **Sedimentation with Coagulation:** Coagulants used to agglomerate the colloidal particle.

Flocculation

Slow mixing or agitation process in which destabilized colloidal particles are brought into intimate contact.

- **Filtration**

Economically effective in controlling guinea worm disease. The use of sand and gravel as filter media for water supplies can be split into three basic filter types: slow sand filters, rapid filters, and roughing filters.

- **Slow sand filter:** In this filter particle size varies between 0.2 to 0.3 mm. In case of high turbidity, it is not used. Bacteria removal efficiency is 98-99%. It required a high initial cost and low maintenance cost. Its construction is simple.
- **Rapid sand filters:** These filters use coarser sand than slow sand filters and the effective size of the filter media is usually greater than 0.55 mm. The flow rates are normally between 4 and 21 m/h. These filters do not remove disease-causing entities as efficiently as slow sand filters and usually need a post-filtration chlorination process. Flocculation and coagulation are sometimes used as pre-treatments. Bacteria removal efficiency is 80-90%.
- **Roughing sand filter**: These filters are used to remove suspended solids by passing the water through material that is much coarser than that used in slow sand filtration or rapid sand filters. The filter material is usually graded so that the water passes through coarse (25mm), medium, and then fine (5 mm) sand. Flow rates are often in the region of 0.3 – 0.6 m/h (i.e., 300 – 600 l/h) per m2 of filter surface area.

- **Different parameters which cause pollution in drinking water:**

Water contains different water quality parameters like physical and chemical water quality parameters.

4.2.1 Physical water quality parameter

- **Suspended solid:** The problem of suspended solid comes only in surface water, not in groundwater.
- **Turbidity:** It is due to the presence of suspended or dissolve solid in water.
- **Colour:** Organic compounds present in water may cause Colour problems.
- **Taste and Odour:** Taste and Odour are caused by dissolved gasses. Algae secretes oily substances that may result in bad taste & Odour.

4.2.2Chemical water quality parameter

- **Total dissolved solids:** Major source of TDS is sodium, calcium, magnesium, sulphate, chloride, silica etc.
- **Alkalinity: A**lkalinity in drinking water is caused due to the presence of carbonate, Bi-carbonate and Hydroxyl ion.
- **pH: I**f pH is less than 6.5 and more than 8.5 then that water cause health issue in drinking water. Also, acidic water causes corrosion & alkaline water causes incrustation of pipe.
- **Hardness: I**t represents the concentration of multivalent metallic cations in solution. Excessive hardness is objectionable because: great deal of soap is required for washing clothes; scale is formed in boilers in hot water heating system, incrustation of pipelines and plumbing fixtures.

4.2.3Biological water quality parameter

It includes Bacteria coli, and Escherichia Coli. The Presence of those in water indicates water is polluted due to pathogenic bacteria. Due to the presence of pathogenic bacteria in drinking water, many water-borne diseases occurred. Diseases caused due to bacteria is Typhoid fever, Cholera, Bacillary Dysentery etc. Protozoa caused amoebic dysentery. The virus caused jaundice, poliomyelitis, infectious etc.

4.2.4 Slow Sand Filters:

Slow sand filters use sand with effective sizes of 0.15 - 0.35 mm to remove a large percentage of coliforms, cryptosporidium and Giardia cysts. They operate most effectively at a flow rate of 0.1 – 0.3 m/h (or m3/h/m2).

These filters use physical processes such as sedimentation, adsorption and straining to remove fine particles as well as microbiological processes to remove organic material and bacteria. Because of the slow filter rates, the raw water sits above the sand for several hours before passing through it, various oxidation reactions break down organic material during this time. Algae, that grows on the sand surface, consumes this oxidized organic material and releases oxygen back into the water.

Roughing filters and sedimentation are often used as pre-treatments to reduce the turbidity of the raw water and therefore reduce the rate at which the slow sand filter becomes clogged. Some aeration, to increase the oxygen content of the raw water, is also desirable.

The flow of raw water through the filter should be continuous, however small-scale filters, for use in individual households, have been designed to work intermittently (i.e., a few hours a day). These have been widely used in several countries around the World.

4.2.5Filtration Mechanism in Slow Sand Filters

Several mechanisms for the removal of turbidity, bacteria, viruses, and organic matter operate in slow sand filters. These can be broken down into two broad groups: physical and mechanical; and biological. Slow sand filters differ from rapid sand filters and roughing filters in the biological processes predominate.

4.2.5.1 Physical and Mechanical Processes

Straining is perhaps the most obvious process whereby particles can be removed from water flowing through a sand bed; that is, particles that are too large to fit through the pores between sand grains become lodged and are therefore removed from the water.

- However, rapid sand filters have been shown to trap particles that are far smaller than the pores. For example, sand grains with diameters of 0.5-1.0 mm will have pores that are approximately 0.1 mm in diameter but can remove particles with sizes of 0.01 mm and bacteria with sizes of0.001 mm. Since these observations have been made using rapid sand filters the removal mechanism is physical rather than biological.

There are two important factors that must occur when particles are physically removed from the water. Firstly, a particle must move into contact with a sand grain (transport) and secondly the particle must become attached to it (attachment).

- **Transport**

Because of the slow flow rates, many of the larger solid particles will settle out in the head of water above the sand bed. The processes that occur within the sand bed can be summarized as followed:

- Interception– the water flows so that particles move close enough to a sand grain to become attached.
- Diffusion– random Brownian motion brings particles close to grains.
- Sedimentation– gravitational forces move particles downwards onto the top surfaces of grains.
- Hydrodynamic– particles in a velocity gradient (i.e., where water is flowing around a grain) often develop a rotation that provides lateral forces that move particles out of the water stream and into contact with sand grains.

- **Attachment**

These processes involve electrostatic and molecular (Van der Waals) forces that are similar to those that occur in coagulation. These attractions are sensitive to the surface charges on the sand grains and therefore the pH of the raw water. For example, virus removal occurs more readily in Low pH environments and for normal sand, E. coli removal is most efficient in water with pH5.

4.2.5.2 Biological Action

Slow sand filters have small flow rates hence most solid particles are removed in the top 0.5 to 2 cm of sand. This top layer of sand develops into a biologically active area. Known as the schmutzdecke (this translates roughly from German as ‘dirty layer’). While most of the biological activity occurs in this region some activity continues down to a depth of about 0.5 m, although faster flow rates will carry organic food, that sustains bacteria, even deeper into the sand bed. Figure 4. shown the Schmutzdecke layer of SSF model.

The Schmutzdecke is perhaps the single most important feature of the slow sand filter and is a sticky reddish-brown layer consisting of decomposing organic matter, iron, manganese, and silica. It acts as a fine filter to remove fine colloidal particles from the raw water and is also the initial layer of bioactivity. The Schmutzdecke takes a while to form and ripen; this may take 2 – 3 weeks depending on the temperature and the biological content (bacteria and organic material) of the raw water. Once the Schmutzdecke started functioning, should remain undisturbed until the filter has to be cleaned – probably 2 – 20 weeks. After cleaning, where the top 1

cm of sand is removed, the Schmutzdecke will take a few days to ripen. The Schmutzdecke is effective against intestinal bacteria because the temperature is lower than body temperature and there is little appropriate food. Also, there are predatory organisms present at the top of the filter bed.

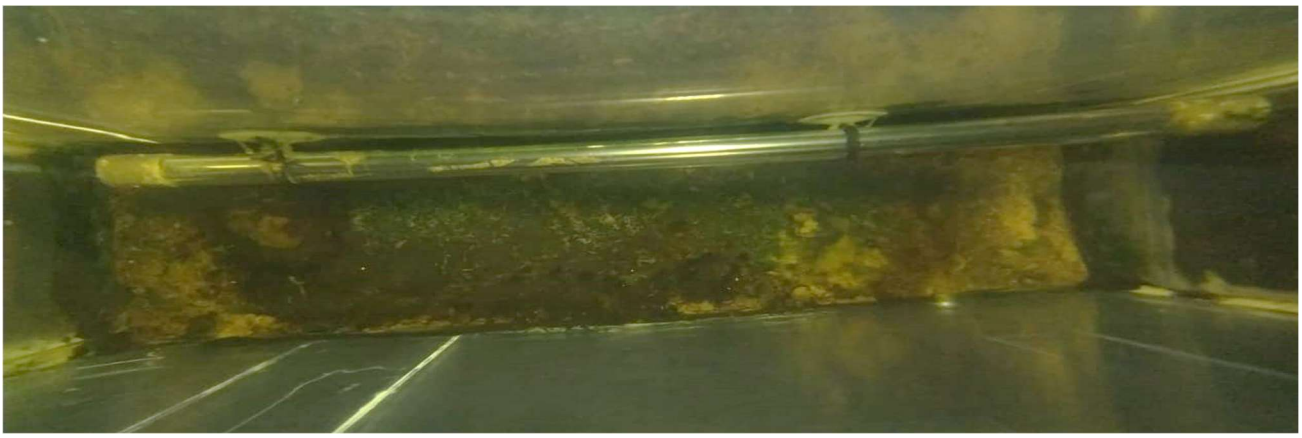


Figure 4.2: Schmutzdecke Layer of SSF model

The effectiveness of the Schmutzdecke relies on there being adequate food (organic material in the raw water), a high enough oxygen content, and a sufficient water temperature. The following points should be observed when operating a slow sand filter:

- The sand must be kept wet to keep the essential micro-organisms alive in the biological zone.
- The biological zone needs food, therefore raw water should be continually fed in and the filter should be run continuously.
- The biological zone needs adequate oxygen for the metabolism of biodegradable components and the consumption of photogenes. If the oxygen content of the filter drops too far anaerobic decomposition occurs producing hydrogen Sulphide, ammonia and other products that affect the taste and Odour of the water.

The oxygen content of the filter should be above 3 mg/l to ensure anaerobic conditions are avoided within the filter. To maintain the oxygen level in the filter:

- Ensure there is a continual flow of water through the filter.
- Provide an aeration treatment before, or as, the raw water enters the filter.
- Do not have an excessive head of water above the sand bed.

The biological layer becomes less effective at lower temperatures. When the air temperature drops to below 2°C for any prolonged period the filter should be covered to prevent heat loss or chlorination should be used on the filtered water as a safeguard.

4.2.5.3Algae

Algae may grow in the rivers, lakes, storage reservoirs, or even in the supernatant of the SSF. The presence of algae in moderate quantities is usually beneficial for the functioning of the SSF units. Most algae are retained by the SSF, but under certain conditions occasional and significant algae growth or algae blooms may develop. Figure 4.2.1 depicted the condition of algae bloom in SSF model. This massive growth may cause a quick

reduction of the permeability of the filtering bed, greatly reducing the filter run. Algae may also play an important role in the production of high concentrations of soluble and biodegradable organics in the water, which may create smell and taste problems, and contribute to microbial growth in the distribution system.

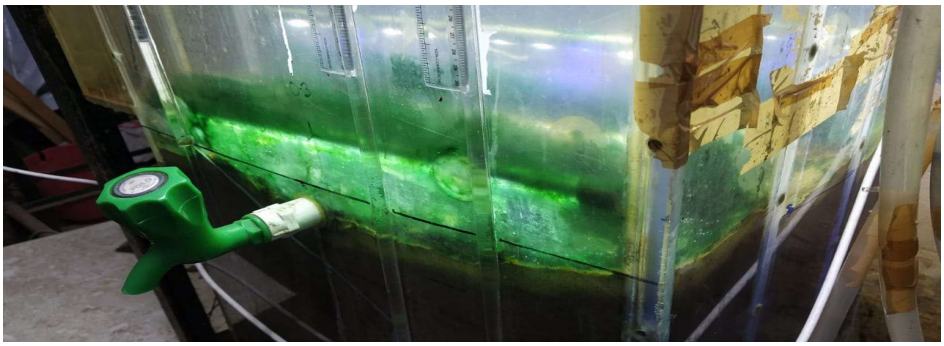


Figure 4.2.1: Algae blooms develop in SSF model

4.2.6 Conditions that inhibit or reduce the efficiency of the treatment process:

Various circumstances can interfere with the treatment process in the SSF units and prevent the expected efficiencies from being obtained. Some of these are related to the short filter runs. Other important inhibiting conditions are low temperatures, low nutrient content, and low dissolved oxygen content.

i. **Temperatures:** A low temperature increases the viscosity of water and reduces the biochemical activity in the sand bed, affecting the treatment efficiency. E. coli removal may be reduced from 99 to 50% when the temperature falls from 20ºC to 2ºC (Huisman and Wood 1974). The strategy in countries that face cold periods during the year has been to cover the filters or to build underground to prevent the freezing of the units and reduce the impact of low temperatures which, of course, has considerable economic implications.

ii. **Nutrients:** The microorganisms active in the sand bed require nutrients such as carbon, nitrogen, phosphorus, and Sulphur for their metabolism and growth. The humic and fulvic acids are rich in carbon but low in the other elements (Spencer and Collins, 1991). This may be part of the explanation for the low removal of natural Colour in SSF treating water sources that are well protected. Bellamy et al. 1985 report that adding nutrients permits increasing the biological activity in experimental SSF units, and improves the removal efficiency for turbidity and for microbiological contamination.

iii. **Dissolved oxygen**: When the flow velocities and the dissolved oxygen level in the water source are low, particularly if this is combined with a high amount of biodegradable material, the oxygen in the water can be depleted resulting in anaerobic conditions in the filter skin (Joshi et al., 1982). This anaerobic condition in the filter must be avoided because it may create serious water quality problems such as bad smell and taste, as well as re-suspension of heavy metals with implications of aesthetic nature or interference with the final disinfection stage.

4.2.7. Operational Factors Affecting Removal in Slow Sand Filtration

Slow sand filtration is proven to achieve excellent removals of pathogenic bacteria, protozoa, viruses, suspended solids, and turbidity. However, removal efficiency is highly dependent on the physical and operational characteristics of the filter including the media size, bed depth, filtration rate, biological maturity of the filter, and cleaning practices.

Generally, there are similarities in the findings of many authors, who report a decrease in filter efficiency with increased media size, increased filtration rate, decreased bed depth, and decreased biological maturity of the sand bed.

A smaller media is favored due to its increased filtration efficiency. Ellis (1985) reports improved bacteria removals with smaller media. Although, the impact of media size on filter performance largely depends on the size distribution and surface chemistry of the particulate matter in the source water. For example, if there are a high proportion of solids in the water with a relatively large particle diameter, they are more likely to be removed, even in larger media. On the other hand, a high proportion of smaller size particles possessing a negative surface charge are more difficult to remove, especially in larger media.

Van der Hoek et al. (1996) documents a varied response from several authors regarding the effect of media size on slow sand filter performance. Interestingly, Bellamy et al. (1985) reported that an increase in effective sand size did not necessarily result in poor filter performance. An increase in effective media diameter from 0.128 mm to 0.615 mm resulted in only a small decrease in bacteria removals from 99.4% to 96%. Likewise, Van der Hoek et al. (1996) found that the use of a smaller range of grain size (d_{10}=0.19) resulted in only slightly better filtrate quality than a larger range of grain size (d_{10}=0.25). More importantly, however, a shorter filter run length was observed with the smaller media.

Although a larger media may be desired for longer filter runs, it also allows deeper penetration of schmutzdecke and more sand would need to be removed during cleaning to restore head loss to initial values (Bellamy et al., 1985). This may significantly reduce treatment efficiency after cleaning, leading to an increased risk of pathogen breakthrough.

For example, Burman (1962) found that cleaning of the slow sand filter led to a reduction in the removal of E. coli from 99 to 94%, although removal of coliform bacteria was unaffected. Burman (1962) also found that removal of chlorine-resistant spore forming bacilli ranged from 81 to 88%, and after cleaning these removals dropped from 81 to 73%. Bellamy et al. (1985a) found that cleaning or replacing the sand resulted in a 1 log decrease in bacteria removal efficiency.

Thus, a good compromise is to use a larger effective media diameter, but preserve filtration efficiency by using a media with a relatively low uniformity coefficient (UC). A lower UC ensures that there is not a high proportion of sand that is too fine, which would lead to premature clogging, and not a high proportion of sand that is too large, which would reduce filtration efficiency (Goitom, 1990).

The filtration rate is another important factor affecting removal in slow sand filters. In particular, sedimentation and biological mechanisms are dependent on the filtration rate (Ellis, 1985). This is because a lower filtration allows less turbulent conditions in the sand interstices and facilitates gravitational sedimentation, reduces fluid

shear on deposited particles, and increases the hydraulic retention time in biologically active regions of the filter.

As expected, Poynter and Slade (1977) found that the removal of viruses decreased with an increased filtration rate. In addition, Muhammad et al. (1996) found that Colour removals, which depend mostly on sedimentation, were significantly decreased at higher filtration rates. This confirms that biological treatment and sedimentation are indeed influenced by filtration rate.

Interestingly, Huisman (1977) reported that a higher filtration rate increases the organic loading rate, which results in higher substrate availability and forces microorganisms to live deeper than 300-400 mm in the sand bed, leading to the potential breakthrough of bacteria. In some cases, however, filtration rate does not have an effect on bacteria removals. For example, Poynter and Slade (1977) found that increasing the filtration rate from 0.2 m/h to 0.4 m/h had no effect on removals of coliform bacteria and E. coli.

Bed depth is also an important parameter for slow sand filter performance. The minimum depth for good turbidity and coliform bacteria removal is 300 mm, but 600 mm is necessary for removal of all viruses, and perhaps to complete the oxidation of ammonia (Ellis, 1985). Likewise, the removal of Colour can be significantly increased at bed depths greater than 400 mm (Muhammad et al., 1996).

Bellamy et al. (1985c) found good removals of bacteria with reduced bed depth. In this study, coliform removals dropped from 97% to only 95% by reducing the bed depth from 0.97 m to 0.48 m. This is because most of the biomass and biological treatment occurs in the upper portion of the sand bed. In fact, Williams (1987) found that all bacteria reduction occurs in the top 20 cm of the filter bed. In this study, 1 log removal of fecal coliforms was achieved after 5 cm depth and another 1.3 log removal after 20 cm depth, for a total of 2.3 log removal (99.5%). Overall, bed depth is more important for the removal of smaller particles, including viruses, colloidal matter, and Colour; and less significant for the removal of bacteria.

The biological maturity of the filter also has an important influence on removal efficiency. Basically, if the length of filter run is short and cleaning is frequent, the biological layer will never have enough to time to re-establish equilibrium and maturity. Cleasby et al. (1984b) found that the removal of coliform bacteria increased from 95% to greater than 99% as the filter matured. Likewise, Bellamy et al. (1985a) found that Giardia removal was 98% in new sand, where in biologically mature sand, removal was 3 to 4 logs. Thus, the importance of lengthy filter runs, which allow plenty of time for maturation, cannot be overstated.

- **Performance of Slow Sand Filtration:**

Slow sand filtration produces an effluent low in turbidity, free of impurities and more importantly, virtually free of bacteria, entero-viruses and protozoa (Galvis et al., 1988). Galvis et al. (1998) and Galvis et al. (2002) compiled typical removal efficiencies for slow sand filters from the work of several authors such as Bellamy et al. (1985c), Ellis (1985), Huck (1987), Rachwal et al. (1988), Haarhoff and Cleasby (1991), Hrubec et al. (1991), and Fox et al. (1994). These removal efficiencies are shown in Table 2.2. The original figure was amended to include the results from the work of Cleasby et al. (1984b) and Huisman and Wood (1974). Most of the results are from slow sand filters operating at temperatures above 5°C, filtration rates between 0.04 and 0.2 m/h, bed depths above 0.5 m, and effective media diameters between 0.15 and 0.3 mm.

Table: 4.2.: Typical Removal Efficiencies for Slow Sand Filtration

Adopted from Galvis et al. (1998/2002)

Parameter	Effluent or Removal Efficiency	Comments
Turbidity	< 1 NTU	Treatment efficiency depends on quantity nature, and distribution of particles.
Coliform bacteria	> 99%	Treatment efficiency mostly depends on the biological maturity of the filter.
Enteron bacteria	90 to 99.9%	Treatment efficiency affected by temperature, filtration rate, media size, bed depth, and cleaning practices.
Enteron viruses and Giardia	99 to 99.99%	Effect of cleaning practices on removal efficiency in a biologically mature bed is minimal
True Colour	25 to 40%	Colour is associated with organic material and humic acids. Average 30% removal.
Total organic carbon (TOC)	< 15 - 25%	
Dissolved organic carbon (DOC)	5 - 40%	Mean 16%
Biodegradable dissolved organic carbon (BDOC)	46 - 75%	Mean 60%
Assimilable organic carbon (AOC)	14 - 40%	Mean 26%
UV absorbance (254 nm)	5 - 35%	Mean 16-18%
Trihalomethane (THM)	< 25%	
Iron and manganese	30 to 90%	Fe levels > 1 mg/l reduce filter run length due to precipitation and filter clogging.

4.2.8. Ozone and Slow Sand Filtration:

Ozonation before slow sand filtration can have a positive influence on slow sand filter treatment performance, microbiology, and NOM transformation (Eighmy et al., 1993). As slow sand filtration alone is only capable of removing 5-25% of NOM (McMeen and Benjamin, 1996), pre-ozonation is important for achieving good removals of NOM from surface water.

Generally, ozone increases the biodegradability of NOM, hence increasing biological activity in the filter and increasing the removal of BOM. It works by oxidizing long-chain molecular substances into more easily biodegradable short chain molecular substances. More specifically, Eighmy et al. (1993) found that ozonation of NOM produced low molecular weight substances capable of supporting bacterial growth consisting of obligate aerobic bacteria or facultative anaerobic bacteria with “robust and diverse heterotrophic capacities” Eighmy et al. (1993).

Thus, pre-ozonation increases the BDOC content of NOM increases removal of UV absorbance, and also transforms NOM into more hydrophilic forms, which have a lesser potential for THM formation (Eighmy et al., 1993). Mogren et al. (1990) studied the ozonation of different source waters and found that it increased the BDOC fraction of water from 30 to 60%, 10 to 40%, or 0 to 20%, depending on the characteristics of the source water. This indicates that ozonation is effective in increasing the biodegradability of NOM.

Gould et al. (1984) found NPDOC and UV absorbance removals of 15 to 25% and 39 to 54%, respectively; in pre-ozonated slow sand filter effluent. The ozone dose was 3 to 5 mg O_3/L and the slow sand filtration rate was 0.14 m/h. comparatively, non-ozonated slow sand filter effluent had removals of only 9 to 14% and 11 to 15%, respectively.

Similarly, Zabel (1985) found NPDOC and UV absorbance removals of 35 and 70%, respectively, operating at an ozone dose of 5 mg O_3/L and filtration rate of 0.25 m/h. Whereas, whereas non-ozonated slow sand filters had NPDOC and UV absorbance removals of only 12 and 16%.

Rachwal et al. (1988) found similar trends in the removal of UV absorbance, but more importantly, found that most of the removal occurred during pre-ozonation, as the slow sand filter contributed only 10% of removal. This is confirmed by Eighmy et al. (1993), who report that ozonation of NOM reduces UV absorbance of the source water likely through oxidation of aromatic compounds.

Ellis (1985) found that removal of BOM in pre-ozonated slow sand filter effluent was 75%, compared to 50% achieved by slow sand filtration alone. In addition, removal of TOC in pre- ozonated slow sand filter effluent was 35%, compared to 15% achieved by slow sand filtration alone.

The effects of ozonation on TOC reduction are even more profound during the winter when TOC removal by slow sand filtration alone is generally poor (Seger and Rothman, 1996). Seger and Rothman (1996) found that the reduction of TOC in cold water (<8ºC) improved by 220% with pre-ozonation, compared to an improvement of 75% in warm water (>8ºC). Thus, pre-ozonation is especially important during cold water conditions for optimal removal of NOM in the slow sand filter.

4.2.8.1 Removal of Colour with Ozonation:

Ozonation is also used for the removal of true Colour, as slow sand filtration typically only achieves 30% removal. Greaves et al. (1988) found that pre-ozonation removed true Colour by 74% followed by an additional 20% removal by slow sand filtration. Comparing ozonated and non-ozonated slow sand filter effluent, Cable and Jones (1996) found a 52% removal of true Colour compared to 19% in non-ozonated effluent. In the case of Colour removal, ozonation alone is responsible for most of the removal, due to the alteration of the chemical bonds in humic materials, "leading to a reduction in the conjugation of the molecules" (Cable and Jones, 1996).

4.2.8.2The Effect of Ozone on Filter Run Length:

Another advantage of pre-ozonation is extended slow sand filter run times. Rachwal et al. (1988) found that filter run times were extended due to the oxidation of filter blocking algae. This phenomenon is likely more significant in tropical regions or during the warmer seasons of northern regions.

Conversely, Eighmy et al. (1993) found that pre-ozonation reduced filter run times, most likely due to increased biomass development in the filter. In this case, a larger media with more biomass storage capacity can be used to extend filter run times.

4.2.10 Limitations of Slow Sand Filtration:

- The main drawback of slow sand filtration is its inability to treat high turbidity surface water without the rapid development of head loss and frequent clogging of the filter. Ellis (1985) stated the common belief that "high turbidity in surface waters was the original reason that slow sand filtration had to be rejected in many areas. Most surface waters may reach a turbidity of 30-50 NTU, after heavy runoff it may be reached to 200 NTU (Barrett et al. 1991). It is suggested that slow sand filtration operates best with raw water turbidity below 10 NTU, and can manage peaks up to 50 NTU for one or two days without incurring major increases in head loss (Galvis et al. 1992). However, if the turbidity is consistently as high as 50 NTU, the filter will clog and require frequent cleaning, resulting in inadequate filter run times between cleanings. Furthermore, frequent cleaning of the filter disrupts the biological equilibrium in the filter media and does not allow enough time for biological maturation between cleanings (Galvis et al., 1992), leading to increased risk of pathogen breakthrough.

- The physical process of clogging the filter can also have a detrimental effect on effluent quality. The accumulation of particles in the top of the sand bed results in a decrease in pore size and a subsequent increase in interstitial water velocity. As the interstitial velocity increases, the shearing of the deposited particles increases. This results in the penetration of particles into deeper regions of the filter, and an increased risk of particle breakthrough in the effluent (Huck et al., 2001). In addition, the accumulation of solids can smother bioactive sites in the media, reducing the ability of bacterial predators to prey on harmful bacteria and pathogens (Lloyd, 1974).

- Excessive algal matter in the influent (Cleasby 1991)) can also clog filters and require frequent cleaning. High algal concentrations in the influent can also produce taste and Odour problems in the effluent. In addition, the presence of excessive algae may increase the pH and cause precipitation of calcium and magnesium in the filter bed, resulting in an increase in interstitial velocity and a decrease in filter efficiency (Galvis et al., 1992).

- Slow sand filters are also susceptible to sudden fluctuations in raw water quality, such as sudden increases in solids loading. The biological community in slow sand filters is very dynamic and can adapt to prevailing raw water conditions. However, surface water is prone to sudden fluctuations in water quality due to precipitation events or pollution, thus the biological community in the filter is liable to be upset (Huisman and Wood, 1974). This, in turn, may disrupt the treatment efficiency of the filter.

- Another drawback of slow sand filtration is its limited ability to treat stable suspensions of fine colloidal matter. The colloidal matter is much too fine, stable, and numerous to be completely removed by slow sand filtration alone colloidal matter is usually derived from clay; it ranges in diameter from 0.3 to 1 μm and exists in suspension due to its negative charge (Montgomery, 1985). Many surface water sources have a high percentage of colloidal matter. For example, an examination of water from a reservoir in Dar es Salaam found 50% of particles less than 1 μm (Boller, 1993). Furthermore, Ingallinella et al. (1998) examined surface water where 50% of the particles were below 0.5 μm in size.

- In slow sand filtration experiments, Bellamy et al. (1985a) found poor removals of turbidity, in the range of 27 to 39%, due to the presence of colloidal clay. However, particles ranging in size from 6.35 to 12.7 μm were effectively reduced by 96.8-98%. Similarly, Fogel et al. (1993) found poor turbidity removals of 55% due to a high amount of colloidal matter in the source water, in which 34.4% of all particles were less than 5 μm in diameter.

- The stable behavior of colloidal suspensions can be even more pronounced in the presence of negatively charged humic matter, which absorbs to particle surfaces and prevent particle contact. Ahsan et al. (1996) found that absorbed humic compounds can increase electrostatic repulsion between particles or

cause steric hindrance. Indeed, tests have confirmed that attachment efficiency between suspended particles is reduced in the presence of humic matter (Tipping et al., 1982; Jekel, 1986). Conversely, the presence of Ca^{2+} or Na^{+} in the water can absorb to the surface of the particle and destabilize a suspension (Collins et al., 1994b).

- Slow sand filters are also poor in removing Colour. Colour is a surrogate measure of organics and an aesthetic measure of water quality. The dissolved fraction of Colour is referred to as true Colour. Colour is mainly caused by the presence of organic humic substances (Montgomery, 1985). Due to the stabilizing nature of humic substances on dissolved particles, it is expected that Colour is difficult to remove in slow sand filters. Ellis (1985) found that the average expected removal of true Colour in slow sand filters is 30%. In fact, the common reason for the declining use of slow sand filtration in the United Kingdom is its limited ability in removing organic Colour and dissolved organic carbon (Lambert and Graham, 1995).

- Another important limitation of slow sand filtration is its reduced treatment efficiency at low water temperatures. Huisman and Wood (1974), Schuler et al. (1988), Bellamy et al. (1985c), Burman (1962), and Fogel et al. (1993) all report decreased removal efficiencies at lower temperatures, due to decreased microbiological activity and biological treatment. For example, Huisman and Wood (1974) found that the removal of Escherichia coli (E. coli) reduced from 99% to 50% when the temperature decreased from 20°C to 2°C. Ellis (1985) found similar deficiencies in removal, and attributed it to lower predation activity of protozoa at lower temperatures.

- Furthermore, Burman (1962) found 99% removal of E. coli and coliform bacteria throughout most of the year in a northern climate, but during persistent cold weather removals decreased to 41% and 88%, respectively. Similarly, Bellamy et al. (1985c) found that removal of total coliform bacteria reduced from 97% at 17°C to 87% at 5°C, and removal of standard plate count bacteria reduced from 99.9% at 17°C to 90% at 2°C. On the other hand, despite a low temperature of 5°C, Poynter and Slade (1977) still found 99.6% and 99.5% removals of coliform bacteria and E. coli, respectively. The variation in results from these authors could be site-specific. Perhaps bacteria removals are less affected by temperature in water that is higher in organic content, resulting in higher biomass levels

- Inadequate nutrient loadings, such as dissolved oxygen and organics, can also limit the performance of slow sand filtration. Aerobic microorganisms in the biomass require an adequate supply of oxygen, carbon, nitrogen, and phosphate for metabolic activity and growth. It is recommended that aerobic biological activity can only be sustained with a minimum dissolved oxygen level of 0.5 mg/l (Visscher et al., 1987), however, it should ideally not drop below 3 mg/l (Ellis, 1985).

Finally, from an engineering perspective, a disadvantage of slow sand filtration is its low hydraulic loading rates, forcing the requirements for larger filter areas and higher capital construction costs.

4.2.11 Mathematical Approach:

Slow sand filtration and river bank filtration are two different approaches used for water treatment, particularly for the removal of particulate matter and microorganisms from water sources. Here's a mathematical approach to understanding these processes: Slow sand filtration is a biological water treatment process that relies on the formation of a biologically active layer, the "Schmutzdecke," on the sand bed surface. This layer, a complex ecosystem of microorganisms, algae, and other organisms, traps and degrades contaminants. Mathematical models describe removal mechanisms such as particle removal, using the Yao-Habibian or Rajagopalan-Tien models, and biological degradation through kinetic equations for microorganism growth and substrate consumption. Hydraulic behavior is modeled to optimize design parameters like sand bed depth and filtration rate. River bank filtration involves extracting water from wells near rivers or lakes, where contaminants are

removed as water travels through subsurface soil. This process is mathematically modeled using advection-dispersion equations for contaminant transport, kinetic equations for sorption and biodegradation, and incorporating porous media properties like porosity and hydraulic conductivity to understand contaminant removal.

4.3. FUNDAMENTALS OF GROUND WATER FLOW AND WELL HYDRAULICS:

The underground water found in fully saturated soils and geologic formations below the water table is typically referred to as groundwater. Groundwater is not just an asset. It is a crucial aspect of the natural world; it causes issues with the ecosystem and, occasionally, provides a means for ecological remedies. It is a component of the hydrologic cycle, and knowing how it functions within this cycle is need to support integrated assessments in the evaluation of watershed resources, and in the evaluation of environmental contamination on a regional scale. When it comes to engineering, groundwater helps to such geotechnical issues including land subsidence and slope stability. Groundwater is also essential to comprehending a variety of several different geological process.

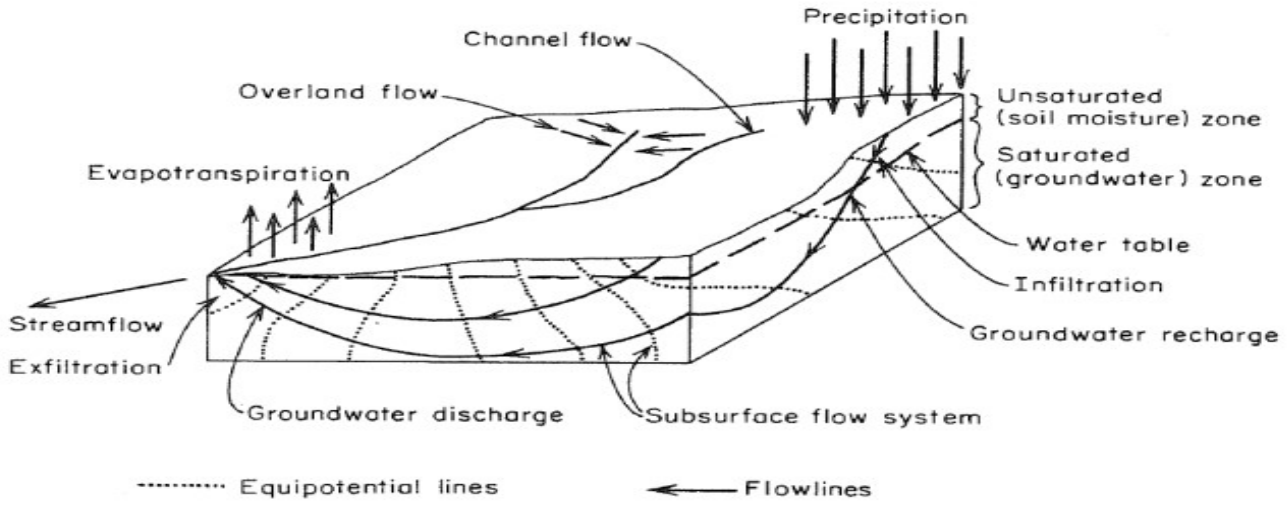


FIG:4.3: Schematic representation of the Hydrologic Cycle (***Freeze & Cherry, 1979***)

Types of groundwater

Connate water refers to the groundwater that is trapped within the pore spaces of sedimentary rocks during their formation. As layers of sediment accumulate over time, pressure increases, squeezing water out of the sediment. However, some water remains trapped within the rock's pores, becoming connate water. This water is distinct from other groundwater sources because it is essentially "fossil water," having been isolated from the hydrological cycle for millions of years. Connate water is typically saline and can be found in reservoirs deep underground. It's an important consideration in various geological and hydrological studies, particularly in the exploration and extraction of oil and natural gas, as well as in understanding groundwater dynamics.

Groundwater and the Hydrologic Cycle:

The water cycle describes where water is on Earth and how it moves. Water is stored in the atmosphere, on the land surface, and below the ground. It can be a liquid, a solid, or a gas. Liquid water can be fresh or saline (salty). Water moves between the places it is stored. Water moves at large scales, through watersheds, the atmosphere, and below the Earth's surface. Water moves at very small scales too. It is in us, plants, and other

organisms. Human activities impact the water cycle, affecting where water is stored, how it moves, and how clean it is.

Oceans store 96% of all water on Earth. Ocean water is saline, meaning it's salty. On land, saline water is stored in saline lakes. The rest of the water on Earth is fresh water. Fresh water is stored in liquid form in freshwater lakes, artificial reservoirs, rivers, and wetlands. Water is stored in solid, frozen form in ice sheets and glaciers, and in snowpack at high elevations or near Earth's poles. Water vapor is a gas and is stored as atmospheric moisture over the ocean and land. In the soil, frozen water is stored as permafrost and liquid water is stored as soil moisture. Deeper below ground, liquid water is stored as groundwater in aquifers. Water in groundwater aquifers is found within cracks and pores in the rock.

As it moves, water can change form between liquid, solid, and gas. Circulation mixes water in the oceans and transports water vapor in the atmosphere. Water moves between the atmosphere and the surface through evaporation, evapotranspiration, and precipitation. Water moves across the surface through snowmelt, runoff, and streamflow. Water moves into the ground through infiltration and groundwater recharge. Underground, groundwater flows within aquifers. Groundwater can return to the surface through natural discharge into rivers, the ocean, and from springs.

Climate change is actively affecting the water cycle. It is impacting water quantity and timing. Precipitation patterns are changing. The frequency, intensity, and length of extreme weather events, like floods or droughts, are also changing. Ocean sea levels are rising, leading to coastal flooding. Climate change is also impacting water quality. It is causing ocean acidification which damages the shells and skeletons of many marine organisms. Climate change increases the likelihood and intensity of wildfires, which introduces unwanted pollutants from soot and ash into nearby lakes and streams.

Vertical Distribution of Groundwater

SATURATED ZONE: This zone, also known as groundwater zone, is the space in which all the pores of the soil are filled with water under hydrostatic pressure. The water table forms its upper limit and marks a free surface, i.e., a surface having atmospheric pressure.

ZONE OF AERATION: In this zone the soil pores are only partially saturated with water. The space between the land surface and the water table marks the extent of this zone. The zone of aeration has three subzones:

Soil Water Zone: This lies close to the ground surface in the major root band of the vegetation from which the water is lost to the atmosphere by evapotranspiration.

Intermediate Vadose Zone: This lies between the soil water zone and the capillary fringe. The thickness of the zone of aeration and its constituent subzones depend upon the soil texture and moisture content and vary from region to region. The soil moisture in the zone of aeration is of importance in agricultural practice and irrigation.

Capillary Fringe: In this the water is held by capillary action. This zone extends from the water table upwards to the limit of the capillary rise.

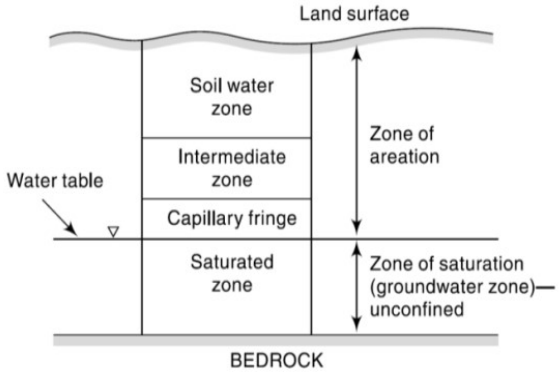


FIG:4.3.1: Divisions of subsurface water (***Subramanya, 2008***) Saturated Formation

All earth materials, from soils to rocks have pore spaces. Although these pores are completely saturated with water below the water table, from the groundwater utiliza- tion aspect only such material through which water moves easily and hence can be extracted with ease are significant. On this basis the saturated formations are classi- fied into four categories.

AQUIFER: An aquifer is a saturated formation of earth material which not only stores water but yields it in sufficient quantity. Thus, an aquifer transmits water relatively easily due to its high permeability. Unconsolidated deposits of sand and gravel form good aquifers.

AQUITERD: It is a formation through which only seepage is possible and thus the yield is insignificant compared to an aquifer. It is partly permeable. A sandy clay unit is an example of aquitard. Through an aquitard appreciable quantity of water may leak to an aquifer below it

AQUICLUDE: It is a geological formation which is essentially impermeable to the flow of water. It may be considered as closed to water movement even though it may contain large amounts of water due to its high porosity. Clay is an example of an aquiclude

AQUIFUGE: It is a geological formation which is neither porous nor permeable. There are no interconnected openings and hence it cannot transmit water. Massive compact rock without any fractures is an aquifuge.

The definitions of aquifer, aquitard and aquiclude as above are relative. A formation which may be considered as an aquifer at a place where water is at a premium (e.g. arid zones) may be classified as an aquitard or even aquiclude in an area where plenty of water is available.

The availability of groundwater from an aquifer at a place depends upon the rates of withdrawal and replenishment (recharge). Aquifers play the roles of both a transmission conduit and a storage. Aquifers are classified as unconfined aquifers and confined aquifers on the basis of their occurrence and field situation. An unconfined aquifer (also known as water table aquifer) is one in which a free water surface, i.e. a water table exists. Only the saturated zone of this aquifer is of importance in groundwater studies. Recharge of this aquifer takes place through infiltration of precipitation from the ground surface. A well driven into an unconfined aquifer will indicate a static water level corresponding to the water table level at that location.

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aquifer takes place through infiltration of precipitation from the ground surface. A well driven into an unconfined aquifer will indicate a static water level corresponding to the water table level at that location.

On the other hand, a confined aquifer (also known as artesian aquifer) is an aquifer which is confined between two impervious beds such as aquicludes or aquifuges. Recharge of this aquifer takes place only in the area where it is exposed at the ground surface. The water in the confined aquifer will be under pressure and hence the piezometric level will be much higher than the top level of the aquifer. At some locations, the piezometric level can attain a level higher than the land surface and a well driven into the aquifer at such a location will flow freely without the aid of any pump. A confined aquifer is called a leaky aquifer if either or both of its confining beds are aquitards.

Whether a stream feeds water into groundwater storage or the other way around depends on the location of the water table in relation to the water level in the stream. During times of low stream flows, if the stream's bed is below the groundwater table, the water surface may drop below the general the groundwater and the level of the water table both influence the stream's flow. These streams that are receiving Effluent streams are groundwater flows. These include streams and rivers that are perennial.

If, however, the water table is below the bed of the stream, the stream-water percolates to the groundwater storage and a hump is formed in the groundwater. Such streams which contribute to the ground water are known as influent streams. Intermittent rivers and streams which go dry during long periods of dry spell (i.e., no rain periods) are of this kind.

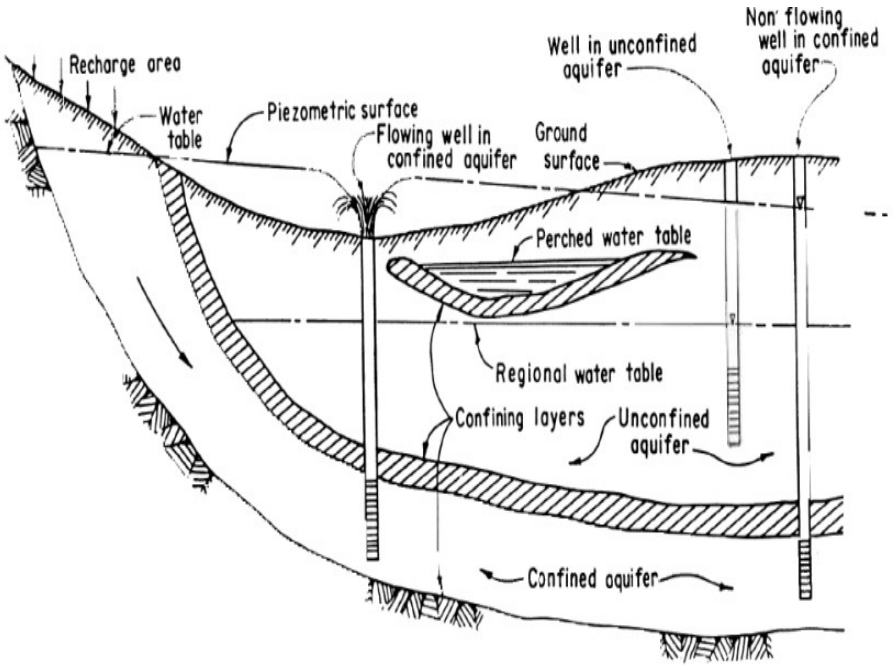


FIG:4.3.2: Types of aquifers (***U.S. Bureau of Reclamation, 1995***)

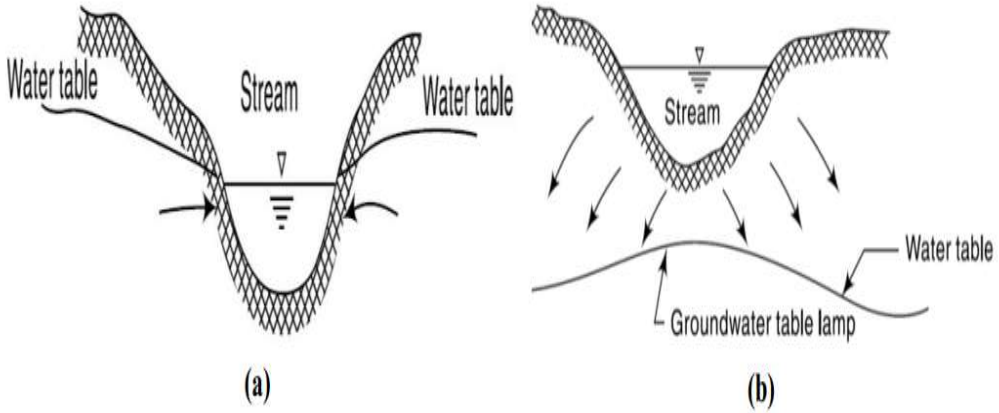


FIG:4.3.3: (a) *Effluent Stream* **(b)** *Influent Stream* (***Subramanya, 2008***)

Aquifer Properties:

POROSITY:

Aquifer porosity refers to the volume percentage of pore space within a rock or sediment that can contain water. It's a critical parameter in hydrogeology because it determines how much water a formation can store and how easily water can flow through it. Porosity ($\phi\phi$) is commonly expressed as a fraction or percentage.

The equation to calculate porosity is:

$\phi = Vv/Vt$ ……4.3.1

Where: ϕ is the porosity (dimensionless)

Vv Vv is the volume of void space (pore space) within the rock or sediment (cubic meters or cubic feet)

VtVt is the total volume of the rock or sediment (cubic meters or cubic feet)

If you have access to bulk density ($\rho b\rho$ b) and grain density ($\rho g\rho$ g) of the material, you can also use the equation:

$\phi = (\rho g - \rho b)/(\rho g - \rho w)$ ……4.3.2

Where: ρw is the density of water (typically around 1000 kg/m³ or 62.4 lb/ft³)

This equation is based on the assumption that the solid grains making up the rock have a uniform density. It's important to note that porosity is affected by factors such as grain size, sorting, and packing arrangement of grains within the rock. So, in some cases, more complex equations or empirical methods may be used to estimate porosity accurately.

Primary porosity comprises the original interstices created when a rock or soil was formed in its present state. In soil and sedimentary rocks, the primary interstices are the spaces between grains or pebbles. In intrusive igneous rocks the few primary interstices result from cooling and crystallization. Extrusive igneous rocks may have large openings and high porosity resulting from the expansion of gas, but the openings may or may not be

connected.
Metamorphism of igneous or sedimentary rocks generally reduces the primary porosity and may 'virtually obliterate it.

Fractures such as joints, faults, and openings along planes of bedding or schistosity in consolidated rocks having low primary porosity and permeability may afford appreciable secondary porosity. In some rocks such secondary porosity affords the only means for the storage and movement of ground water. Solution of carbonate rocks such as limestone or dolomite by water containing dissolved carbon dioxide takes place mainly along joints and bedding planes and may greatly increase the secondary porosity. Similarly, solution of gypsum or anhydrite by water alone may greatly increase the secondary porosity.

Specific Yield and Specific Retention:

Specific yield and specific retention are two important parameters used in hydrogeology to describe how water is stored and moves within an aquifer.

Specific Yield (Sy): Specific yield refers to the ratio of the volume of water that an aquifer will yield by gravity drainage to the total volume of the aquifer. It represents the portion of water that an aquifer releases under the influence of gravity and is typically expressed as a percentage or decimal fraction.

The equation to calculate specific yield is:

$Sy=Vw/Vt$.....(4.3.3)

Where:

Sy is the specific yield (dimensionless)

Vw is the volume of water that drains out of the aquifer due to gravity (cubic meters or cubic feet)

Vt is the total volume of the aquifer (cubic meters or cubic feet)

Specific Retention (Sr): Specific retention refers to the volume of water retained in an aquifer per unit volume of aquifer material. It represents the portion of water that is retained within the pore spaces of the aquifer material against the pull of gravity and is typically expressed as a percentage or decimal fraction.

The equation to calculate specific retention is:

$Sr=Vr/Vt$.....(4.3.4)

Where:

$Sr$is the specific retention (dimensionless)

Vr is the volume of water retained within the aquifer material (cubic meters or cubic feet)

Vt is the total volume of the aquifer (cubic meters or cubic feet)

It's important to note that specific yield and specific retention are often determined through laboratory tests or estimated using empirical relationships based on the characteristics of the aquifer material, such as porosity, grain size distribution, and hydraulic conductivity. These parameters play a crucial role in understanding groundwater storage, flow, and availability within aquifer systems.

While porosity gives a measure of the water-storage capability of a formation, not all the water held in the pores is available for extraction by pumping or draining by gravity. The pores hold back some water by molecular attraction and surface tension. The actual volume of water that can be extracted by the force of gravity from a unit volume of aquifer material is known as the specific yield.

Storage Coefficient or Storativity:

Storage coefficient, also known as storativity, is a dimensionless parameter used in hydrogeology to describe the ability of an aquifer to store water per unit decline or rise in hydraulic head. It represents the volume of water that a unit volume of aquifer material releases or takes in under a unit change in hydraulic head. Storativity takes into account both specific yield (which accounts for gravity drainage) and specific storage (which accounts for compression and expansion of the aquifer material).

The equation to calculate storativity (S) is:

$S=Sy+Ss$……(4.3.5)

Where:

S is the storage coefficient or storativity (dimensionless)

Sy is the specific yield (dimensionless)

Ss is the specific storage (dimensionless)

Specific storage (Ss) represents the compressibility of the aquifer material and is typically expressed in units of inverse length (e.g., 1/m or 1/ft).

The relationship between storativity, specific yield, and specific storage can be complex and depends on factors such as the porosity, compressibility, and hydraulic properties of the aquifer material. Storativity is an important parameter in groundwater flow modeling and aquifer analysis, as it influences the response of aquifers to changes in groundwater levels, such as those caused by pumping or recharge events. It helps hydrogeologists understand how much water can be extracted from or stored in an aquifer under various conditions.

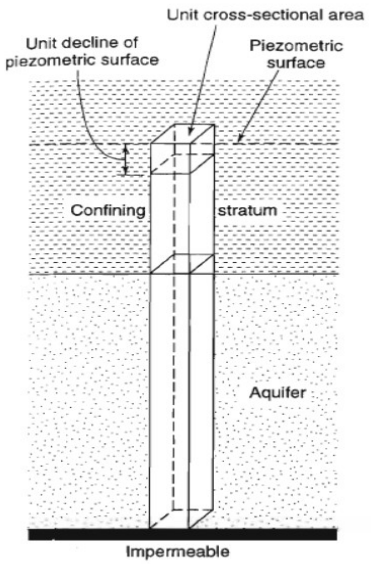


FIG:4.3.4: Illustrative sketches for defining storage coefficient of a confined aquifer
(***Todd & Mays, 2005***)

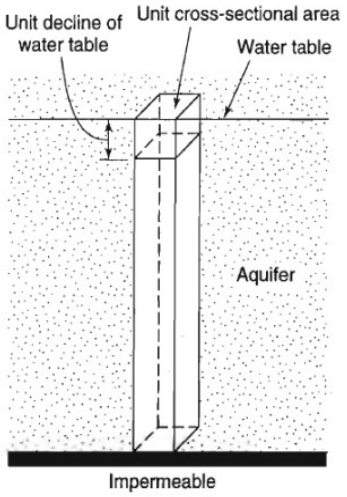


FIG:4.3.5:*Illustrative sketches for defining storage coefficient of an unconfined aquifer*
(***Todd & Mays, 2005***)

Specific Storage:

Specific storage (Ss) is a parameter used in hydrogeology to describe the ability of an aquifer material to release or take in water per unit volume per unit change in hydraulic head. It represents the compressibility of the aquifer material. Specific storage is particularly important in unconfined aquifers or where changes in hydraulic head lead to significant changes in the volume of water stored in the aquifer.

The equation to calculate specific storage is:

$Ss=(1/n)*(\Delta V/\Delta h)$……4.3.6

Where:

Ss is the specific storage (units of 1/length, often expressed in m−1 or ft−1)

n is the porosity of the aquifer material (dimensionless, ranging from 0 to 1)

ΔV is the change in volume of water in the aquifer (cubic meters or cubic feet)

Δh is the change in hydraulic head (meters or feet)

Specific storage quantifies how much the volume of water stored in the aquifer changes with a change in hydraulic head. It is a measure of the compressibility of the aquifer material, with higher values indicating greater compressibility.

Specific Storage:

Specific storage is a crucial parameter in groundwater flow modeling, especially when analyzing transient or time-varying conditions. It influences the rate at which water flows into or out of the aquifer in response to changes in pumping rates, recharge rates, or other hydrological events.

Darcy's Law:

Darcy's Law is a fundamental principle in hydrogeology and fluid dynamics that describes the flow of fluids (usually water) through porous media, such as soil or rock. It's named after the French engineer Henry Darcy who first formulated it in the 19th century.

The law states that the rate of flow of water through a porous medium is directly proportional to the hydraulic gradient and the cross-sectional area through which the water flows, and inversely proportional to the length of the flow path and the fluid's viscosity. Mathematically, it can be expressed as:

$Q=-k*(A/L)*(h2-h1)$……(4.3.7)

Where:

Q is the volumetric flow rate (volume of fluid passing through a given cross-sectional area per unit time),

$k$kis the hydraulic conductivity of the porous medium (a measure of its ability to transmit water), typically measured in units of velocity (e.g., meters per second or feet per day),

A is the cross-sectional area through which the fluid flows (orthogonal to the flow direction),

L is the length of the flow path,

$h1$ and $h2$h2 are the hydraulic heads (elevation of the water surface relative to a reference point) at points 1 and 2 along the flow path, respectively.

In this equation, the hydraulic gradient $(h2-h1)/L$ represents the change in hydraulic head per unit length of flow path, and $-k$ accounts for the resistance to flow posed by the porous medium.

Darcy's Law is applicable under certain conditions, such as when the flow is steady, the fluid is incompressible, and the porous medium is homogeneous and isotropic. Despite its simplifications, it serves as a foundational concept in groundwater hydrology and is widely used in various engineering applications, including groundwater modeling, contaminant transport, and petroleum reservoir engineering.

Coefficient of Permeability:

The coefficient of permeability, often denoted as k or K, is a fundamental property of porous media that quantifies its ability to transmit fluids. It's a key parameter in Darcy's Law, as mentioned earlier.

The coefficient of permeability is defined as the rate of flow of fluid through a unit cross-sectional area of the porous medium under a unit hydraulic gradient. Mathematically, it can be expressed as:

$k=Q\cdot LA\cdot\Delta h$……..4.3.8

Where:

k is the coefficient of permeability (often in units of velocity, such as m/s or cm/s),

Q is the volumetric flow rate of fluid passing through the medium (m^3/s or cm^3/s),

L is the length of the flow path (m or cm),

A is the cross-sectional area perpendicular to the flow direction (m^2 or cm^2),

Δh is the difference in hydraulic head (m or cm) between two points along the flow path.

This equation essentially states that the coefficient of permeability is the proportionality constant relating the flow rate of fluid to the hydraulic gradient, cross-sectional area, and length of the flow path. A higher coefficient of permeability indicates greater ease of fluid flow through the porous medium.

The coefficient of permeability is influenced by various factors including the properties of the fluid (such as viscosity), the properties of the porous medium (such as porosity and grain size distribution), and the geometry of the medium. It's typically determined experimentally through laboratory tests such as constant head or falling head permeability tests, where the flow rate through a sample of the porous medium is measured under controlled conditions.

The coefficient of permeability is a crucial parameter in fields like hydrogeology, civil engineering, and soil mechanics, as it governs the movement of fluids through soils, rocks, and other porous materials. Understanding this property is essential for various applications, including groundwater flow modeling, design of drainage systems, and assessment of contaminant transport in aquifers.

Transmissibility:

In hydrogeology, the transmissibility of water, often denoted as TT, refers to the ability of an aquifer to transmit water through it under a unit hydraulic gradient. It's a measure of the aquifer's hydraulic conductivity in combination with its thickness. Transmissibility is particularly relevant when analyzing the flow of groundwater through porous media.

The equation for transmissibility is:

$T=k\cdot b$.....4.3.9

Where:

T is the transmissibility (often in units of velocity times thickness, such as m^2/s or ft^2/day),

k is the hydraulic conductivity of the aquifer (m/s or ft/day),

b is the thickness of the aquifer through which water is flowing (m or ft).

This equation indicates that transmissibility is the product of hydraulic conductivity and aquifer thickness. It essentially represents the capacity of the aquifer to transmit groundwater flow per unit width of the aquifer. A higher transmissibility value indicates a greater ability of the aquifer to transmit water.

Transmissibility is a critical parameter in groundwater hydrology, as it influences the rate and direction of groundwater flow within an aquifer. It's used extensively in groundwater modeling to simulate and predict groundwater flow patterns, drawdown effects from pumping wells, and contaminant transport.

Understanding transmissibility is essential for water resource management, environmental protection, and various engineering applications related to groundwater, such as well field design, aquifer storage and recovery projects, and groundwater remediation strategies.

Stratification of aquifers:

The stratification of aquifers refers to the occurrence of multiple layers of porous materials with different hydraulic properties stacked on top of each other beneath the Earth's surface. These layers, known as aquifer units or aquifer systems, may have varying permeability, porosity, thickness, and other hydraulic characteristics.

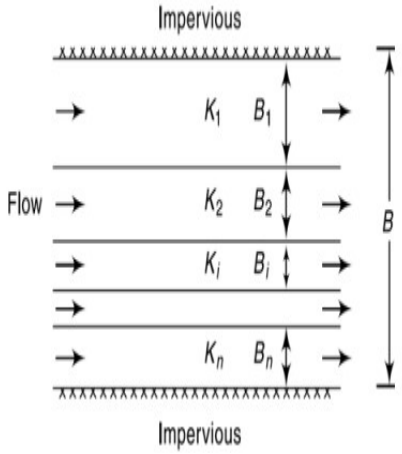


FIG:4.3.6 Flow parallel to the stratification (Subramanya, 2008)

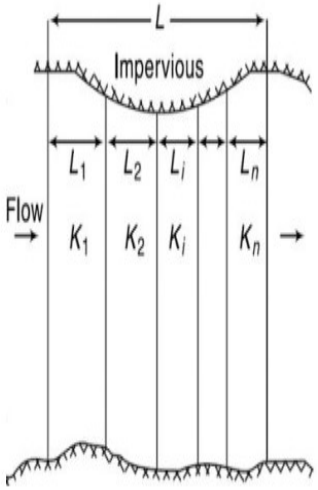


FIG:4.3.7: Flow normal to the stratification (Subramanya, 2008)

In this diagram, we have three layers representing different types of aquifers stacked vertically. The top layer represents an unconfined aquifer, followed by a semi-confined aquifer in the middle, and a confined aquifer at the bottom.

Equation-wise, we can represent the flow through a stratified aquifer system using Darcy's Law, modified to account for the characteristics of each individual layer. Let's denote the hydraulic conductivity, thickness, and hydraulic head of each layer as ki, bi, and hi respectively, where ii represents the layer number.

Then, the flow through each layer can be described by:

$Qi=-ki \cdot Ai \cdot ((hi+1)-(hi))/Li$.....4.3.9

Where:

Qi is the volumetric flow rate through layer i

ki is the hydraulic conductivity of layer i

Ai is the cross-sectional area of layer i

hi+1 and hi are the hydraulic heads at the boundaries of layer i,

Li is the thickness of layer i.

The total flow through the stratified aquifer system can then be obtained by summing the flow through each layer:

Qtotal=$\sum iQi$

This equation accounts for the varying properties of each layer and how they contribute to the overall flow within the aquifer system.

Understanding the stratification of aquifers is crucial for groundwater management and resource evaluation, as it affects the movement and distribution of groundwater, as well as the recharge and discharge processes within the aquifer system.

Anisotropy of Hydraulic Conductivity:

Anisotropy of hydraulic conductivity refers to the directional variation in the ability of a porous medium to transmit fluid. In other words, the hydraulic conductivity of the medium is different in different directions. This phenomenon is commonly encountered in naturally occurring geological formations where the sedimentary or structural features lead to preferential flow paths along certain directions.

Mathematically, anisotropy of hydraulic conductivity can be represented using a tensorial approach, where the hydraulic conductivity tensor KK describes the hydraulic conductivity in three dimensions. For an isotropic medium (where hydraulic conductivity is the same in all directions), this tensor simplifies to a scalar value. However, for anisotropic media, the tensor has distinct components corresponding to different directions.

In a Cartesian coordinate system, the hydraulic conductivity tensor K can be represented as:

Where:

$$K = \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix}$$

Kxx, Kyy, and Kzz represent the hydraulic conductivities in the x, y, and z directions respectively.

Kxy=Kyx=Kyx, Kxz=Kzx=Kzx, and Kyz=Kzy=Kzy represent the cross-components of hydraulic conductivity, indicating how the conductivity changes when moving in a combination of directions.

Anisotropy can also be quantified using a parameter called the anisotropy ratio (λ), which is defined as the ratio of the maximum hydraulic conductivity to the minimum hydraulic conductivity:

λ=kmax$K$minλ=Kmin Kmax

Where Kmax and Kmin are the maximum and minimum hydraulic conductivities respectively.

The anisotropy of hydraulic conductivity has significant implications for groundwater flow and contaminant transport in subsurface systems. Understanding and characterizing anisotropy is crucial for accurately modeling and predicting groundwater flow patterns and the migration of contaminants in heterogeneous geological formations.

Compressibility of aquifers:

In confines aquifers, the total overburden pressure at any point is borne by the combined action of the pore water pressure and inter-granular pressure. The compressibility of the aquifer and also that of the pore water causes a readjustment of these pressures whenever there is a change in storage and thus have an important bearing in the storage characteristics of the aquifer.

i. The elemental volume is constrained in the lateral directions and undergoes change of length in the z-direction only, i.e., ΔA **is constant.**
ii. The pore water is compressible.
iii. The solid grains of the aquifer are incompressible but the pore structure is compressible.

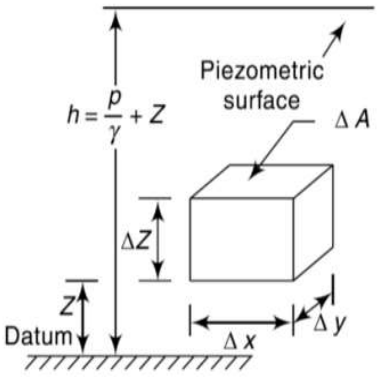


FIG:4.3.8: Elemental volume of a compressible aquifer (Subramanya, 2008)

The reciprocal of the bulk modulus of elasticity of a substance is indeed a measure of its compressibility. Bulk modulus of elasticity (often denoted as K) is a measure of a substance's resistance to compression under uniform pressure. It quantifies how much a material will compress under a given pressure.

The bulk modulus of elasticity K is defined as the ratio of hydrostatic pressure change (dp) to the resulting fractional volume change (dV/V):

$$K=-(dp)/(dV/V) \quad \text{.....4.3.11}$$

The reciprocal of the bulk modulus of elasticity K gives us the compressibility (C) of the substance:

$$C=1/K$$

For water, the bulk modulus of elasticity is approximately (2.2×10)9 N/m². Therefore, the compressibility of water can be calculated as:

C=1/(2.2×10)9 m2/N

$$\frac{d(\Delta M)}{\rho\,\Delta V} = n\,\beta\,dp + \alpha\,(1-n)\,dp + n\,\alpha\,dp = (n\,\beta + \alpha)dp = \gamma\,(n\,\beta + \alpha)dh = S_s\,dh$$

This gives us a measure of how much volume change water undergoes per unit change in pressure. In other words, it tells us how easily water can be compressed. The compressibility of water is relatively low compared to many other fluids, indicating that it is not easily compressed under typical environmental conditions.

Groundwater Movement:

Groundwater movement, a vital component of the Earth's hydrological cycle, entails the flow of water through porous geological formations beneath the surface. Governed by physical laws such as Darcy's Law, groundwater migrates through interconnected pore spaces within aquifers, driven by hydraulic gradients and influenced by aquifer properties like porosity and permeability. This slow but persistent flow sustains ecosystems, supplies water for agriculture, industry, and human consumption, and serves as a buffer against droughts. Additionally, fracture flow, occurring through geological faults or fractures, contributes to more rapid groundwater transport in certain settings. Understanding groundwater movement is essential for managing water resources, assessing groundwater availability, and safeguarding against contamination. Through a combination of field studies, numerical modeling, and remote sensing techniques, hydrogeologists strive to unravel the complex dynamics of groundwater flow, ensuring its sustainable use and protection for future generations.

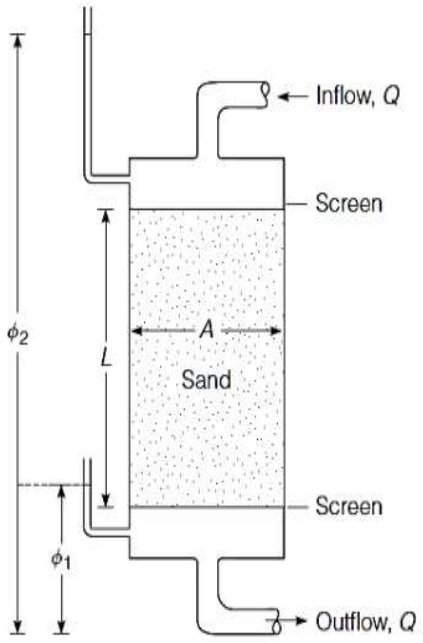


FIG:4.3.9: Schematic diagram of Darcy's experimental setup (Chin, 2013)

Limitations of Darcy's Law:

Homogeneous and Isotropic Media: Darcy's Law assumes that the porous medium through which groundwater flows is homogeneous (uniform properties) and isotropic (uniform in all directions). This limitation restricts its applicability to situations where aquifers exhibit significant heterogeneity or anisotropy.

Steady-State Flow: Darcy's Law is most accurate for steady-state flow conditions, where flow rates and hydraulic gradients remain constant over time. In unsteady flow situations, such as during recharge events or pump tests, the law may not accurately represent transient flow behavior.

Linear Flow Assumption: Darcy's Law assumes that flow is linear, meaning that the relationship between hydraulic gradient and flow rate is constant. In reality, flow in some aquifers may exhibit non-linear behavior, especially under high gradients or turbulent flow conditions.

Neglects Gravitational Effects: Darcy's Law does not account for the effects of gravity on groundwater flow, which can be significant in situations where vertical gradients are pronounced, such as in deep aquifers or near hillsides.

Neglects Density Variations: Darcy's Law assumes that groundwater density remains constant, neglecting variations due to temperature, salinity, or chemical composition. In situations where these variations are significant, such as in saline intrusion or thermal convection, the law may not accurately predict flow behavior.

Neglects Chemical Reactions: Darcy's Law does not consider the effects of chemical reactions on groundwater flow, such as dissolution, precipitation, or redox reactions. In aquifers with reactive minerals or contaminant plumes, these reactions can influence flow patterns and alter hydraulic properties over time.

The equation for Darcy's Law is:

$Q=-k*(A/L)*(h2-h1)$…….4.3.12

Where:

Q is the volumetric flow rate,

k is the hydraulic conductivity of the porous medium,

A is the cross-sectional area through which flow occurs,

L is the length of the flow path,

$h1$ and $h2$ are the hydraulic heads at two points along the flow path.

Understanding these limitations is crucial for interpreting groundwater flow data and for applying Darcy's Law appropriately in hydrogeological studies.

Darcy's law indicates a linear relationship between the flow rate and the gradient in the piezometric head measured in the direction of flow. This linear relationship is the same as for laminar flow in pipes under low Reynolds number (Hagen-Poiseuille flow) and is symptomatic of the dominance of viscous forces as water flows through the pore spaces. Flow in porous media is typically laminar under natural conditions. As the Reynolds number increases, viscous forces become less dominant, and the flow rate deviates from being linearly proportional to the piezometric head gradient, and the relationship becomes nonlinear.

General 3-D Flow Equation in a porous medium:

Consider the control volume as shown in the figure the net mass inflow rate to the control volume is given by,

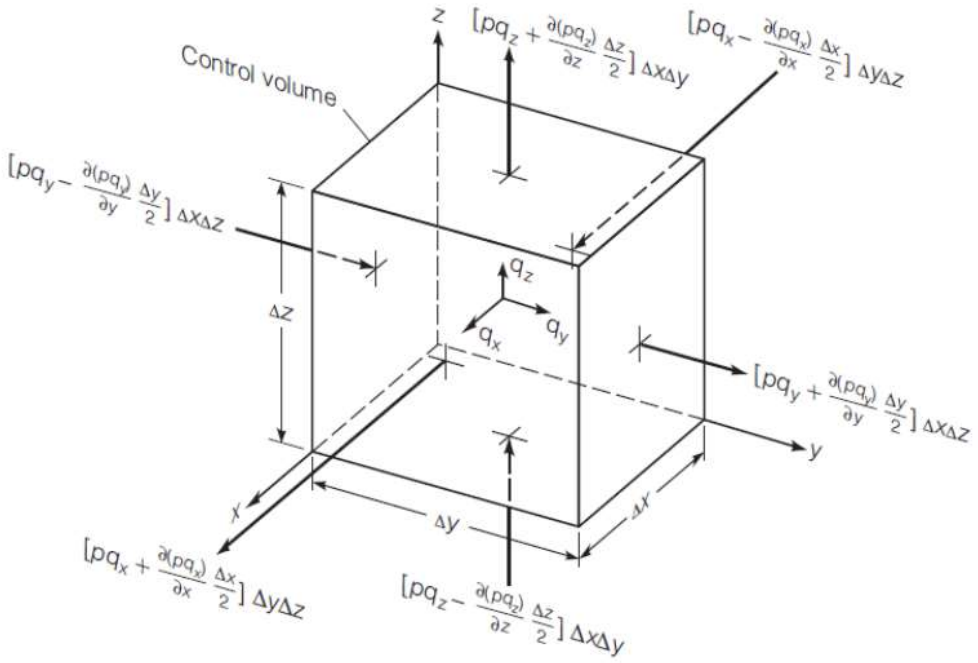


FIG:4.3.10: Control volume in a porous medium (Chin, 2013)

$$\text{Net mass inflow rate} = \left[(\rho q_x) - \frac{\partial(\rho q_x)}{\partial x}\frac{\Delta x}{2}\right]\Delta y\,\Delta z - \left[(\rho q_x) + \frac{\partial(\rho q_x)}{\partial x}\frac{\Delta x}{2}\right]\Delta y\,\Delta z$$
$$\left[(\rho q_y) - \frac{\partial(\rho q_y)}{\partial y}\frac{\Delta y}{2}\right]\Delta x\,\Delta z - \left[(\rho q_y) + \frac{\partial(\rho q_y)}{\partial y}\frac{\Delta y}{2}\right]\Delta x\,\Delta z$$
$$\left[(\rho q_z) - \frac{\partial(\rho q_z)}{\partial z}\frac{\Delta z}{2}\right]\Delta x\,\Delta y - \left[(\rho q_z) + \frac{\partial(\rho q_z)}{\partial z}\frac{\Delta z}{2}\right]\Delta x\,\Delta y$$

To derive a general equation applicable to both non-homogeneous and isotropic/anisotropic formations, we start with the fundamental principles of fluid mechanics and adapt them to accommodate spatial variations in hydraulic properties. Let's outline the steps:

Conservation of Mass (Continuity Equation): Begin with the conservation of mass equation, which represents the balance between inflow and outflow within a control volume. In vector form, the continuity equation for groundwater flow can be expressed as:

$\nabla \cdot q + (\partial S/\partial t) = 0$……4.3.13

Where:

q is the Darcy velocity vector,

S is the aquifer storage coefficient,

$\nabla \cdot$ is the divergence operator,

$\partial/\partial t$ is the partial derivative with respect to time.

Generalized Darcy's Law: Modify Darcy's Law to accommodate spatial variability in hydraulic conductivity. Introduce a tensorial form of hydraulic conductivity K to account for anisotropy and heterogeneity:

$q=-K\cdot\nabla h$……..4.3.13

Where K is the hydraulic conductivity tensor.

Substitution and Simplification: Substituting the generalized Darcy's Law into the continuity equation yields:

$\nabla\cdot(-K\cdot\nabla h)+\partial S/\partial t=0$……4.3.14

This equation accounts for spatial variations in hydraulic conductivity and hydraulic head, allowing for the consideration of both non-homogeneous and anisotropic formations.

Additional Assumptions and Boundary Conditions: Apply additional assumptions and boundary conditions as necessary, considering the specific characteristics of the aquifer system. These may include assumptions of isotropy or anisotropy, homogeneity or heterogeneity, steady-state or transient flow conditions, and various types of boundary conditions.

Solution and Analysis: Solve the resulting partial differential equation numerically using appropriate methods such as finite difference, finite element, or finite volume techniques. Solutions provide insights into groundwater flow patterns, hydraulic gradients, and aquifer behavior in non-homogeneous and anisotropic formations.

By incorporating a tensorial form of hydraulic conductivity and accounting for spatial variations in hydraulic properties, the derived equation can provide a comprehensive framework for modeling groundwater flow in a wide range of geological settings, including non-homogeneous and isotropic/anisotropic formations.

2-D Approximations in unconfined aquifers:

In case of unconfined aquifers, the general flow equation, can be simplified by using an approximation first suggested by Dupuit (1863). The Dupuit approximation is that the equipotential lines can be assumed to be vertical, making the streamlines horizontal, and the head gradients constant over the depth, in which case

$$q_x = -K_{xx}\frac{\partial \emptyset}{\partial x} \approx -K_{xx}\frac{\partial h}{\partial x}$$
$$q_y = -K_{yy}\frac{\partial \emptyset}{\partial y} \approx -K_{yy}\frac{\partial h}{\partial y} \qquad \text{…….4.3.15}$$

where is the thickness of the saturated zone. The Dupuit approximation is equivalent to assuming that the vertical pressure distribution in the aquifer is hydrostatic, leading to two-dimensional flow in the horizontal plane.

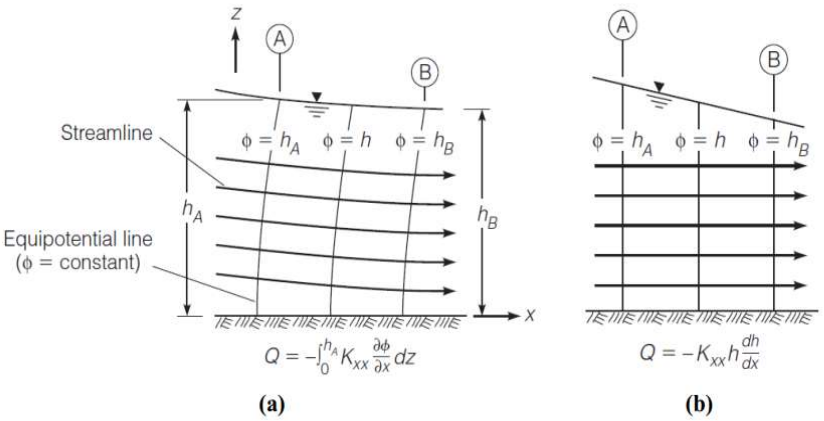


FIG:4.3.11:(a) *Actual case* **(b)** *Dupuit approximation* (***Chin, 2013***)

Dupuit's approximation is a simplified analytical approach used to analyze steady-state groundwater flow in unconfined aquifers. It assumes that the flow is two-dimensional, horizontal, and occurs in an unconfined aquifer with a flat, horizontal free water table. The method simplifies the governing equations to make them solvable with relatively simple mathematical techniques. Here's an elaboration of the Dupuit's formula along with its equation:

Assumptions:

Steady-state flow: Dupuit's method assumes that the groundwater flow regime is steady, meaning that hydraulic heads do not change with time.

Horizontal flow: The method assumes that groundwater flow occurs predominantly in the horizontal direction, with negligible vertical flow components.

Homogeneous aquifer: Dupuit's approximation assumes that the aquifer properties (hydraulic conductivity, porosity) are uniform throughout the entire flow domain.

Constant recharge: It assumes a constant recharge rate across the aquifer, typically as a result of infiltration from precipitation or surface water bodies.

Governing Equation: Dupuit's formula is derived from the Laplace equation under the assumption of horizontal flow in a confined aquifer. It can be expressed as:

$Q = -k \cdot b \cdot dh dx$ 4.3.16

Where:

Q is the flow rate per unit width (m²/s),

k is the hydraulic conductivity of the aquifer (m/s),

b is the thickness of the saturated zone (m),

dh/dx is the hydraulic gradient (m/m) along the direction of groundwater flow.

Interpretation: Dupuit's formula suggests that the flow rate per unit width is proportional to the product of hydraulic conductivity, thickness of the saturated zone, and the hydraulic gradient. It implies that groundwater flows from areas of higher hydraulic head to areas of lower hydraulic head, and the rate of flow is influenced by the permeability of the aquifer and the slope of the water table.

Applications: Dupuit's formula is particularly useful for preliminary analysis of groundwater flow in unconfined aquifers, where more complex numerical models may be unnecessary. It provides insights into flow patterns, groundwater velocities, and the influence of aquifer properties on flow behavior.

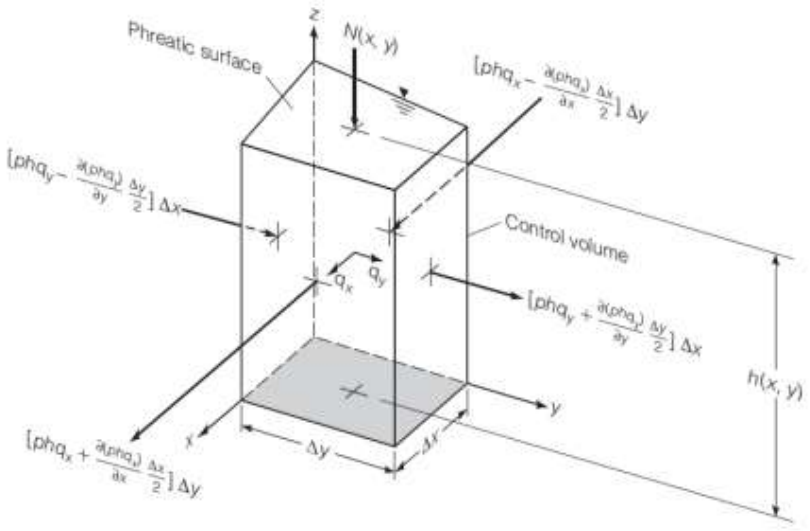


FIG:4.3.12: Control volume in an unconfined aquifer (***Chin, 2013***)

The general 2-D flow equation in an anisotropic and non-homogenous unconfined aquifer is given by,

$$\frac{\partial}{\partial x}\left(K_{xx}h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}h\frac{\partial h}{\partial y}\right)+N=S_y\frac{\partial h}{\partial t} \qquad \text{……4.3.17}$$

Limitations: Dupuit's approximation may not accurately represent flow in heterogeneous aquifers, areas with significant vertical flow components, or situations with variable recharge rates. It also neglects the effects of aquifer boundaries, such as rivers or impermeable layers, which can influence flow patterns. Therefore, it's essential to consider the assumptions and limitations of Dupuit's formula when applying it in practice

2-D Approximations in confined aquifers: Consider the case of a confined aquifer of thickness **b** illustrated,

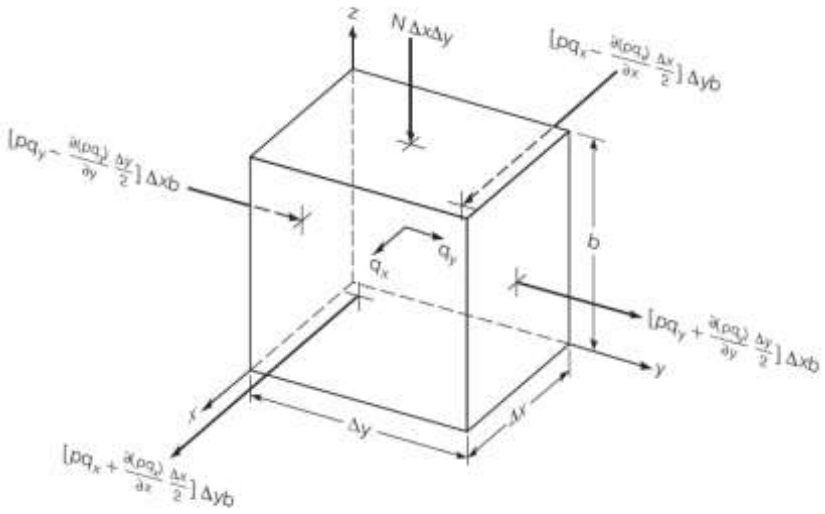


FIG:4.3.13: Control volume in a confined aquifer (***Chin, 2013***)

The general 2-D flow equation in an anisotropic and non-homogenous confined aquifer is given by

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial \emptyset}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial \emptyset}{\partial y}\right)+\frac{N}{b}=\frac{S}{b}\frac{\partial \emptyset}{\partial t}$$

…….4.3.18

Steady-State Well Hydraulics:

Steady-State Well Hydraulics: Steady-state well hydraulics refers to the condition where the rate of water withdrawal from a well remains constant over time, and the groundwater system reaches a stable equilibrium. This condition is often assumed in groundwater modeling and analysis to simplify calculations.

Pre-pumping Water Level: The pre-pumping water level, also known as the initial groundwater level or static water level, is the natural level of groundwater in an aquifer before any pumping activity occurs. It represents the equilibrium condition where the rate of recharge equals the rate of discharge.

Pumping Water Level: The pumping water level is the groundwater level observed in a well or pumping borehole during pumping. It is typically lower than the pre-pumping water level due to the extraction of water from the aquifer.

Drawdown: Drawdown is the decrease in groundwater level observed in a well or observation point as a result of pumping. It represents the difference between the pre-pumping water level and the pumping water level.

Cone of Depression: The cone of depression is the conical-shaped depression formed in the water table or potentiometric surface around a pumping well due to drawdown. It represents the extent of influence of the pumping well on the surrounding groundwater flow regime.

Radius of Influence: The radius of influence, also known as the capture radius or radius of influence, is the distance from a pumping well within which the drawdown caused by pumping is significant. It defines the area from which the pumping well extracts groundwater.

Unsteady Flow: Unsteady flow refers to groundwater flow conditions where hydraulic head or groundwater levels change with time. This typically occurs during pumping or recharge events, when the groundwater system is not in equilibrium.

Steady Flow: Steady flow refers to groundwater flow conditions where hydraulic head or groundwater levels remain constant over time. This occurs when the rate of water extraction or recharge remains constant, and the groundwater system reaches a stable equilibrium.

Recuperation or Recovery: Recuperation or recovery is the process by which groundwater levels return to their pre-pumping levels after pumping ceases. It represents the natural recharge of the aquifer and the restoration of groundwater levels following pumping activity.

Understanding these terms is essential for assessing groundwater resources, designing well systems, and managing groundwater extraction sustainably. They provide insights into the behavior of aquifers and the effects of pumping on groundwater levels and flow patterns.

Well in a confined aquifer:

The general 2-D flow equation in an anisotropic and non-homogenous confined aquifer is given by

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial \emptyset}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial \emptyset}{\partial y}\right)+\frac{N}{b}=\frac{S}{b}\frac{\partial \emptyset}{\partial t} \qquad \text{…….4.3.19}$$

When the effective hydraulic conductivity of the aquifer is homogeneous as well as isotropic in the horizontal plane become,

$$K\frac{\partial^2 \emptyset}{\partial x^2}+K\frac{\partial^2 \emptyset}{\partial y^2}+\frac{N}{b}=\frac{S}{b}\frac{\partial \emptyset}{\partial t}$$

$$\text{or, } \frac{\partial^2 \emptyset}{\partial x^2}+\frac{\partial^2 \emptyset}{\partial y^2}+\frac{N}{K\,b}=\frac{S}{K\,b}\frac{\partial \emptyset}{\partial t} \qquad \text{……4.3.20}$$

In polar coordinate system,

$$\frac{\partial^2 \emptyset}{\partial r^2}+\frac{1}{r}\frac{\partial \emptyset}{\partial r}+\frac{1}{r^2}\frac{\partial^2 \emptyset}{\partial \theta^2}+\frac{N}{K\,b}=\frac{S}{K\,b}\frac{\partial \emptyset}{\partial t} \qquad \text{……..4.3.21}$$

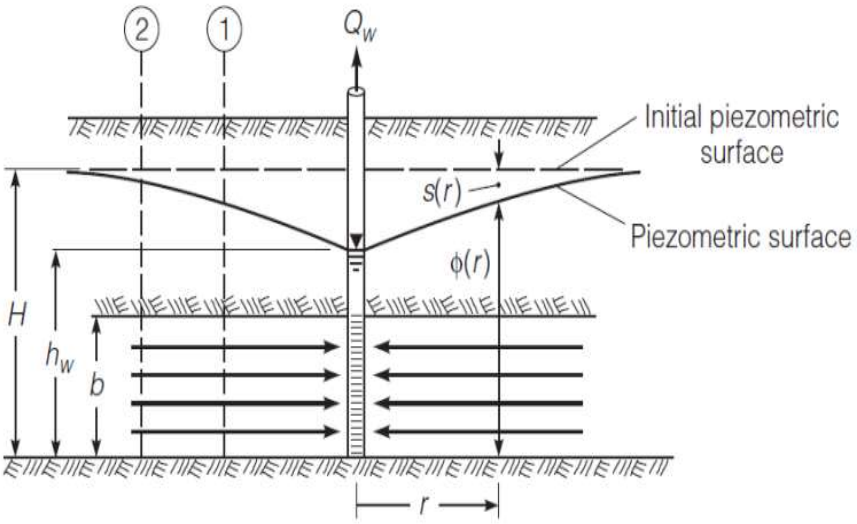


FIG:4.3.14: Fully penetrating well in a confined aquifer (***Chin, 2013***)

The Thiem equation is a fundamental solution for steady-state radial flow to a well in a confined aquifer. It is derived from Dupuit's equation under certain assumptions and boundary conditions. Let's establish the Thiem equation for a general 2-D flow equation in an anisotropic and non-homogeneous confined aquifer from Dupuit's equation:

Dupuit Equation: Dupuit's equation for radial flow to a well in a confined aquifer can be expressed as:

$Q = -2\pi T \cdot h \cdot (dh/dr)$ 4.3.22

Where:

Q is the discharge rate from the well (volume per unit time),

T is the transmissivity of the aquifer (length squared per time),

h is the hydraulic head (length) at radial distance rr from the well,

(dh/dr) is the hydraulic gradient (dimensionless) with respect to radial distance.

Thiem Equation: The Thiem equation is derived by assuming steady-state radial flow to a well in a confined aquifer. It simplifies Dupuit's equation under the assumption of horizontal flow and uniform properties:

$Q = 2\pi T(h1 - h2)/\{\ln (r2/r1)\}$ 4.3.23

Where:

Q is the discharge rate from the well (volume per unit time),

T is the transmissivity of the aquifer (length squared per time),

$h1$ is the hydraulic head (length) at radial distance $r1$ from the well,

$h2$ is the hydraulic head (length) at radial distance $r2$ from the well,

$\ln(r2/r1)$ is the natural logarithm of the ratio of radial distances.

Extension to Anisotropic and Non-Homogeneous Aquifer: To extend the Thiem equation to an anisotropic and non-homogeneous aquifer, we replace the transmissivity T with the appropriate tensorial form of transmissivity T, which accounts for the anisotropy of the aquifer. Additionally, hydraulic heads $h1$ and $h2$ and radial distances $r1$ and $r2$ should be considered with appropriate directional components to reflect the anisotropic nature of the aquifer.

Boundary Conditions: Boundary conditions for the Thiem equation typically include specifying the hydraulic head at the well (pumping rate), as well as boundary conditions at the outer boundary of the aquifer system (e.g., no flow or specified head).

By establishing the Thiem equation from Dupuit's equation and extending it to an anisotropic and non-homogeneous confined aquifer, we can analyze radial flow to a well under more complex hydrogeological conditions. This equation provides valuable insights into well performance and groundwater extraction in real-world aquifer systems.

Well in an unconfined aquifer:

In an unconfined aquifer, the distribution of piezometric head for 2-D flows by Dupuit approximation, which can be simplified as follows considering an isotropic and homogenous state of the aquifer.

The general 2-D flow equation in an anisotropic and non-homogenous confined aquifer is given by,

$$\frac{\partial}{\partial x}\left(K_{xx}h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}h\frac{\partial h}{\partial y}\right)+N=S_y\frac{\partial h}{\partial t}$$

……4.3.24

In cases where the hydraulic conductivity of the aquifer is homogeneous, describes the distribution of saturated thickness $\boldsymbol{h}$

$$K_{xx}\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)+K_{yy}\frac{\partial}{\partial y}\left(h\frac{\partial h}{\partial y}\right)+N=S_y\frac{\partial h}{\partial t}$$

……..4.3.25

Therefore, this simplifies to,

$$K_{xx}\frac{\partial^2 h^2}{\partial x^2}+K_{yy}\frac{\partial^2 h^2}{\partial y^2}+2N=2S_y\frac{\partial h}{\partial t}$$

……..4.3.26

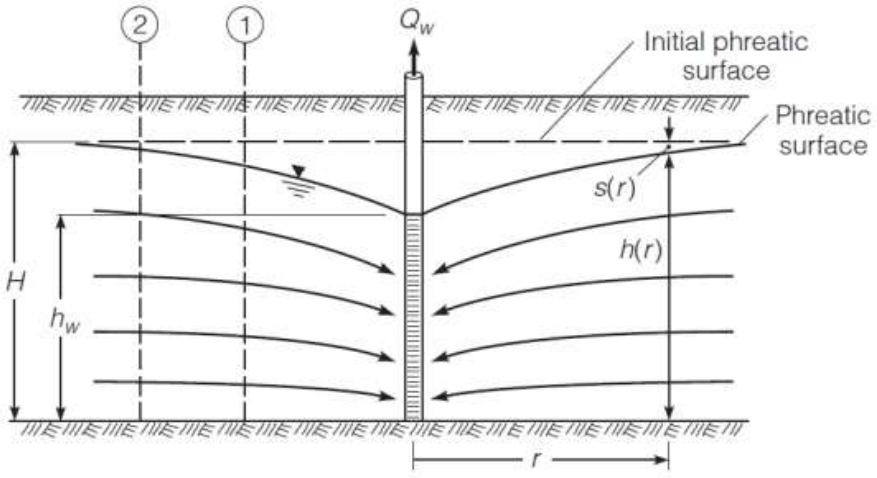


FIG:4.3.15:Fully penetrating well in an unconfined aquifer (Chin, 2013)

The expression for the head distribution induced by a fully penetrating pumping well in an unconfined aquifer is given by:

$$h(r) = \sqrt{h_0^2 + \frac{Q}{4\pi T} W(u)}$$

……4.3.27

Where:

$h(r)$ is the hydraulic head at radial distance rr from the pumping well,

h0 is the initial hydraulic head (before pumping begins),

Q is the pumping rate (volume per unit time),

T is the transmissivity of the aquifer (length squared per time),

$W(u)$ is the well function, which depends on the dimensionless variable uu,

u is defined as u=$(r2S)/(4Tt$u)

S is the storativity (dimensionless), representing the storage coefficient of the aquifer,

t is the time since pumping began.

This expression represents the distribution of hydraulic head around the pumping well in the unconfined aquifer. It shows how the hydraulic head varies with radial distance from the well and over time as pumping continues. The term inside the square root represents the drawdown induced by pumping, and the initial hydraulic head h0 is added to this drawdown to obtain the total head distribution.

boundary condition, the head distribution is given by,

$$\boldsymbol{h(r) = \sqrt{h_w^2 + (H - h_w)^2 \frac{ln(\frac{r}{r_w})}{ln(\frac{R}{r_w})}}}$$

……4.3.28

Well in a leaky confined aquifer:

In isotropic and homogeneous semiconfined (leaky) aquifers, the distribution of piezometric head for 2-D flows is given by Eq.

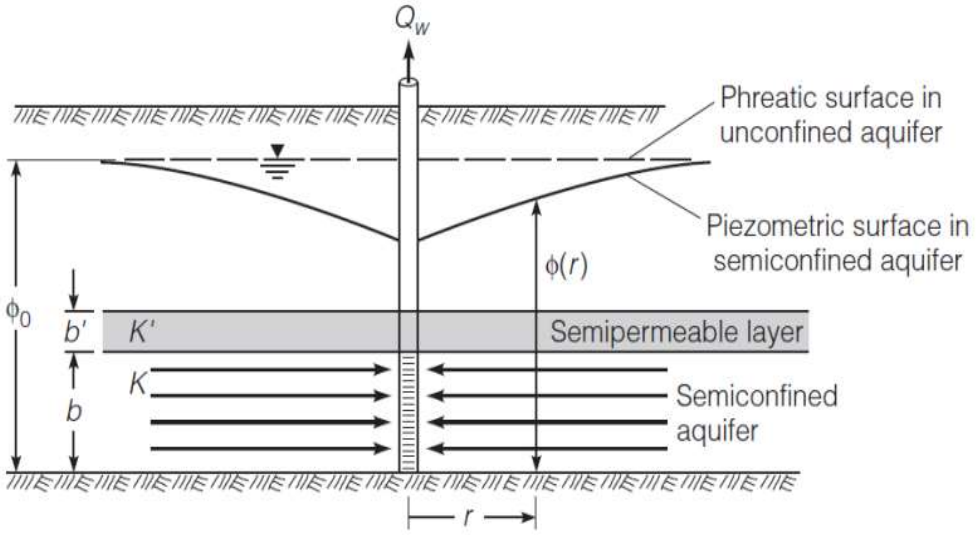


FIG:4.3.16:Fully penetrating well in a semi-confined aquifer (***Chin, 2013***)

If a well fully penetrates the semiconfined aquifer and withdraws water at a constant rate uniformly over the aquifer thickness,

$$\frac{d^2\phi}{dr^2}+\frac{1}{r}\frac{d\phi}{dr}+\frac{N}{Kb}=0 \qquad \text{…….4.3.29}$$

Leakage into the semiconfined aquifer can be calculated by applying Darcy's law across the semipermeable layer, in which case,

$$N=-K'\frac{\phi-\phi_0}{b'} \qquad \text{……..4.3.30}$$

the piezometric head above the semipermeable layer, assumed to be constant.

Bessel's equation is a second-order ordinary differential equation that arises in many areas of mathematical physics, including problems involving wave propagation, heat conduction, and fluid dynamics. It is named after the German mathematician Friedrich Bessel, who studied these equations extensively in the early 19th century.

The standard form of Bessel's equation of order ν is:

$$x^2\frac{d^2y}{dx^2}+x\frac{dy}{dx}+(x^2-\nu^2)y=0 \qquad \text{……..4.3.31}$$

Where:

y is the unknown function to be solved for,

x is the independent variable,

dy/dx and $d2y/dx2$ are the first and second derivatives of y with respect to x, respectively, and

$\nu\nu$ is a constant parameter known as the order of the Bessel equation.

The solutions to Bessel's equation are called Bessel functions, denoted as $J\nu(x)$ or $Y\nu(x)$, depending on whether they are regular ($J\nu(x)$ or irregular ($Y\nu(x)$ at the origin. The behavior of these functions depends on the order $\nu\nu$.

Bessel functions are widely used in various fields of physics and engineering, particularly in problems with circular or cylindrical symmetry, such as electromagnetic wave propagation in circular waveguides, heat conduction in cylindrical objects, and fluid flow in cylindrical pipes.

Bessel's equation and its solutions play a crucial role in understanding the behavior of physical phenomena governed by cylindrical symmetry, providing elegant mathematical tools to solve such problems.

In this case, there are two aquifer properties: transmissivity, and leakage factor These aquifer properties can be estimated using with drawdown measurements at two locations.

Denoting the drawdown measurements by yields,

$$s(r) = \frac{Q_w}{2\pi T} \frac{K_0\left(\frac{r}{\lambda}\right)}{\left(\frac{r_w}{\lambda}\right) K_1\left(\frac{r_w}{\lambda}\right)}$$

……..4.3.32

$$T = \frac{Q_w}{2\pi s_1} \frac{K_0\left(\frac{r_1}{\lambda}\right)}{\left(\frac{r_w}{\lambda}\right) K_1\left(\frac{r_w}{\lambda}\right)}$$

……4.3.33

can be used to estimate the leakage factor from the drawdown measurements. This leakage factor can subsequently be used to calculate the transmissivity of the semiconfined aquifer. The derived leakage factor can be used to classify the leakiness of the semi-confining layer using the classification system in that was originally suggested by Sen (1995). Aquifers with leakage factors exceeding 10,000 m can be treated as confined aquifers. The equations derived in this section assume that the flow is horizontal in the aquifer and vertical in the semi-confining (leaky) layer. Errors introduced by these assumptions are generally less than 5%, provided that the hydraulic conductivity of the aquifer is more than two orders of magnitude greater than that of the semi-confining layer (Neuman and Witherspoon, 1969).

➢ Theory of Pumping Test:

Pumping test (sometimes also called field pumping test) can be defined as a field investigation in which a well is pumped in a specific fashion and the resulting drawdowns are measured in the pumping well itself and/or observation wells installed at different locations over the groundwater basin under investigation. Many modern books on groundwater/hydrogeology mostly use the terminology 'Aquifer test' instead of the widely-used terminology 'Pumping test'. Although the use of both the terms is recommended, the 'aquifer test' is a broader term which encompasses non-conventional tests also. Note that the phrases 'pumping test' and 'pump test' convey completely different meanings, and hence they should be used cautiously.

o Purpose of Pumping Test:

he pumping test or aquifer test is the only standard method available to date for determining the hydraulic characteristics of various aquifer systems [e.g., T, K, S or Sy, leakage factor (B) and hydraulic resistance (C)] and those of production wells (e.g., well parameters, safe well yield, etc.). Long-term time-drawdown pumping tests can also provide information about the presence of subsurface hydraulic barriers, if any, as well as the existence of a boundary and its type (recharge, impermeable or leaky boundary). Properly placed observation wells at different locations and in different directions can provide information about the degree of heterogeneity and anisotropy of aquifer systems. Further, step-drawdown tests can provide important information about the hydraulic characteristics of production wells (i.e., aquifer loss coefficient, well loss coefficient, well efficiency, well specific capacity, and safe well yield) and the condition of production wells.

- **Types of Pumping Tests:**

There are primarily four types of pumping tests/aquifer tests. They are as follows:

(1) Time-Drawdown Test:

(a) Interference Test

(b) Distance-Drawdown Test

(c) Single Well Test

(2) Recovery Test

(3) Step-Drawdown Test or Variable Rate Test

(4) Injection Tests:

(a) Time-Groundwater Level Rise Test

(b) Step-Injection Test

Aquifer tests (1) and (2) are mainly used for determining various hydraulic parameters of different aquifer systems (viz., confined, leaky confined and unconfined aquifers). However, the step-drawdown test is used for determining the hydraulic characteristics of production wells and for evaluating the condition of existing production wells.

Instead of a production well, if an injection well is used to conduct a pumping test, it is called an injection test. The injection test can be designed to observe 'time-groundwater level rise' in an injection well itself or in nearby observation wells. In addition, the injection test can be designed to conduct a 'step-groundwater level

rise' or 'step-injection' test. Since in injection tests, water is injected into a production well instead of pumping, it is not technically sound to call it a pumping test; aquifer test is a better terminology to assimilate this type of test. Thus, the term 'aquifer test' includes both pumping tests and injection tests.

When aquifer tests 1(a, b, c), (2), and 4(a) are conducted until an equilibrium (steady-state) or quasi-equilibrium (quasi steady-state) condition is reached, they are called steady-state tests. On the other hand, when these tests are conducted for a relatively short period and are completed before the steady-state or quasi steady-state condition is reached, they are called unsteady-state tests or transient tests.

The type of pumping test/aquifer test performed depends on the purpose, available resources (labor, money, instruments/equipment, etc.) and time, and site-specific limitations. Site-specific limitations, for instance, could be limited water disposal facilities, water quality constraints, or noise restrictions.

- Tests for Determining Hydraulic Parameters of Aquifers

1.Steady and Unsteady Time-Drawdown Tests

Time-drawdown pumping tests are suitable for the determination of aquifer parameters. Based on the type of data yielded by time-drawdown pumping tests, these tests fall into two categories: (a) unsteady-state tests or transient tests, and (b) steady-state tests or equilibrium tests. In both the categories, the pumping rate is kept constant throughout the duration of the test. In unsteady-state tests, groundwater level changes in response to a constant pumping rate are measured over a period of time. The data obtained from transient tests are useful for determining almost all the hydraulic parameters of aquifer systems.

In steady-state tests, pumping is continued until near-equilibrium conditions are reached (i.e., there are negligible changes in groundwater levels with time). In practice, steady-state tests approach only quasi-steady-state conditions in most aquifer systems. This is because true equilibrium may never be obtained under field conditions because of ever-present aquifer recharge or discharge in a groundwater system. The data obtained from steady-state tests can be used to calculate only aquifer transmissivity or hydraulic conductivity and, in some cases, leakance (leakage coefficient); storage coefficient of an aquifer system cannot be determined from these data.

While conducting time-drawdown tests, drawdown can be measured either in one or more observations wells (called 'interference test') or in the pumping well itself (called 'single well test'). They are described below.

a) Interference Test

The measurement of groundwater level changes (drawdowns) in response to pumping in one or more observation wells is known as an interference measurement as shown in Fig. 13.1. Depending upon the nature of the interference test, it can be steady-state test and/or unsteady-state test. Unlike pumping well measurements, interference measurements contain no turbulent flow components, and hence the drawdown measured in observation wells is the representative of that in aquifers. This is the reason that interference-test data are

preferred for determining aquifer parameters. For interference tests, it is essential that the observation wells should be completed in the same aquifer as the pumping well

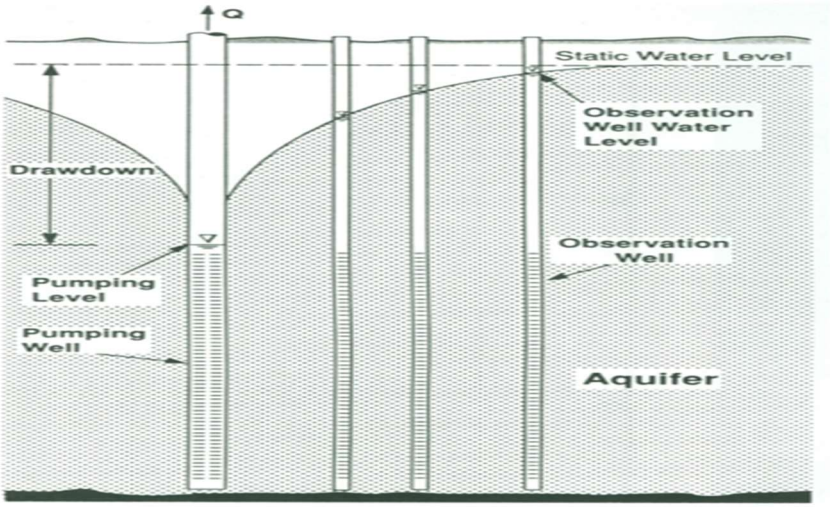


Fig:4.3.17: Illustration of an interference pumping test.

(Source: Roscoe Moss Company, 1990)

Determination of aquifer transmissivity (T) or hydraulic conductivity (K) from the steady-state test data usually requires the steady drawdown data from two observation wells or the steady drawdown data from at least one observation well in addition to the pumping well; the drawdown measured in a pumping well needs to be corrected for well losses. However, the steady drawdown data from one observation well or pumping well can also be used for computing K or T, if the radius of influence is known. On the other hand, the determination of aquifer parameters including the storativity (storage coefficient) requires transient drawdown data from one observation well only. As a rule, the more observation wells available for measurement during a time-drawdown test, the more reliable the information obtained on aquifer characteristics. Since real-world aquifer systems exhibit significant heterogeneity, it is essential that the time-drawdown measurements during a pumping test should be done at as many locations as possible and that time-drawdown tests should be conducted at various sites over a basin or sub-basin so as to account for the aquifer heterogeneity. If the observation wells are oriented in different directions away from the pumping well, aquifer anisotropy can also be determined.

b) Distance-Drawdown Test

In distance-drawdown tests, drawdown is measured in three or more observation wells located at different radial distances from a pumping well, and thereby a set of distance-drawdown data is obtained. This test as such is not conducted separately in the field; rather one can create such dataset from the time-drawdown measurements at different locations during a time-drawdown test. Thus, depending on the nature of time-drawdown tests, the distance-drawdown data can be of two types: distance-steady drawdown data or distance-unsteady drawdown data; the former dataset can yield only aquifer transmissivity (T) or hydraulic conductivity (K), whereas the latter dataset can yield both T and storage coefficient (S). The distance-drawdown data are useful for cross-checking the aquifer parameters obtained from time-drawdown data. In addition, the distance-drawdown data can be used to calculate ‘radius of influence’ (R0) and ‘well loss’ (and hence ‘well efficiency’).

c) Single Well Test

If the time-drawdown aquifer test is conducted in such a way that the drawdown is measured only in a pumping/production well itself, it is known as a single well test. Single well test is normally conducted when there are no observation wells in a basin or sub-basin and it is not possible to install observation wells due to money and/or time constraints. Hence, single well tests are less expensive than the interference tests.It should be noted that the drawdown in a pumping well consists of two types of head losses: (a) aquifer loss or formation loss (drawdown due to laminar flow in the aquifer which is known as ‘theoretical drawdown’), and (b) well

loss (drawdown due to turbulent flow in the immediate vicinity of the pumping well through the screen and/or gravel pack as well as due to flow inside the well to the pump intake) as shown in Fig.2. Since the well loss is associated with turbulent flow, it is proportional to an nth power of the pumping rate (well discharge) where n is a constant greater than one. Thus, the total drawdown in a pumping well or well drawdown (sw) is given as (Fig.2):

sw = Aquifer Loss + Well Loss

$$sw = BQ + CQ^n \quad \text{.....4.3.23}$$

Where, B = aquifer/formation loss coefficient, Q = pumping rate (well discharge), and C = well loss coefficient which is a function of the radius, construction and condition of the pumping well.

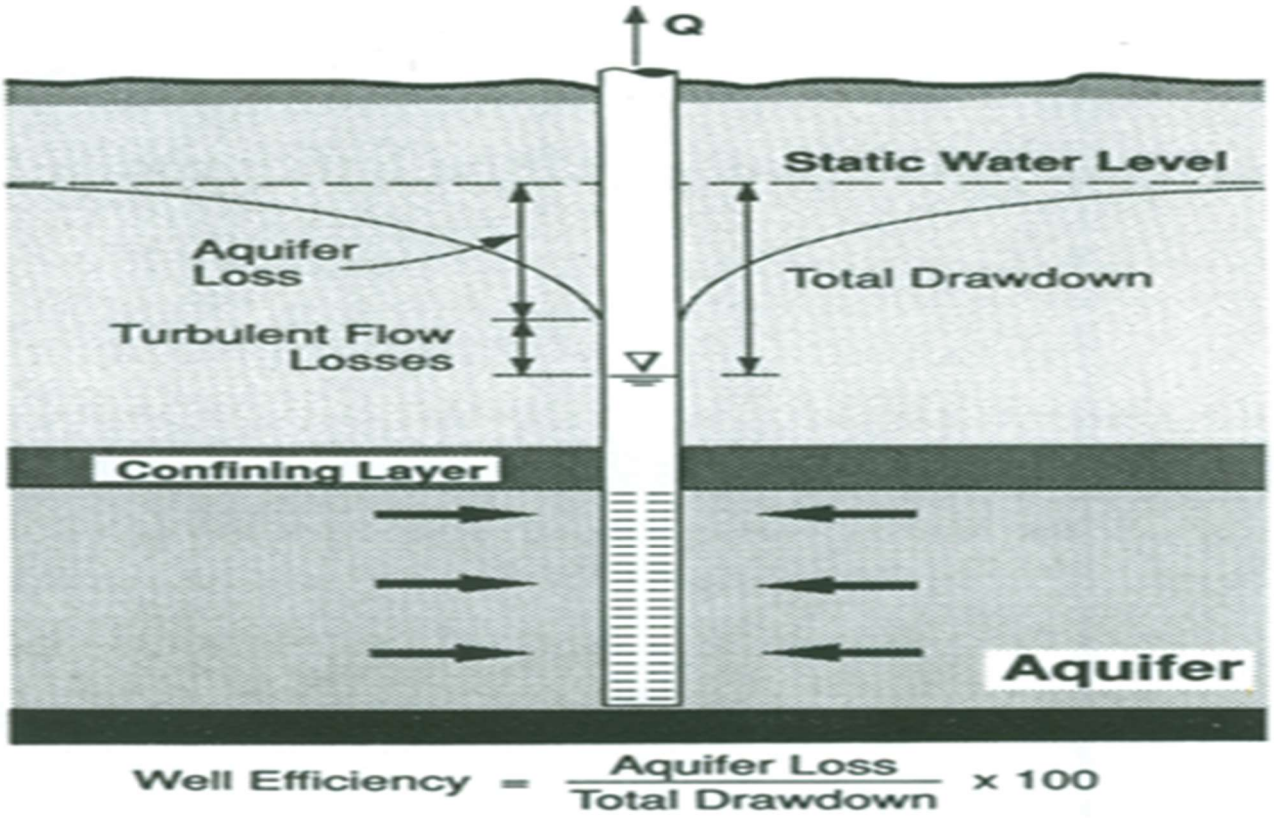


Fig:4.3. 18: .

(Source: Roscoe Moss Company, 1990)

It is obvious from Eqn. (2) that the aquifer loss increases linearly with increasing pumping rate, while the well loss increases non-linearly with increasing pumping rate. Therefore, the well loss can be a sizeable component of the well drawdown (i.e., total drawdown) when pumping rates are large. The first term (aquifer loss) on the right-hand side of Eqn. (2) can be calculated by using Thiem equation (if the well drawdown is steady) or Theis equation (if the well drawdown is unsteady). However, the second term (well loss) can be determined by step-drawdown test (described later in this lesson) or can be estimated from distance-drawdown data. Well losses can be minimized by proper design and development of pumping wells. However, clogging or deterioration of well screens can increase well losses in old pumping wells.

Thus, the drawdown measured in pumping wells is not the representative of that in the aquifer. Consequently, single well test is generally avoided unless the value of well loss for a particular pumping well is known so that the measured well drawdowns could be corrected to be representative of aquifer drawdowns. Note that the time-drawdown data obtained from single well tests should be used for the determination of T or K only, because these data do not yield reliable estimates of S.

2. Recovery Test

Recovery test is conducted at the end of a time-drawdown aquifer test. It is an unsteady-state aquifer test in which groundwater rise is measured with time in a pumping/production well or in an observation well after pumping has been stopped (Fig. 3). It is apparent from Fig. 3 that if the pumping of a well is stopped, the groundwater level in the aquifer gradually starts increasing and it should theoretically return to its pre-pumping groundwater level; this time period is known as recovery period or recovery phase. From the water-level data measured during recovery period, 'residual drawdown' (difference between the pre-pumping groundwater level and the depth to groundwater after the pump is stopped) or 'recovery' (difference between the extrapolated time-drawdown curve and the residual drawdown) is computed at different times during recovery period (Fig. 3). The 'time-residual drawdown' data or the 'time-recovery' data thus obtained are used for determining aquifer parameters.

In general, the data obtained during the recovery period are more reliable than during the pumping period due to the lack of water-level fluctuations caused by discharge variations and the absence of turbulence. Like the time-drawdown data from single well tests, the time-recovery data measured in pumping wells can yield only T or K. However, if the time-recovery data are measured in observation wells, both T and S can be determined.

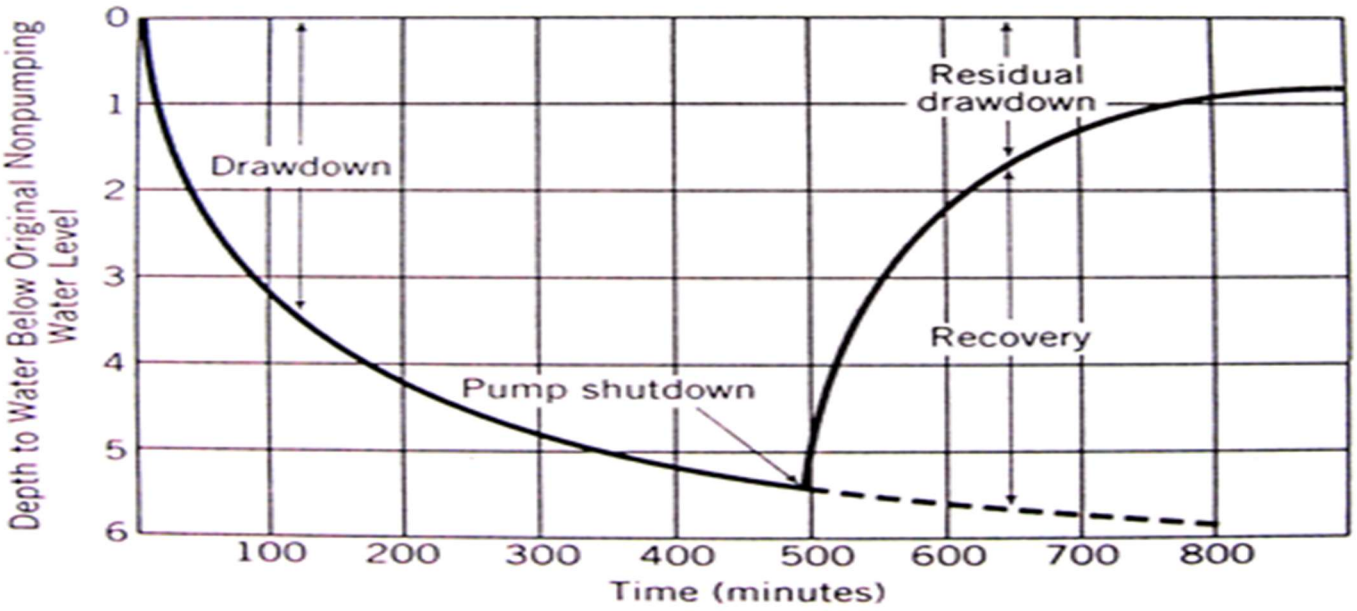


Fig:4.3. 19: Illustration of time-drawdown and recovery tests.

(Source: Schwartz and Zhang, 2003)

Since additional expenses are not required for conducting a recovery test, it is always recommended to carry out this test during an aquifer-test program for a basin or sub-basin. The recovery test provides an independent

and additional estimate of aquifer parameters, which can be compared with the aquifer parameters obtained from time-drawdown data to gain confidence in the analysis.

4 Injection Tests

In the area where artificial recharge projects using the well injection technique are running, injection tests can be conducted in that area. The test procedures and the equations used for analyzing injection well test data are similar to those of drawdown tests, except that the injection pressure head (i.e., difference between the static groundwater level and the groundwater level during injection) is substituted for drawdown, and the injection rate for pumping rate (Roscoe Moss Company, 1990). Thus, the data of time-groundwater level rise test can be used for determining hydraulic parameters of aquifer systems. Similarly, the data of step injection test can be used for determining the hydraulic characteristics of production wells.

a)Step-Drawdown Test

In a step-drawdown test (or variable rate test), changes in the drawdown of a pumping/production well are measured corresponding to the changes in pumping rate (i.e., well discharge) as illustrated in Fig.4. This test is normally conducted by pumping a production well at successively greater pumping rates (i.e., $Q_1 < Q_2 < Q_3 < Q_4 < Q_5$) for 5 to 8 steps (pumping rates). The entire test is done in one day. Generally, the drawdown for a particular step (pumping rate) is measured until a steady-state or quasi-steady-state condition is reached. Alternatively, this test can also be conducted by pumping a production well for about 1-2 hours at each successively greater pumping rate and observing unsteady drawdown at the end of each step (i.e., after 1-2 hours of pumping). However, the analysis of 'discharge-unsteady drawdown' data becomes somewhat complicated. Thus, a set of 'discharge-drawdown' data for a particular pumping well is obtained from a step-drawdown test.

The 'discharge-drawdown' data obtained from a step-drawdown test are analyzed to determine the hydraulic characteristics of a production well such as

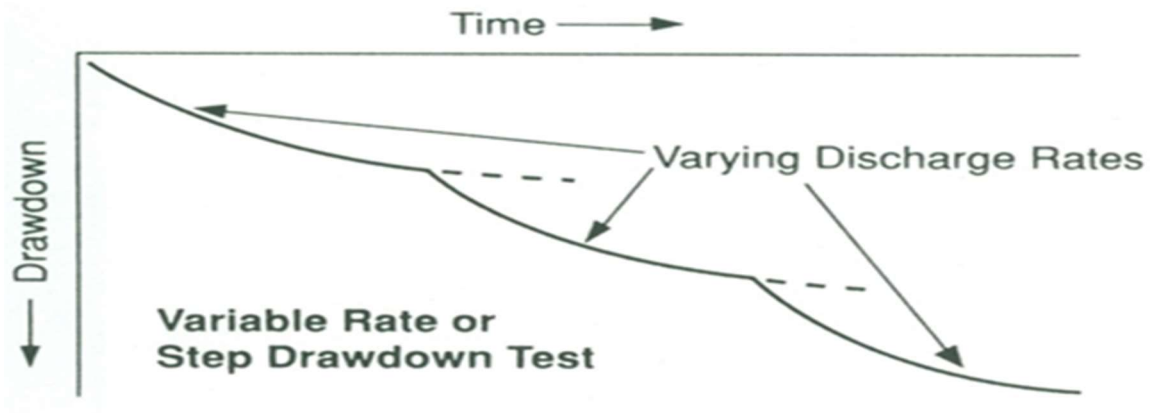


Fig:4.3.20: Illustration of a step-drawdown test.

(Source: Roscoe Moss Company, 1990)

safe well yield, aquifer loss and well loss coefficients, specific capacity of the well (ratio of the well discharge to the corresponding drawdown), well efficiency (ratio of the theoretical drawdown to the observed well drawdown as shown in Fig. (2), and the relationships between drawdown and discharge, between well efficiency or specific capacity and discharge as well as the evaluation of the condition of existing production wells. Thus, the step-drawdown tests are of great significance for the design and monitoring of pumping plants as well as for estimating site-specific safe aquifer yields over a basin or sub-basin.

5.3 Critical Pumpage and Safe Well Yield

Based on the step-drawdown test data, a safe pumping rate or safe well yield for a production well can be determined. The safe well yield is generally defined as the highest pumping rate at which equilibrium conditions can be maintained in the aquifer system (Roscoe Moss Company, 1990). When the equilibrium rate is exceeded, the pumping level continues to decline at a rate proportional to the well and aquifer parameters. When this decline is quite rapid (e.g., several centimeters per minute), the well may dewater in a relatively short time period, with the pump 'breaking suction'; the latter condition is very serious and could result in the collapse of well casing.

The pumping rate (well discharge) at which a rapid decline in groundwater level occurs is known as critical pumpage or critical discharge (Roscoe Moss Company, 1990). This condition varies widely from one area to another as well as from one well to another in an area. For example, in the areas having high-yielding aquifers (i.e., high values of T and S), the full capacity of a pump may not be able to create a critical pumpage situation. However, in the areas having low-yielding aquifers (i.e., low values of T and S), a rapid dewatering of the well may be achieved quite easily. Besides these factors, water quality (e.g., saltwater intrusion or contaminated water migration) also limit the safe pumping rate. This situation necessitates reduced pumping rate below the potential of production wells. Note that the safe pumping rate or safe well yield should always be less than the critical pumpage in order to ensure sustainable groundwater utilization in a basin.

6.Design of Pumping Test

Proper planning and design of a pumping test is essential for ensuring good-quality pumping-test data. Besides the adequate knowledge of the local lithology and types of aquifers, a proper selection of production wells to be pumped and the observations wells for drawdown measurement is also necessary. The latter requires the field information such as depth, design and condition of pumping wells; availability of water disposal facility; and the number of observation wells and their depth, design and location. On top of it, some additional decisions are to be made prior to the execution of pumping tests. These points are described in this section.

6.1 Placement of Observation Wells and Number of Tests

Ideally, observation wells should be placed in four quadrants surrounding the production well at radial distances ranging from 3 m to 300 m (Roscoe Moss Company, 1990). Spacing between the observation wells should be closer near to the pumping well where drawdown changes are the greatest. Observation wells should be placed considering both the duration of a pumping test and aquifer parameters, because the shape of the cone of depression depends upon these two major factors. For instance, the cones of depression in the aquifers having low transmissivity are steep and limited compared to the broad and flat cones of depression in the aquifers having high transmissivity (Fig. 13.5). Similarly, if the duration of a pumping test is longer, the cone of depression is expected to extend up to a larger distance from the pumping well in comparison with the short-duration pumping test.

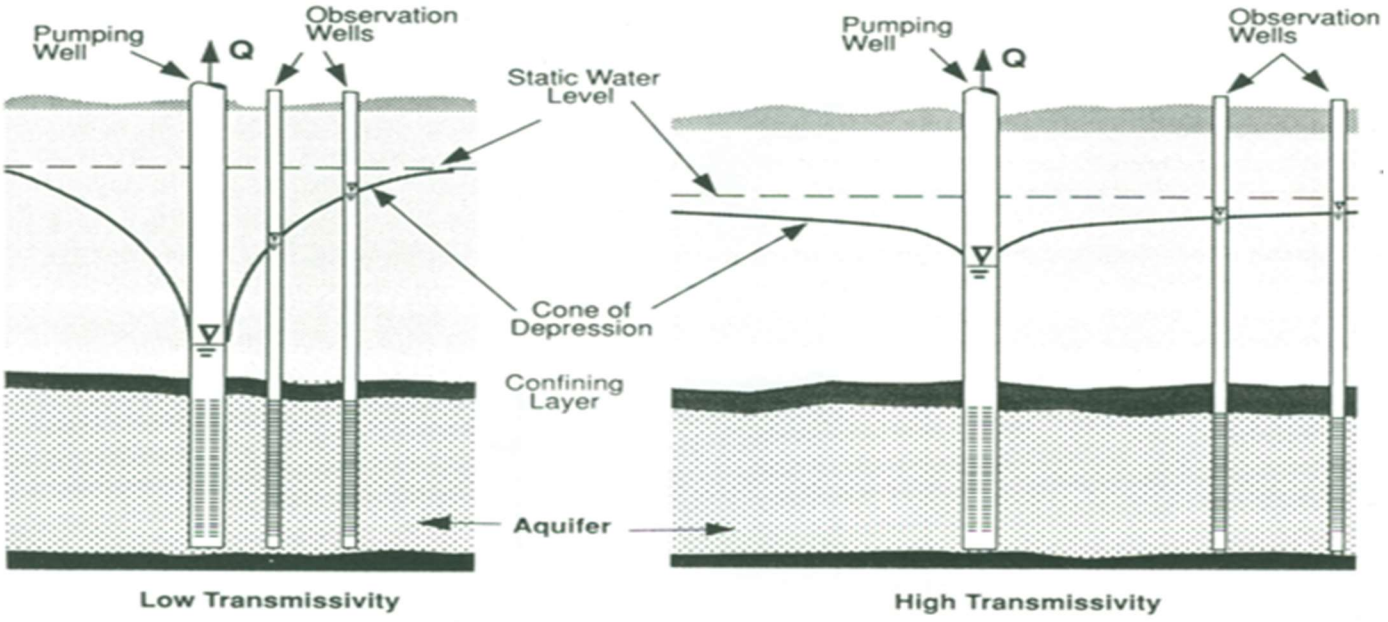


Fig:4.3.21: Placement of observation wells for a pumping test. (Source: Roscoe Moss Company, 1990)

Moreover, proper knowledge of the aquifer type is also important for the placement of observation wells. For example, groundwater level changes in unconfined aquifers may be measurable within only relatively short distances from the pumping well (e.g., 30 to 150 m), whereas confined aquifers may show significant changes in groundwater level hundreds (100 to 250 or more) to thousands of meters away from the pumping well (Roscoe Moss Company, 1990). Furthermore, if hydrogeologic boundaries are known or anticipated, it is desirable to place observation wells between the boundary and the pumping well. In most cases, placing observation wells at about 10 to 100 m from the center of the pumping well provides good results. The observation wells should be placed in the same aquifer in which the pumping well is installed. Also, both the pumping well and the observation well should fully penetrate the aquifer under investigation so as to avoid the complexity in the analysis of pumping-test data.

As far as the number of pumping tests (or aquifer tests) and the number of observation wells are concerned, they depend on the amount of information desired, degree of precision expected, heterogeneity/anisotropy of the aquifer, and the availability of fund and time for investigation. In general, the number should be as many as techno-economically feasible for a better understanding of the spatial variation in aquifer parameters over a basin.

6.2 Pumping Rate and Test Duration

The rate of pumping during aquifer tests should be such that an appreciable drawdown occurs in most of the observation wells placed at different radial distances. It should also be ensured that the drawdowns measured during an aquifer test are not affected by any other factors. If any external factor affects the drawdown measured in a given observation well, the data become erroneous (noisy) and such data are usually not considered for analysis.

As to the duration of aquifer tests, it depends on both the test purpose and the hydraulic properties of the aquifer. Since the hydraulic properties of an aquifer are to be determined by aquifer tests, they are not known prior to conducting aquifer tests. Therefore, the duration of aquifer tests mainly depends on whether one wishes to conduct unsteady-state tests or steady-state tests. The duration of unsteady-state tests is shorter (a few hours only) than that of steady-state tests which can vary from several hours to days. Essentially, the duration of an aquifer test should ensure that sufficient number of drawdown data with significant differences from one another is obtained so that the data are well spread in the graph to be plotted during analysis. Under average

conditions, a leaky aquifer should be pumped for 15 to 20 hours, a confined aquifer should be pumped for 1 day, and an unconfined aquifer for 3 days or more in order to achieve steady-state (equilibrium) flow condition (Roscoe Moss Company, 1990). As such, there exist no hard and fast universal guidelines for deciding the duration of aquifer tests. However, the guidelines suggested in Table 13.1 can be followed to ensure that the aquifer-test duration exceeds the minimum pumping time mentioned in this table.

Table4.3.1: Guidelines for deciding the duration of aquifer tests

(Source: Todd, 1980)

Sl. No.	Predominant Aquifer Material	Minimum Pumping Time
1	Silt and Clay	170 hours
2	Fine Sand	30 hours
3	Medium Sand and Coarser Materials	4 hours

6.3 Measurement of Pumping Rate and Groundwater Level

The essential measurements taken during any aquifer test are time, pumping rate (well discharge), and depth to groundwater level (i.e., drawdown or groundwater rise). Measurements of the time of start, stop and pumping interval must be made with a reasonable accuracy (±0.1 min). The pumping rate or well discharge should preferably be kept constant throughout the aquifer test. During an aquifer test, well discharge is measured at regular intervals and an adjustment is made to keep it constant. If the well discharge is small, it can be accurately measured by the volumetric method. However, if the well discharge is large, a water meter or an orifice meter installed in the delivery pipe of the pump, or a 90º V-notch (fitted with a conveyance channel wherein pumped water is diverted for disposal) can be used. The depth to groundwater level can be measured either manually using a water-level indicator and/or automatically by a water-level recorder (‘clock and chart type water-level recorder’ or ‘water-level sensor’).

6.4 Schedule of Data Collection

Once an aquifer test is initiated, the groundwater levels in a pumping well or an observation well decline (after start of pumping) or recover (after stop of pumping) very rapidly during first one or two hours. Therefore, initially groundwater level is measured at short time intervals and thereafter the time interval is gradually increased as the pumping proceeds. The data-collection schedule presented in Table 2 should be followed for measuring groundwater levels in pumping wells and/or nearby observation wells during an aquifer test. Frequency of measurement is less important for the observation wells located at larger distances from the pumping well.

Table 4.3.2: Frequency of groundwater-level measurement during aquifer tests (Source: Roscoe Moss Company, 1990)

Time Since Pumping Started or Stopped	Time Interval
0-5 min	1 min
5-60 min	5 min
60-120 min (i.e., 1-2 hours)	15 min
2-6 hours	1 hour
6 hours - End of Test	2 hours

7. Response of Bounded Aquifers to Pumping

The general theory of groundwater hydraulics assumes that the aquifer is infinite in areal extent. In reality, however, aquifers are not infinite because they can be cut by tight faults (e.g., fault barriers) or they can end abruptly due to changes in geology (e.g., limited aquifer conditions or impermeable bedrock) These impermeable boundaries of an aquifer system effectively halt the spread of the cone of depression and significantly affect the pattern of drawdown in the vicinity of pumping wells (Todd, 1980; Fetter, 1994; Schwartz and Zhang, 2003). Similarly, if an aquifer system is bounded by a surface-water body (e.g., a fully penetrating stream, lake, or reservoir) or an adjacent segment of aquifer having considerably high transmissivity or Storativity, these recharge boundaries can halt the spread of a cone of depression by providing a source of recharge to the aquifer. They also influence the pattern of drawdown in the vicinity of pumping wells.

In general, the theory of well hydraulics cannot cope with the presence of one of above-mentioned aquifer boundaries. The method of images, which plays an important role in the mathematical theory of electricity, is employed in conjunction with the principle of superposition for assessing the influence of aquifer boundaries on the well flow (Ferris, 1959). This theory permits treatment of the aquifer that is limited in one or more directions. However, the additional assumption of straight-line boundaries is added, which renders aquifers of rather simple geometric form.

7.1 Image Well Theory

Boundaries are considered to be either a recharge boundary or an impermeable boundary (or a barrier boundary). A recharge boundary is a region in which the aquifer is replenished. An impermeable boundary or a barrier boundary is an edge of the aquifer where it terminates either by thinning or abutting a low-permeability formation or has been eroded away (Fetter, 1994).

When a pumping well is located near a recharge or barrier (impermeable) boundary, there are considerable deviations in the radial-flow pattern towards a pumping well. As a result, the solution to the flow towards wells

under such conditions becomes complicated and the radial-flow equations (Theim or Theis equations) cannot be applied. For boundaries, the wells that create the same effect as a boundary are called image wells. The theory of image well was formulated (Ferris, 1959) to tackle flow problems in bounded aquifers using analytical techniques. In this theory, the effect of a recharge or leaky boundary is simulated by considering an imaginary recharging well, which is known as a 'recharging image well' . Similarly, the effect of an impermeable boundary is simulated by considering an imaginary pumping well, which is known as a 'discharging image well'. Thus, an image well (imaginary recharging well or imaginary pumping well) creates a hydraulic system equivalent to the effects caused by a physical boundary on the flow system. In essence, image wells enable us to transform the aquifer of finite extent to the aquifer to infinite extent. Consequently, the radial flow equations can be applied to analyze the well flow near aquifer boundaries. This is described below for the two types of aquifer boundaries.

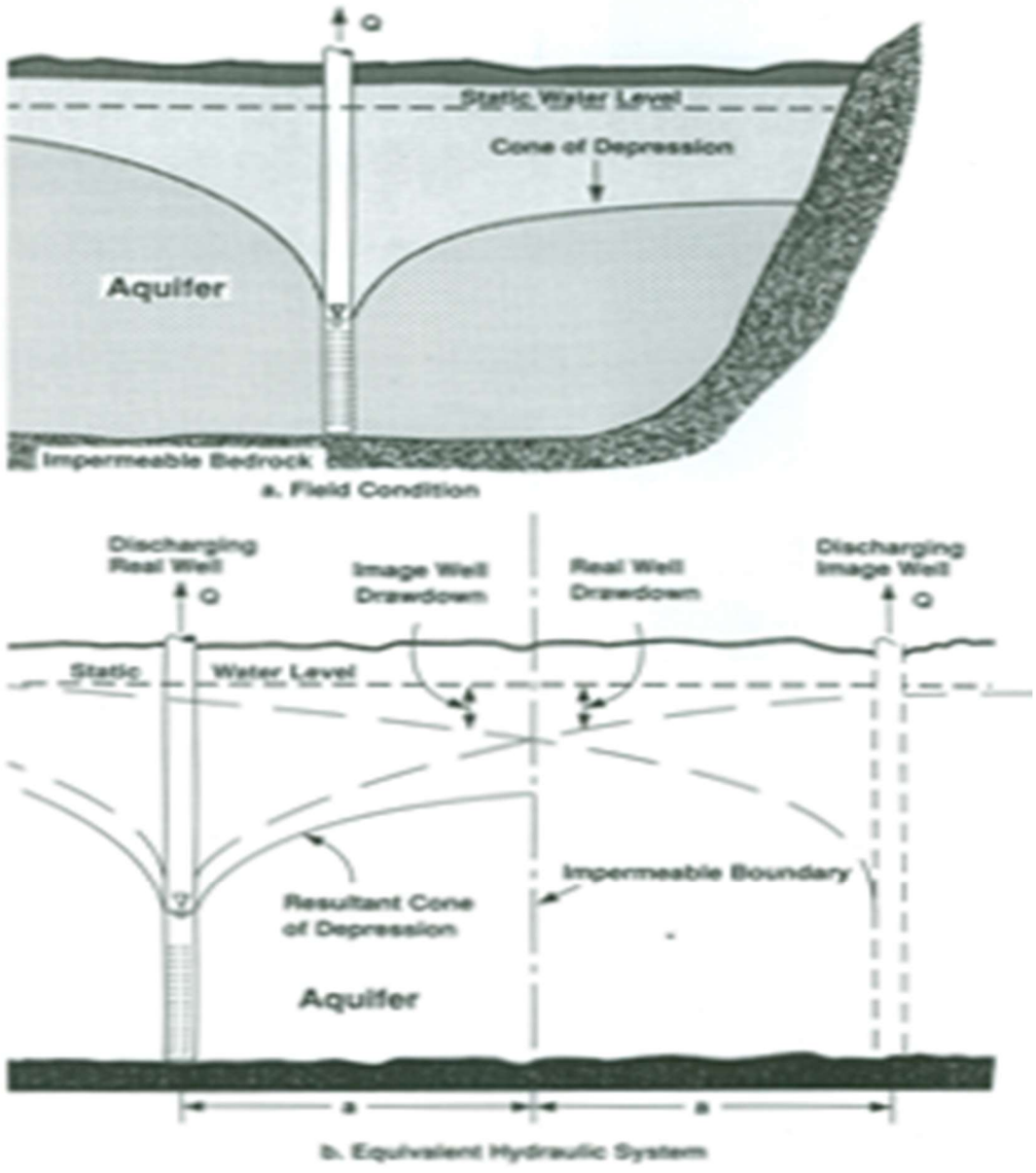


Fig:4.3.22: Pumping well near a recharge boundary.

(Source: Roscoe Moss Company, 1990)

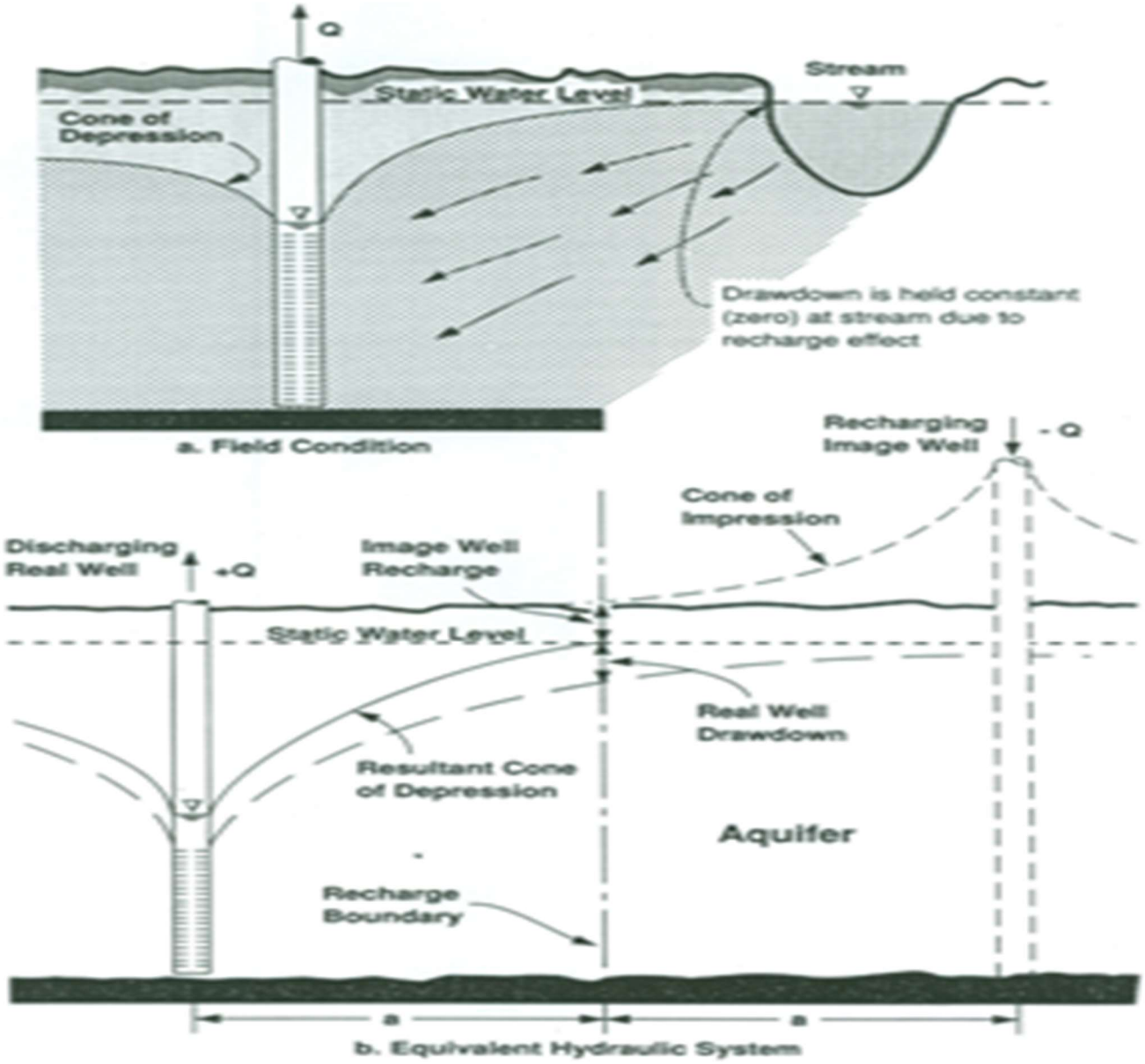


Fig4.3.23: Pumping well near an impermeable boundary.

(Source: Roscoe Moss Company, 1990)

7.2 Pumping Near Recharge Boundary

Figure. 6. shows a pumping well in an aquifer bounded by a recharge boundary. As the recharge boundary provides a source of recharge to the aquifer, once the cone of depression extends to the recharge boundary, it initially stops the spread of a cone of depression and then starts reducing the rate of drawdown. When the rate of recharge from the boundary becomes equal to the rate of pumping (well discharge), steady-state (equilibrium) flow condition is established in the aquifer and the drawdown becomes stationary. As mentioned above, the recharge boundary can be simulated by a recharging image well located an equivalent distance away from the recharge boundary but on the opposite side (Fig. 4.3.20).

Using the Theis equation, the unsteady drawdown in an observation well under the influence of a recharge boundary can be given as follows:

$$s(r,t)=\frac{Q}{4\pi T}\left[W\left(\frac{4Tt}{r^2S}\right)-W\left(\frac{4Tt}{r_i^2S}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3.24)}$$

Using the Cooper-Jacob equation (Cooper-Jacob's approximation for the Theis well function evaluation), we have:

$$s(r,t)=\frac{Q}{4\pi T}\left[\ln\frac{2.25Tt}{r^2S}-\ln\frac{2.25Tt}{r_i^2S}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3.25)}$$

Where, s(r,t) = drawdown in an observation well under the influence of a recharge boundary, r = distance of the observation well from the real well (i.e., pumping well), r_i = distance of the observation well from the image well (i.e., recharging image well), and the remaining symbols have the same meaning as defined earlier.

If steady-state flow condition is established in the aquifer, the drawdown will stabilize and will not change with time any longer. In this case, the steady drawdown in an observation well under the influence of a recharge boundary can be given as:

$$s(r)=\frac{Q}{2\pi T}\ln\frac{r_i}{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3.26)}$$

If the distance between the pumping well (real well) and the recharge boundary is a and f is the angle between the line joining the real and image wells and the line joining the real well and observation well (Fig. 3.8), then Eqn. (3.5) can be expressed as:

$$s(r)=\frac{Q}{2\pi T}\ln\left(\frac{\sqrt{4a^2+r^2-4ar\cos\phi}}{r}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3.27)}$$

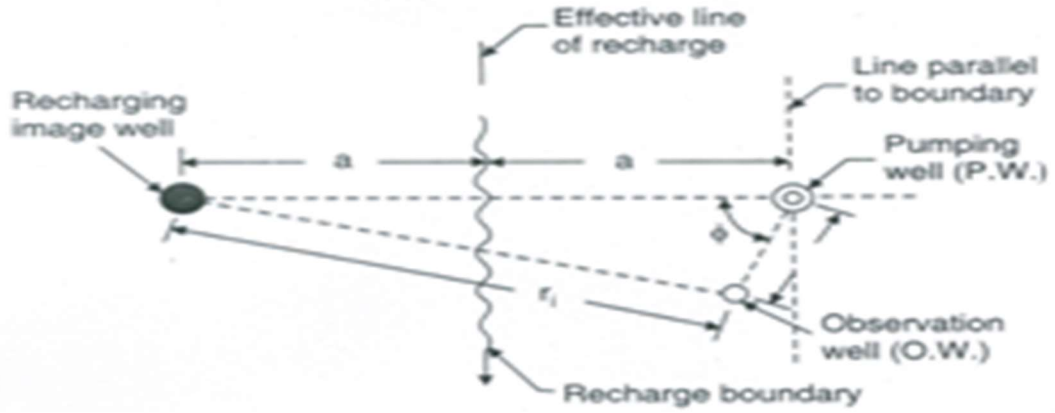


Fig:4.3.24: Typical configuration of pumping well, observation well and image well in an aquifer bounded by a recharge boundary. (Source: Raghunath, 2007)

Moreover, the expression for steady drawdown in a pumping well (i.e., steady drawdown at the well face) under the influence of a recharge boundary can be obtained as follows by substituting $r = r_w$ and $r_i = 2a - r_w$ in Eqn. (5):

$$s_w = \frac{Q}{2\pi T}\ln\left(\frac{2a - r_w}{r_w}\right) \quad \text{..... (4.3.28)}$$

7.3 Pumping Near Impermeable Boundary

Figure 13.7 shows a pumping well in an aquifer bounded by an impermeable boundary. Impermeable boundaries have the most dramatic impact on the drawdown of a pumping well for the aquifer with no source of vertical recharge. As the well withdraws water only from the aquifer storage, the drawdown continues as a function of the logarithm of time (Fetter, 1994). The impermeable boundary is simulated by a discharging image well located an equivalent distance away from the boundary but on the opposite side (Fig. 3.7). The unsteady drawdown in an observation well under the influence of an impermeable boundary can be expressed as:

$$s(r,t) = \frac{Q}{4\pi T}\left[W\left(\frac{4Tt}{r^2 S}\right) + W\left(\frac{4Tt}{r_i^2 S}\right)\right] \quad \text{..... (4.3.29)}$$

Using the Cooper-Jacob equation (Cooper-Jacob's approximation for the Theis well function evaluation), we have:

$$s(r,t) = \frac{Q}{4\pi T}\left[\ln\frac{2.25Tt}{r^2 S} + \ln\frac{2.25Tt}{r_i^2 S}\right] \quad \text{..... (4.3.29a)}$$

Or

$$s(r,t) = \frac{Q}{4\pi T}\left[2\ln\frac{2.25Tt}{r^2 S} + \ln\frac{r^2}{r_i^2}\right] \quad \text{..... (4.3.29b)}$$

Where, r_i = distance of the observation well from the image well (i.e., discharging image well), and the remaining symbols have the same meaning as defined earlier.

Furthermore, the unsteady drawdown in a pumping well (i.e., unsteady drawdown at the well face) under the influence of an impermeable boundary can be expressed as:

$$s_w(t) \text{ or } s(r_w,t)=\frac{Q}{4\pi T}\left[2\ln\frac{2.25Tt}{r_w^2 S}+\ln\frac{r_w^2}{(2a-r_w)^2}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3.30)}$$

8.4 Impact of Aquifer Boundaries on Time-Drawdown Curve

Figure 9 shows a theoretical straight-line plot of drawdown as a function of time on the semi-logarithmic paper. It is evident from this figure that the impact of a recharge boundary is to slow down (retard) the rate of drawdown. The change in drawdown can become zero if the well is supplied entirely with recharged water. In contrast, the impact of a barrier boundary or an impermeable boundary on flow in some region of the aquifer is to accelerate the drawdown rate (Fig.9). In this case, the groundwater level declines faster than the theoretical drawdown curve (straight line shown in Fig.9).

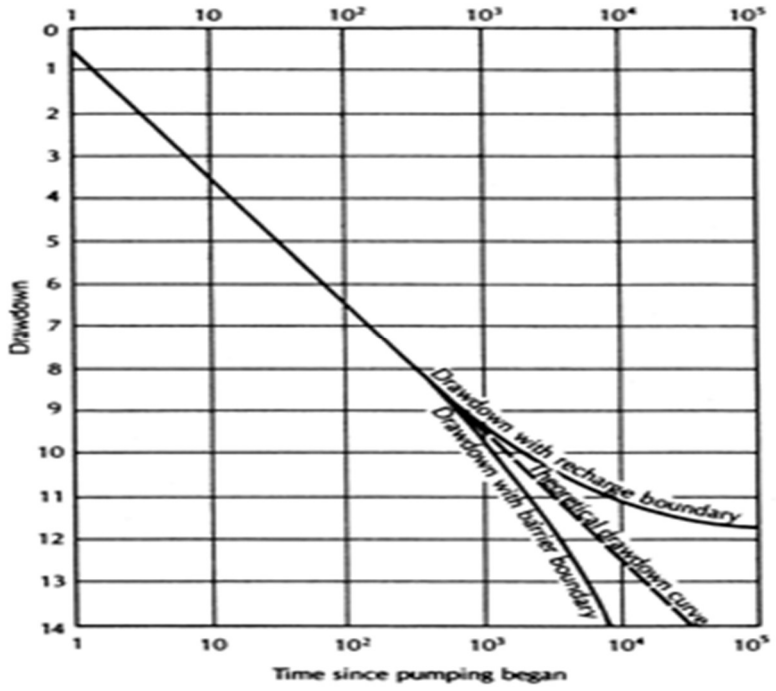


Fig:4.3.25: Impact of recharge and impermeable boundaries on the time-drawdown curve. (Source: Redrawn from Fetter, 1994)

Theis Method of Solution:

The drawdown is given by

The Theis method is a mathematical solution used in hydrogeology to analyze the behavior of groundwater flow to a pumping well in an unconfined aquifer. It was developed by Joseph H. Theis in 1935 and is widely used for estimating drawdown (the lowering of the water table) in aquifers due to pumping.

The Theis equation describes the drawdown of groundwater in response to pumping from a well in an unconfined aquifer. It is derived from the principles of groundwater flow and assumes radial flow towards the pumping well. The basic equation is:

$$s(u) = \left(\frac{Q_w}{4\pi T}\right) W(u)$$

The ***Boltzman variable*** can be rearranged and written as

$$\frac{r^2}{t} = \left(\frac{4T}{S}\right) u \qquad \text{…….4.3.34}$$

Where:

s is the drawdown at the pumping well,

Q is the pumping rate (in volume per unit time),

T is the transmissivity of the aquifer,

$W(u)$ is the well function, which is a mathematical function that depends on a dimensionless variable uu that represents time and distance.

The Theis solution assumes certain simplifying assumptions, including steady-state pumping, homogeneous and isotropic aquifer properties, and absence of boundaries that might influence flow. Despite these limitations, the Theis method is widely used because it provides a reasonably accurate estimation of drawdown in many practical situations.

The Theis method is often used in groundwater modeling and aquifer pumping tests to estimate parameters such as transmissivity and hydraulic conductivity of the aquifer. It's an essential tool for hydrogeologists and engineers involved in groundwater management and water resource development.

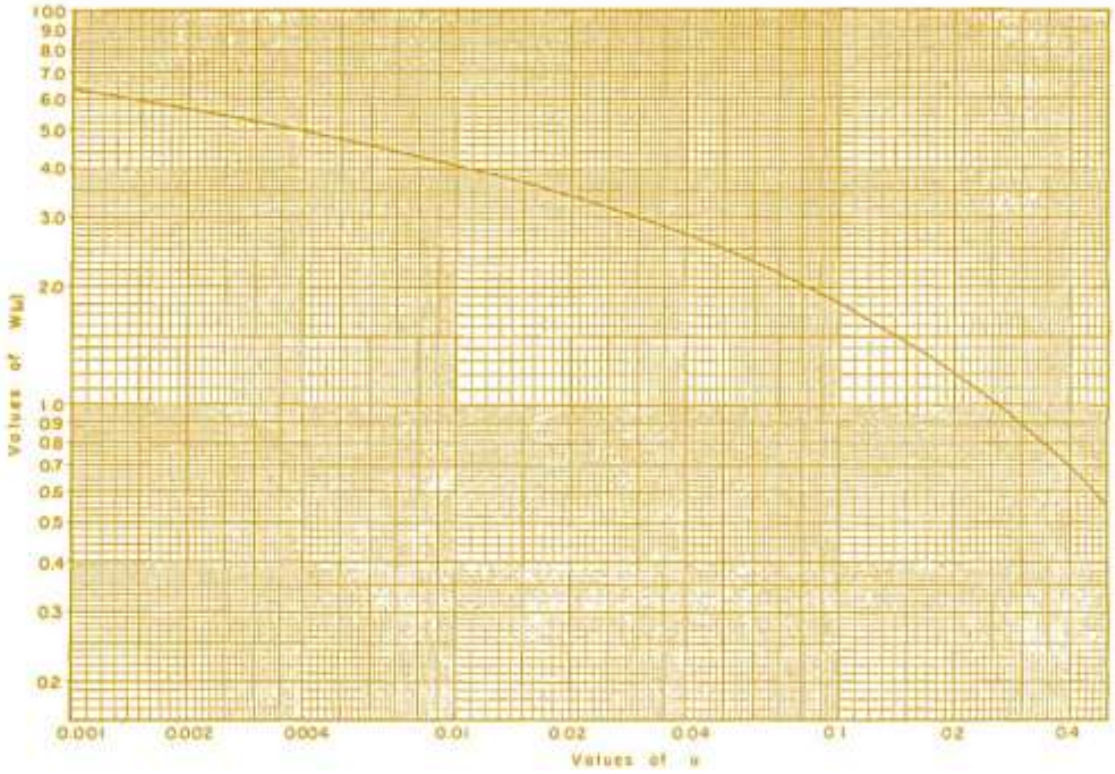


FIG:4.3.26:Plot of W(u) versus u known as a ***type curve***
(***Bruin & Hudson Jr., 1961***)

Table:4.3.3Values of W(u) & u

u	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
$\times 1$	0.2194	0.1489	0.0130	0.0038	0.0011	0.0004	0.0001	0.0000	0.0000
$\times 10^{-1}$	1.8229	1.2227	0.9057	0.7024	0.5598	0.4544	0.3738	0.3106	0.2602
$\times 10^{-2}$	4.0379	3.3547	2.9591	2.6813	2.4679	2.2953	2.1508	2.0269	1.9187
$\times 10^{-3}$	6.3315	5.6394	5.2349	4.9482	4.7261	4.5448	4.3916	4.2591	4.1423
$\times 10^{-4}$	8.6332	7.9401	7.5348	7.2472	7.0242	6.8420	6.6879	6.5545	6.4368
$\times 10^{-5}$	10.9357	10.2428	9.8372	9.5494	9.3264	9.1440	8.9899	8.8564	8.7386

Type curve:

In hydrogeology, a type curve is a standardized graphical representation used to analyze and interpret data from pumping tests conducted in aquifers. The type curve method is often employed in conjunction with solutions like Theis or Cooper-Jacob to estimate aquifer parameters.

It works:

Data Collection: During a pumping test, data such as drawdown (change in water level) at the pumping well versus time is collected.

Normalization: The drawdown data is then normalized using appropriate dimensionless parameters. For example, in the case of Theis solution, the drawdown is divided by the pumping rate and the aquifer transmissivity to normalize the data.

Plotting: The normalized data is plotted on a graph. On the same graph, a pre-calculated type curve is also plotted. This type curve represents the expected behavior of drawdown versus time for a specific set of aquifer parameters.

Comparison: By comparing the normalized field data to the type curve, hydrogeologists can estimate aquifer parameters such as transmissivity or hydraulic conductivity. If the field data matches the type curve closely, it suggests that the aquifer parameters are similar to those represented by the type curve.

Iterative Process: Often, the matching process involves adjusting the aquifer parameters until the field data closely matches the type curve. This iterative process helps in refining the estimates of aquifer properties.

Type curves provide a convenient way to analyze pumping test data and estimate aquifer parameters without needing complex mathematical calculations for each dataset. They are widely used in hydrogeology for their simplicity and efficiency in interpreting pumping test results.

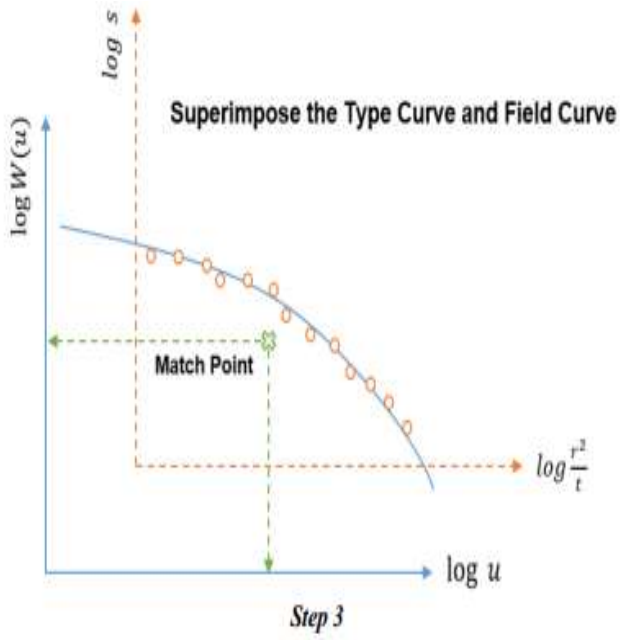


Fig:4.3.27: Theis method for solution of the non-equilibrium equations.

Cooper-Jacob Method of Solution:

The Cooper-Jacob method provides a systematic approach to solving the nonlinear flow equations governing groundwater movement. By discretizing the domain and iteratively solving the linearized equations, it allows for the approximation of complex groundwater flow scenarios. This method is particularly valuable in practical groundwater management and engineering applications where accurate predictions of groundwater behavior is essential. The groundwater flow equation, typically expressed as Darcy's law combined with the continuity equation, represents the fundamental equation in groundwater hydrodynamics:

$\nabla \cdot (K \nabla h) = S$

Where:

h is the hydraulic head,

K is the hydraulic conductivity tensor,

S is the source/sink term.

Method Steps:

Discretization: The domain is divided into discrete elements (e.g., finite difference cells or finite elements) to approximate the continuous flow equations.

Linearization: Nonlinear terms in the equations are linearized using an iterative approach.

Iteration: The linearized equations are solved iteratively until convergence is achieved.

Update: Hydraulic head values are updated based on the iterative solution.

Convergence Criterion: The iteration continues until the difference between successive iterations falls below a predefined tolerance level.

The utility of the series expression for W(u) given by Eq. is that for small values of (u) is,

$$W(u) = -0.5772157 - \ln u$$

Therefore, $s(u) = \frac{Q_w}{4\pi T}\left[-0.5772157 - \ln u\right]$

or, $s(u) = \frac{Q_w}{4\pi T}\left[-0.5772157 - \ln\left(\frac{r^2 S}{4Tt}\right)\right]$

or, $s(u) = \frac{2.303\, Q_w}{4\pi T} \log\left(\frac{2.25\, T\, t}{r^2 S}\right)$

……..4.3.35

This approximation was first applied to the analysis of groundwater flow by *Cooper and Jacob (1946)* and is commonly referred to as the *Cooper–Jacob approximation*. For u < 0.03 and the error is less than 1%, and for u = 0.1 the error is about to 5%. Typical applications of the *Cooper-Jacob approximation* are limited to u < 0.05 .

Application of the *Cooper-Jacob approximation* in cases where there is a constant pumping rate, usually consists of the following steps:

Step 1: Plot s versus (r^2/t) from measurements taken at one or more monitoring wells; different values of r can be used.
Step 2: Fit a straight line to the data corresponding to $u < 0.05$.
Step 3: Determine a and b from the equation of the best-fit line.
Step 4: Solve for T and S using Eq. (1.116a.) and Eq. (1.116b.).

Application:

The Cooper-Jacob method in groundwater hydrodynamics finds application in various groundwater modeling scenarios, including:

Aquifer Simulation: Modeling flow and transport in aquifers with heterogeneous properties.

Well Hydraulics: Analyzing the behavior of pumping wells and their impact on groundwater levels.

Contaminant Transport: Simulating the movement of contaminants through groundwater systems.

Managed Aquifer Recharge: Optimizing strategies for injecting water into aquifers for storage and later recovery.

Time-Drawdown Method:

Time is plotted along the logarithmic X-axis and drawdown is plotted along the linear Y-axis. Transmissivity and Storativity are calculated as follows:

$$T = \frac{2.303\, Q_w}{4\pi \Delta s} \log\left(\frac{t_2}{t_1}\right)$$

$$S = \frac{2.25\, T\, t_0}{r^2}$$

where, Δs is the amount of drawdown ……..4.3.36

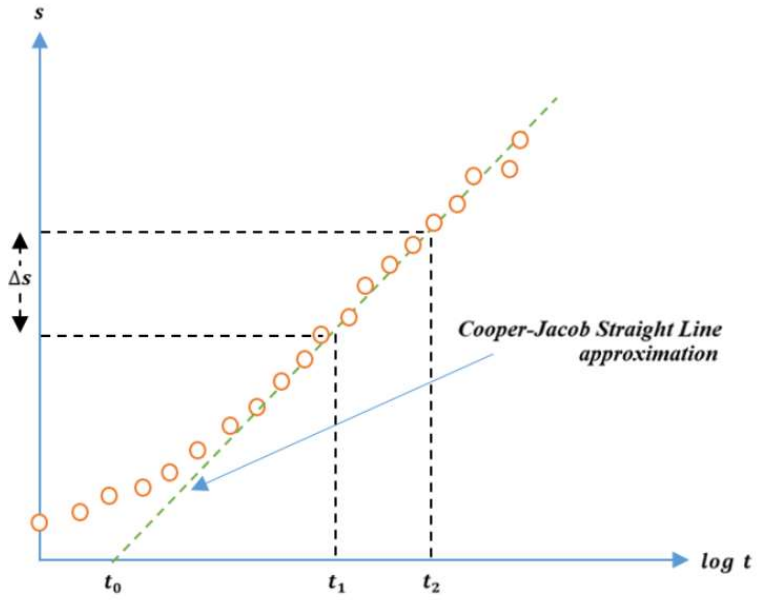


FIG:4.3.28: Cooper-Jacob Approximation using Time-Drawdown Method

Distance-Drawdown Method: The observation well distance is plotted along the logarithmic X-axis and drawdown is plotted along the linear Yaxis. Transmissivity and Storativity are calculated as follow

$$T = \frac{2.303\ Q_w}{4\pi\ \Delta s}\ log\left(\frac{r_2}{r_1}\right)$$

$$S = \frac{2.25\ T\ t}{r_0^2}$$

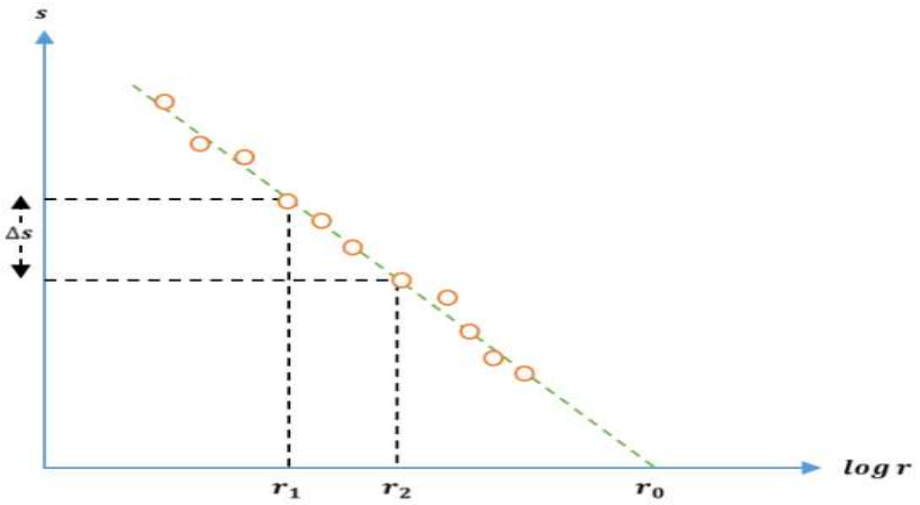


FIG:4.3.29: Cooper-Jacob Approximation using Distance-Drawdown Method

Therefore, under the restriction that S << **2H,** the governing equation and associated initial and boundary conditions are exactly the same as the governing equation and associated initial and boundary conditions that describe unsteady drawdown in a confined aquifer, with the only

exception being that the storage coefficient, $\boldsymbol{S}$ in the confined aquifer case is replaced by the specific yield, in the unconfined aquifer case.

The aquifer response in pumping tests carried out in unconfined aquifers frequently varies for small and large times. More specifically, compared to large-time data, the storage coefficient that is derived from small-time data may be substantially smaller. The usual explanation for this phenomena is that gravity drains from the pores above The water table does not rise instantly, and the first water release is solely connected to the compressibility of the aquifer's material and water. Gradually, gravity drainage starts to contribute much to aquifer recharging, resulting in a yield that is noticeably delayed. seen in aquifer materials with finer grain sizes, and it could take weeks for them to empty completely **(Gorelick et al.,1993).**

Neuman (1975; 1973; 1972) derived the following solution for a pumping well in an unconfined aquifer with delayed yield,

$$s = \frac{Q_w}{4\pi T} W(u, u_y, \Gamma)$$

where, $W(u, u_y, \Gamma)$ is called the ***unconfined well function*** 4.3.37

Neuman's well function equation, also known as the Theis well function, is a fundamental solution derived by Charles Vernon Theis in 1935. It's used extensively in hydrogeology to describe the drawdown at a pumping well in an unconfined or confined aquifer. Neuman further extended and refined Theis's work, and his formulation is often referred to as Neuman's well function.

The equation for Neuman's well function, denoted as $W(u)$W(u), is expressed as:

$$W(u) = \int_u^\infty \frac{e^{-s}}{s} ds \qquad \text{.....4.3.38}$$

Where:

u is a dimensionless parameter related to time and aquifer properties, defined as u=$(r2S)/(4Tt)$,

r is the radial distance from the pumping well to the observation point,

S is the storage coefficient of the aquifer,

T is the transmissivity of the aquifer, and

t is time.

Neuman's well function provides a solution to the Theis equation, which describes transient groundwater flow in a confined or unconfined aquifer under steady-state pumping conditions. It represents the integral of the exponential integral function, which accounts for the effects of pumping on drawdown over time and space.

The well function $W(u)$ is typically tabulated or calculated numerically for various values of u. It serves as a fundamental tool for analyzing pumping tests and designing pumping schemes in hydrogeological studies. By using Neuman's well function, hydrogeologists can estimate drawdown at observation points for different pumping rates and aquifer properties without needing to solve the full differential equation governing groundwater flow.

Neuman's well function remains a cornerstone of groundwater hydrogeology and is widely used in practice to analyze and interpret data from pumping tests, groundwater modeling studies, and aquifer characterization efforts.

The equation derived by Neuman typically takes the form of a type curve, which relates dimensionless parameters representing aquifer properties, pumping rate, and time to the dimensionless drawdown at the pumping well. The general form of the equation can be expressed as:

$s=W(u)-2\cdot(Q/4\pi T)\cdot t$.....4.3.39

Where:

s is the drawdown at the pumping well,

$W(u)$ is a dimensionless function representing the delayed yield effect,

Q is the pumping rate,

T is the transmissivity of the aquifer,

t is time, and

u is a dimensionless parameter related to time and aquifer properties.

The function $W(u)$ encapsulates the delayed drainage effect and depends on the dimensionless parameter uu, which accounts for the time-dependent behavior of the aquifer's response to pumping.

This solution allows hydrogeologists and engineers to estimate drawdown at a pumping well for given aquifer conditions and pumping rates without needing to solve the full differential equation governing groundwater flow. The type curve approach provides a convenient tool for analyzing pumping tests and designing pumping schemes in unconfined aquifers.

Neuman's contributions have had a profound impact on groundwater hydrology and have been instrumental in advancing the understanding of unconfined aquifer behavior under pumping stress. His work remains foundational in the field of hydrogeology and continues to be widely used and cited in groundwater studies.

$\frac{1}{u}$	Γ								
	0.001	**0.01**	**0.06**	**0.2**	**0.6**	**1.0**	**2.0**	**4.0**	**6.0**
4.0×10^{-1}	0.0234	0.0240	0.0230	0.0217	0.0188	0.0170	0.0138	0.00933	0.00639
8.0×10^{-1}	0.144	0.140	0.131	0.119	0.0988	0.0849	0.0603	0.0317	0.0174
1.4×10^{0}	0.358	0.345	0.318	0.279	0.217	0.175	0.107	0.0445	0.0210
2.4×10^{0}	0.662	0.633	0.570	0.483	0.343	0.256	0.133	0.0476	0.0214
4.0×10^{0}	1.02	1.46	0.849	0.688	0.438	0.300	0.140	0.0478	0.0215
8.0×10^{0}	1.57	1.88	1.23	0.918	0.497	0.317	0.141	0.0478	0.0215
1.4×10^{1}	2.05	2.27	1.51	1.03	0.507	0.317	0.141	0.0478	0.0215
2.4×10^{1}	2.52	2.61	1.73	1.07	0.507	0.317	0.141	0.0478	0.0215
4.0×10^{1}	2.97	3.00	1.85	1.08	0.507	0.317	0.141	0.0478	0.0215
8.0×10^{1}	3.56	3.23	1.92	1.08	0.507	0.317	0.141	0.0478	0.0215
1.4×10^{2}	4.01	3.37	1.93	1.08	0.507	0.317	0.141	0.0478	0.0215
2.4×10^{2}	4.42	3.43	1.94	1.08	0.507	0.317	0.141	0.0478	0.0215
4.0×10^{2}	4.77	3.45	1.94	1.08	0.507	0.317	0.141	0.0478	0.0215
8.0×10^{2}	5.16	3.46	1.94	1.08	0.507	0.317	0.141	0.0478	0.0215

Table:4.3.4:Values of $W(u)$ for unconfined aquifers

$\frac{1}{u_y}$	Γ								
	0.001	0.01	0.06	0.2	0.6	1.0	2.0	4.0	6.0
4.0×10^{-1}	5.62	3.46	1.96	1.13	0.589	0.421	0.248	0.149	0.113
8.0×10^{-1}	5.62	3.46	1.98	1.18	0.667	0.506	0.357	0.266	0.231
1.4×10^{0}	5.63	3.47	2.01	1.24	0.780	0.642	0.517	0.445	0.419
2.4×10^{0}	5.63	3.49	2.06	1.35	0.954	0.850	0.763	0.718	0.703
4.0×10^{0}	5.63	3.51	2.13	1.50	1.200	1.13	1.08	1.06	1.05
8.0×10^{0}	5.64	3.56	2.31	1.85	1.68	1.65	1.63	1.63	1.63
1.4×10^{1}	5.65	3.63	2.55	2.23	2.15	2.14	2.14	2.14	2.14
2.4×10^{1}	5.67	3.74	2.86	2.68	2.65	2.65	2.64	2.64	2.64
4.0×10^{1}	5.70	3.90	3.24	3.15	3.14	3.14	3.14	3.14	3.14
8.0×10^{1}	5.76	4.22	3.85	3.82	3.82	3.82	3.82	3.82	3.82
1.4×10^{2}	5.85	4.58	4.38	4.37	4.37	4.37	4.37	4.37	4.37
2.4×10^{2}	5.99	5.00	4.91	4.91	4.91	4.91	4.91	4.91	4.91
4.0×10^{2}	6.16	5.46	5.42	5.42	5.42	5.42	5.42	5.42	5.42
8.0×10^{2}	6.47	6.11	6.11	6.11	6.11	6.11	6.11	6.11	6.11
1.4×10^{3}	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67
2.4×10^{3}	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21	7.21
4.0×10^{3}	7.72	7.72	7.72	7.72	7.72	7.72	7.72	7.72	7.72
8.0×10^{3}	8.41	8.41	8.41	8.41	8.41	8.41	8.41	8.41	8.41
1.4×10^{4}	8.97	8.97	8.97	8.97	8.97	8.97	8.97	8.97	8.97

**Source: David A. Chin (2013)*

Table:4.3.5: Values of $W(u_y)$ for unconfined aquifers

These ***Type A*** and ***Type B curves*** are tabulated in Tables and can be used to determine the aquifer parameters based on small-time and large-time pumping data using the relations

$$s = \frac{Q_w}{4\pi T} W(u, \Gamma), \text{ for small time}$$
$$s = \frac{Q_w}{4\pi T} W(u_y, \Gamma), \text{ for large time} \qquad \text{……4.3.40}$$

The application of above equation is illustrated in Fig. below , where ***Type A curves*** merge into the Theis curve shown on the left, and ***Type B curves*** merge into the Theis curve shown on the right.

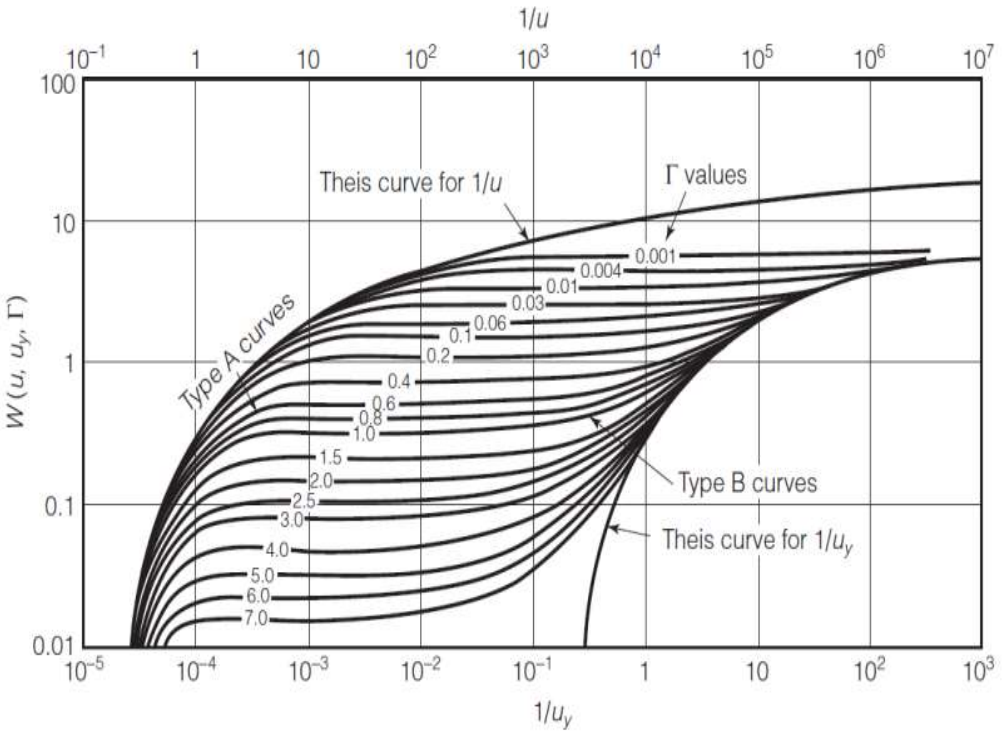


FIG :4.3.30: Unconfined aquifer well functions

In unconfined aquifers, the time-drawdown curve usually consists of three separate segments, as illustrates. The first part starts as soon as pumping starts, when water extracted from the aquifer is connected to the matrix's compressibility and subsurface water. These emissions are parameterized by the aquifer's storage coefficient. The second descent section depicts the transitional phase where the expansion of the Due to gravity drainage and the time-drawdown slope, the cone of depression shrinks. curve dips, indicating recharging. The time-drawdown curves in the third section follow the Theis solution with gravity drainage that is based on a given yield. The latter situation might originate from multiple minutes to several days following the start of pumping. Pump-drawdown information gathered over the previous.

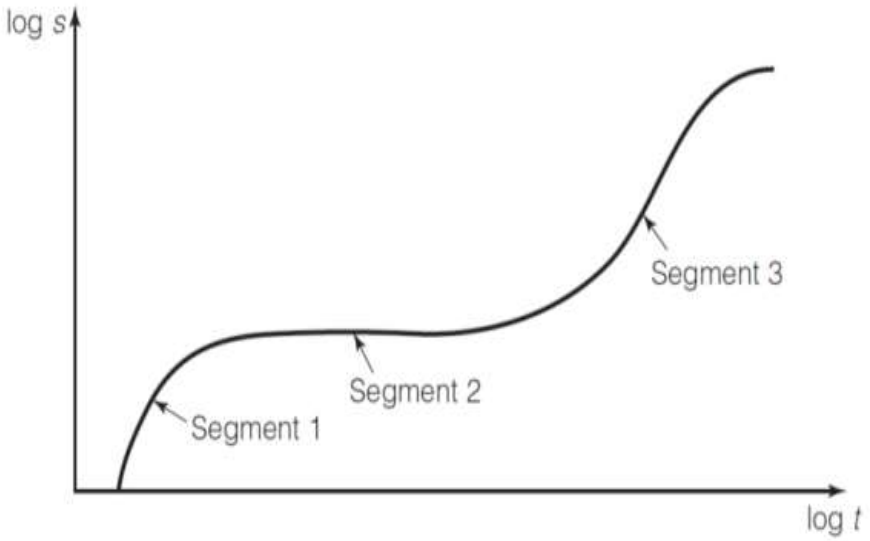


FIG:4.3.31: Three segments of time-drawdown curve in unconfined aquifers (***Chin, 2013***)

8. ***Advantages and Disadvantages of Pumping Tests:***

The advantages of the pumping test method are self-evident. A pumping test provides in situ parameter values and these values are, in effect, averaged over a large and representative volume (Freeze and Cherry, 1979). From a single pumping test, one can obtain both T and S values. Also, in aquifer-aquitard systems (i.e., leaky aquifer systems), it is possible to get very important leakage properties of the system (e.g., leakage factor, hydraulic conductivity and storage coefficient of aquitards, and leakance). Moreover, the step-drawdown test provides hydraulic characteristics of production wells, including safe well yield.However, there are two disadvantages of the pumping test (Freeze and Cherry, 1979): one scientific and one practical. The scientific limitation is that the pumping test interpretation is not unique. For example, similarity in time drawdown response could be found for leaky, unconfined and bounded systems. Thus, unless clear geologic evidence is available, a unique prediction of the effects of any pumping test would be difficult. The fact that a theoretical curve can be matched by the pumping test data in no way proves that the aquifer satisfies the assumptions on which the curve is based. The practical disadvantage of the method lies in its expense, including money, time and labor. Therefore, when only K or T values are required such as in the case of geotechnical and contamination studies or flow net analysis, simple and inexpensive methods like slug test should be used. These simple and cheaper methods are also useful when local conditions do not permit pumping tests or when preliminary and quick results are desired.

4.4 SIEVE ANALYSIS TEST:

4.4.1 Introduction:

The properties of an aquifer material related to its storage function are its porosity and specific yield. Porosity is the ratio of the volume of voids or pores in a soil mass to its total volume. Shape, size and packing of the grains affect the porosity of granular material. The grain size distribution of the formation or aquifer material can be determined by conducting a mechanical analysis test in a nest of standard sieves with the coarsest on top and finest at the bottom, covered with lid on the top and bottom pan as receiver.

A representative sample, about 150-500 gm, is taken in the laboratory by quartering, oven dried and an exact weight poured into the top sieve and covered with lid. The whole nest is shaken through a mechanical sieve shaker (hand operated /electrical) for about 5 minutes and the material retained on each sieve and bottom pan is accurately weighed. Percentage of material passing through each sieve gives a point on the grading curve.

4.4.2 Description:

Sieve diameter (d): In most cases a series of sieves is used for separation of sediment into various size grades provided particles are larger than 0.0625 (= 1/16) mm in diameter. Sieve openings are square in shape. Since a long particle with a very small cross-sectional area can pass through a sieve, sieves classify particles on the basis of their least cross-sectional area and thus this classification is not based purely on size. Sieve diameter "d" of a particle is the size of the sieve opening through which a given particle will just pass.

Nominal diameter (dn),

of a particle is defined as the diameter of a sphere which is having the same volume as the particle. Sedimentation diameter is the diameter of the sphere of the same relative density and the same terminal settling velocity as the given particle in the same sedimentation fluid under the same condition.

Triaxial size: Several geologists and hydraulic engineers have defined particle size based on measurement along three mutually perpendicular axes of a particle. If a is the longest or the major axis, b the intermediate axis and c the shortest or the minor axis, then one can take the intermediate axis b as the index of size. In such a case correlation can be found between the shape of the particle, nominal diameter and the intermediate axis b. Since, the axes are perpendicular, values of a, b and c for a given particle depend on axis is chosen first.

Size terms for particles: It is essential to standardize the terms related to particle size so that they could be used to convey definite ideas regarding the size. The sizes given in Table 1 are in terms of triaxial size (b) for boulders, cobbles and upto coarse gravel, and in terms of sieve diameters (d) for medium gravel to very fine sand; for the finer material sedimentation diameter is recommended.

Table 4.4.1: Grade Scale for Size Terms

Ran Table 1:ge in mm	*Class name*	*Range in mm*	*Class name*	*Range in mm*
4096-2048	Very Large Boulders	**1- ½**	**Coarse Sand**	**1 – 0.5**
2048-1024	Large Boulders	**½ - ¼**	**Medium Sand**	**0.5 – 0.25**
1024-512	Medium Boulders	**¼ - 1/8**	**Fine Sand**	**0.25 – 0.125**
512-256	Small Boulders	**1/8 – 1/16**	**Very Fine Sand**	**0.125 – 0.0625**
256-128	Large Cobbles	1/16 – 1/32	Coarse Silt	0.0625 – 0.03125
128-64	Small Cobbles	1/32 – 1/64	Medium Silt	0.03125 – 0.015625
64-32	Very Coarse Gravel	1/64 – 1/128	Fine Silt	0.015625-0.007813
32-16	Coarse Gravel	1/128 – 1/256	Very Fine Silt	0.007813-0.003906
16-8	**Medium Gravel**	1/256 – 1/512	Coarse Clay	0.003906-0.001953
8-4	**Fine Gravel**	1/512 – 1/1024	Medium Clay	0.001953-0.000977
4-2	**Very Fine Gravel**	1/1024 – 1/2048	Fine Clay	0.000488-0.000224
2-1	**Very Coarse Sand**	1/2048 – 1/4096	Very Fine Clay	0.000224-0.000112

The **effective size** (d_{10}) is the size corresponding to 10% of the material being finer and 90% coarser (i.e., the size corresponding to p = 10%) and an index of fineness of the soil.

The ***uniformity coefficient*** **(C_u)** is the average slope of the grade curve between 10% and 60% sizes and is given by

$$Cu = \frac{d60}{d10} \text{.....4.3.41}$$

and gives an idea of the grading or particle size distribution in the material. Lower values $(C_u < 2)$ indicate more uniform material or poor grading and higher values indicate well graded material.

Another term to indicate the effective distribution of grain size is the '***range sizes' C_r*** defined on the basis of the mean slope of the grain size curve. And gives an idea of the grading or particle size distribution in the material. Lower values $(C_u < 2)$ indicate more uniform material or poor grading and higher values indicate well graded material. Another term to indicate the effective distribution of grain size is the '***range sizes' C_r*** defined on the basis of the mean slope of the grain size curve. A uniformly graded sand has a higher porosity than a less uniform, fine and coarse mixture because in the latter the fines occupy the voids in the coarse material. Wider the range in size, lower the porosity.

Specific Yield: The volume of water, expressed as a percentage of the total volume of the saturated aquifer, that can be drained by gravity is called the ***specific yield*** (S_y) and the volume of water retained by molecular and surface tension forces, against the force of gravity, expressed as a percentage of the total volume of the saturated aquifer, is called ***specific retention*** (S_r) and corresponds to field capacity.

Porosity = Specific Yield + Specific Retention

4.4.3 Need and Scope:

The grain size analysis is widely used in classification of soils. The data obtained from grain size distribution curves is used in the design of filters for earth dams and to determine suitability of soil for road construction, air field etc. Information obtained from grain size analysis can be used to predict soil water movement although *permeability tests* are more generally used.

4.4.4 Instruments/Apparatus required:

- **Mechanical/Vibrating Sieve Shaker** (Carries upto 7 sieves, driven by 1/4th H.P. Motor. A pair of rods and a holder are supplied, operation on 230 Volts)
- **Test Sieves** (IS 460) Brass Frame, diameter 200 mm with a stainless steel wire machine made : 33 numbers

  Available sizes of the sieves are 11.2 mm, 5.60 mm, 4.75 mm, , 3.35 mm, mm, 2.3 mm, 1.70 mm, 850 micron, 500micron, 300 micron, 250 micron, 120 micron, 90 micron, **Lid** (top cover) and **Pan** (Receiver).*(1 micron = 1 μm = 1/1000 mm)*
- **Hot Air Oven**
- **Rubber pestle and Mortar** (for crushing the soil if lumped or conglomerated)
- **Electronic Digital Balance** (The balance, to be used, should be sensitive to the extent of 0.1% of total weight of sample taken).

5.0 METHODOLOGY:

In this chapter, to achieve various activities of the study objectives are discussed and the various activities carried out in the study are shown through the flow chart in Figure 5.1.

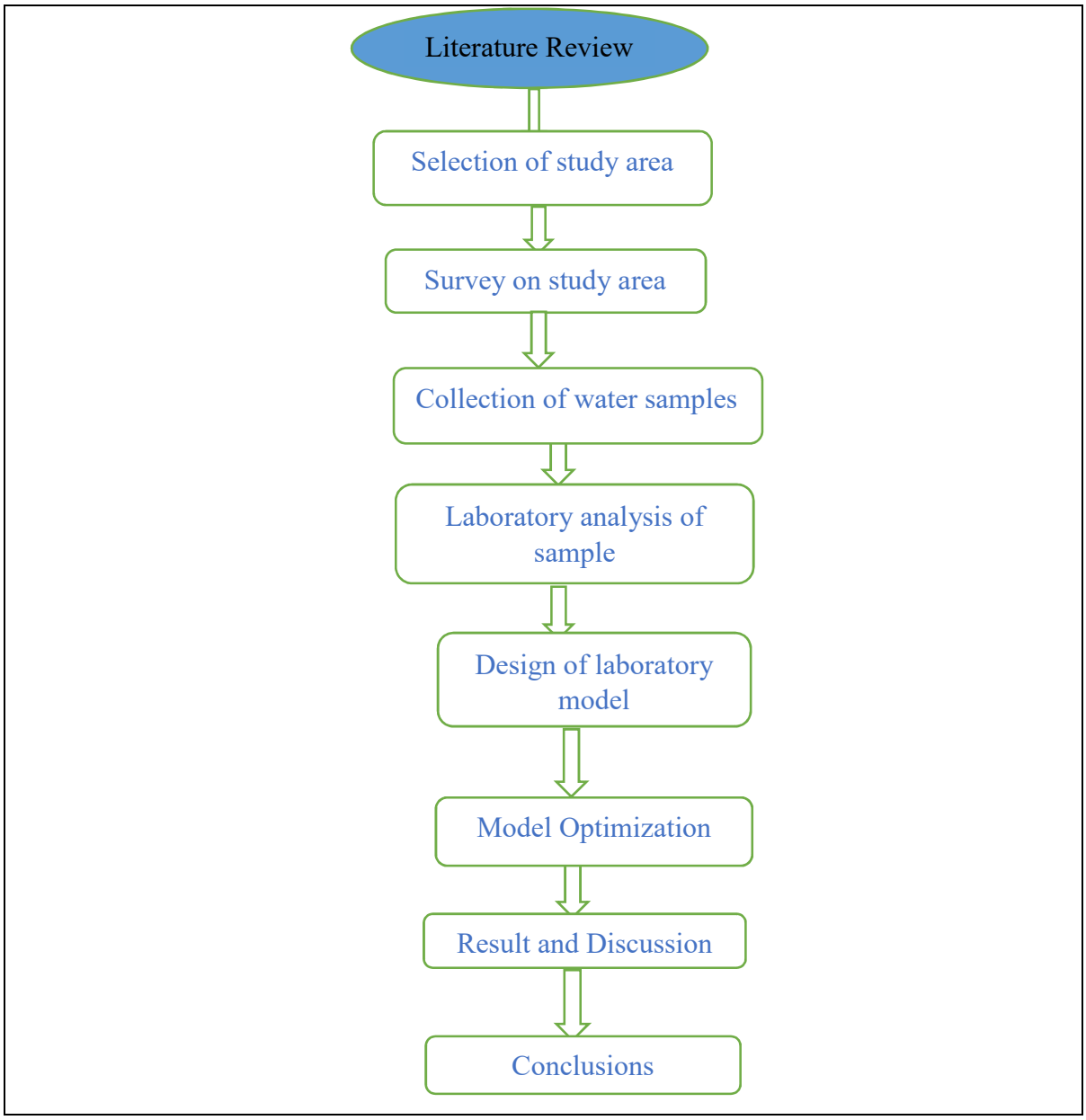


Figure 5.1 :Flowchart of Methodology

In this study, it is embarked on a comprehensive investigation of water quality in select blocks of Bardhhaman district, West Bengal. Our goal was to assess the pollution status of the sampled water, design a lab-scale model for water treatment, and ultimately optimize a Slow Sand

Filtration (SSF) system to address the most critical water quality parameters in our study area. Here is a detailed account of our methodology and findings.

5.1. Literature Review:

The literature review section of our thesis on the RBF is a water-treatment process that makes use of surface water that has naturally infiltrated into groundwater through the riverbed or bank(s) and is recovered by a pumping well. Infiltration is typically enhanced by the hydraulic gradient imposed by a nearby pumping-water supply or other well(s). Riverbank filtrate is water emanating from a pumping well that originated nearby as surface water and traveled through the subsurface, mixing to some degree with other groundwater. Through RBF, microbial pathogens, fecal indicator organisms, and other surrogates are removed by contact with aquifer materials. The removal process is most efficient when groundwater velocity is slow and when the aquifer is made of granular materials with open pore space for water flow around the grains. In these granular porous aquifers, the flow path is tortuous, thereby providing ample opportunity for organisms to come into contact with and attach to a grain surface. If detachment does occur, it will typically occur at a very slow rate. Organisms typically remain attached to a grain for long periods. When groundwater velocity is exceptionally slow or when little or no detachment occurs, the organism will become inactivated before it can enter a well. Thus, RBF relies on attachment to the soil and inactivation to remove microorganisms from infiltrating surface water.

5.2 Preliminary Survey and Data Collection:

Our research initiative commenced with a comprehensive preliminary survey within Bardhhaman district, encompassing diverse blocks. During this phase, meticulously examined population data to ascertain demographic trends. Additionally, it also conducted an extensive review of prior research papers that focused on water quality within the region. This dual-pronged approach allowed us to gain valuable insights into the geographical distribution of the population and to understand historical perspectives on water quality issues in Bardhhaman. By collating and analysing this data, it is able to identify key areas of concern that subsequently guided our focused investigation and intervention strategies

5.3 Selection of Study Area and Sample Collection:

Utilizing the insights derived from our preliminary survey, it is conducted a methodical and deliberate process of delineating specific blocks within Bardhhaman that would serve as the focal points of our study. This decision-making was underpinned by a judicious analysis of the data acquired during the survey, which included factors such as demographic trends and water quality.

5.3.1 Yield Test and Recuperation Test:

Besides the main bore well of 200 mm diameter situated 10.1 m away from the river bank (Puratangram Site), there were three observation wells situated 9.891 m (Observation well 1: Obs-1), 19.958 m (Observation well 2: Obs-2) and 55.089 m (Observation well 3: Obs-3) away from the main well as depicted in Fig 1

In order to adjudge various hydrogeological parameters, the detailed investigation was carried out from 16th march to 19th march 2024 in the presence of the representatives of the Research Team Members of SWRE, JU and officials from PHED. A long-duration pumping test was intended to be carried out for 72 hours. Since the stable drawdown had been achieved in 25.51 hours, pumping was stopped and instantly a recuperation test was started. During the withdrawal at a constant discharge, drawdowns were noted in the pumping well and three observation wells. The readings were taken at one-minute intervals only for the period of the first one hour followed by two minutes' intervals for the next half an hour duration. Gradually depending upon the rate of change of drawdown, intervals were increased from two minutes to two hours. After the cessation of pumping, a recuperation test was carried out by continuous monitoring of the augmentation of the water table with respect to time in the main as well as in the three observation wells. After continuous six hours of monitoring, it was observed that almost the original level of the water table was regained. Accordingly, the water level data as obtained from the main, as well as the observation wells, were plotted in semi-log and log-log graph papers. The initial data of the pumping test arrangement is depicted in fig no 5.3.1

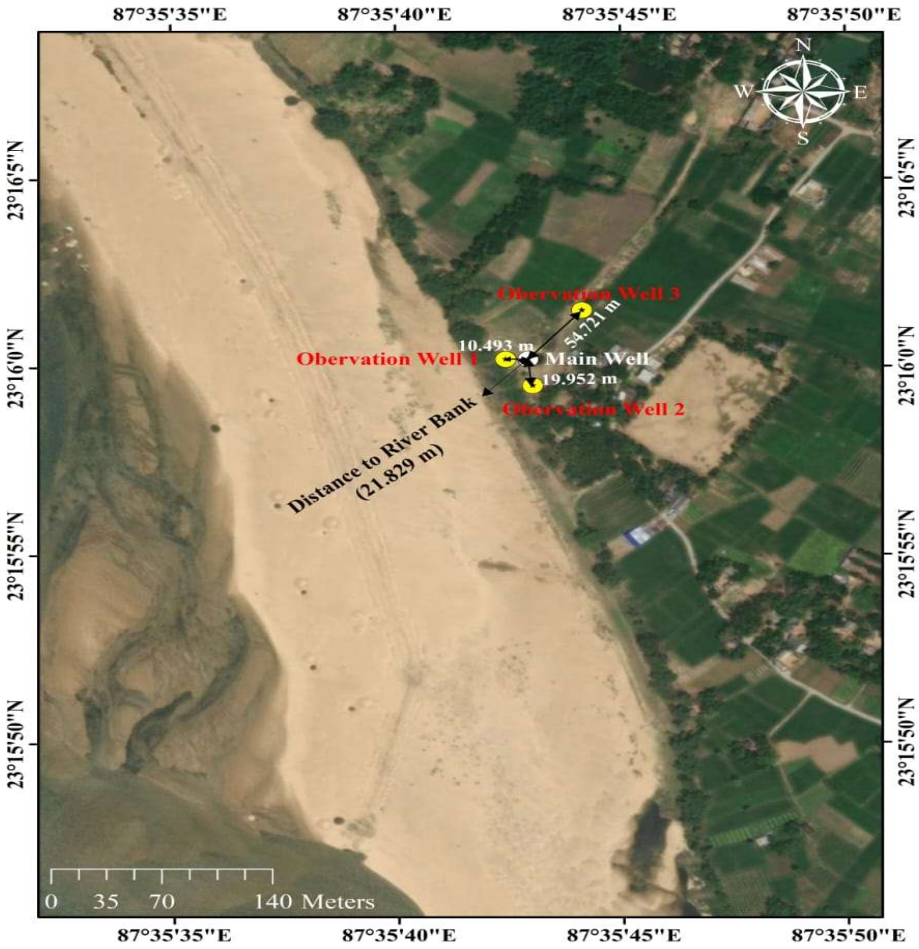


Figure 5.3.1: Layout of the main (pumping) well and three observation wells.

Determination of Hydraulic Parameters using Drawdown Data for Unconfined Aquifer

The response of an unconfined aquifer to pumping is complicated. Once a cone of depression forms, it naturally decreases the aquifer thickness and transmissivity because the upper boundary of the aquifer is the water table. Also, the way in which water comes out of storage in the aquifer changes with time. At an early time, when the water from the main well is first pumped out, water is released from storage due to compression of the matrix and expansion of the water. This response is the same as Theis behavior that applies to confined aquifers. Thus, early-time versus drawdown data, plotted on a semi-log graph paper, follow the Thesis-type curve. The Storativity values would be comparable to those for confined aquifers, 10^{-4} or 10^{-5}. As pumping continues, water comes out from the slow gravity drainage of water from pores as the piezometric water table falls near the well. The pattern of drawdown depends on the vertical and horizontal hydraulic conductivity and the thickness of the aquifer. Once this delayed drainage begins, drawdown data starts to deviate from the Theis curve. The drawdown is less

than expected, resembling the pattern of drawdown in a leaky aquifer. Eventually, the contribution of water comes when delayed drainage ceases. Flow in the aquifer is mainly radial, and the drawdown versus time data plot again shows a Theis-type curve pattern.
The specific yield (S_y) is the ratio of the volume of water that drains from a rock or sediment by gravity to the volume of the rock or soil. The Storativity of the aquifer now is the same as the specific yield.
Calculation of drawdown by correcting the estimate for a confined aquifer was done using equation 1.

$$s' = s - \frac{s^2}{2b} \quad \text{.....5.3.1}$$

where, *s* is the drawdown for the unconfined aquifer and s' is the drawdown for the equivalent confined aquifer.

The following methodology has been adopted to determine the hydraulic parameters using the Distance Drawdown Method by taking the following steps:

- Calculate the corrected drawdown using equation (1)
- Plot corrected drawdowns against *r* on semi-log graph paper
- Approximate the curves versus log(*t*) with a straight line
- Determine the hydraulic parameters using the following equations (2-4):

a) Transmissivity (*T*)

$$T = \frac{2.3Q}{4\pi\Delta} \quad \text{..... 5.3.2}$$

b) Specific Yield /Storativity (*S*)

$$S_y = \frac{2.25Tt_{0y}}{r^2} \text{.....5.3.3}$$

c) **Radius of Influence** $$Q = \frac{2\pi Ts_d}{ln\left(\frac{R}{r}\right)} \text{.....5.3.4}$$

Determination of Aquifer Parameters

Here Neuman's Straight-Line Method has been used to determine the hydraulic parameters. The transmissivity and specific yield of the aquifer are determined by fitting a straight line through the late-time data. The early-time response provides another estimate of transmissivity, and a confined Storativity value for the aquifer can be obtained (Fig 5.3.2)

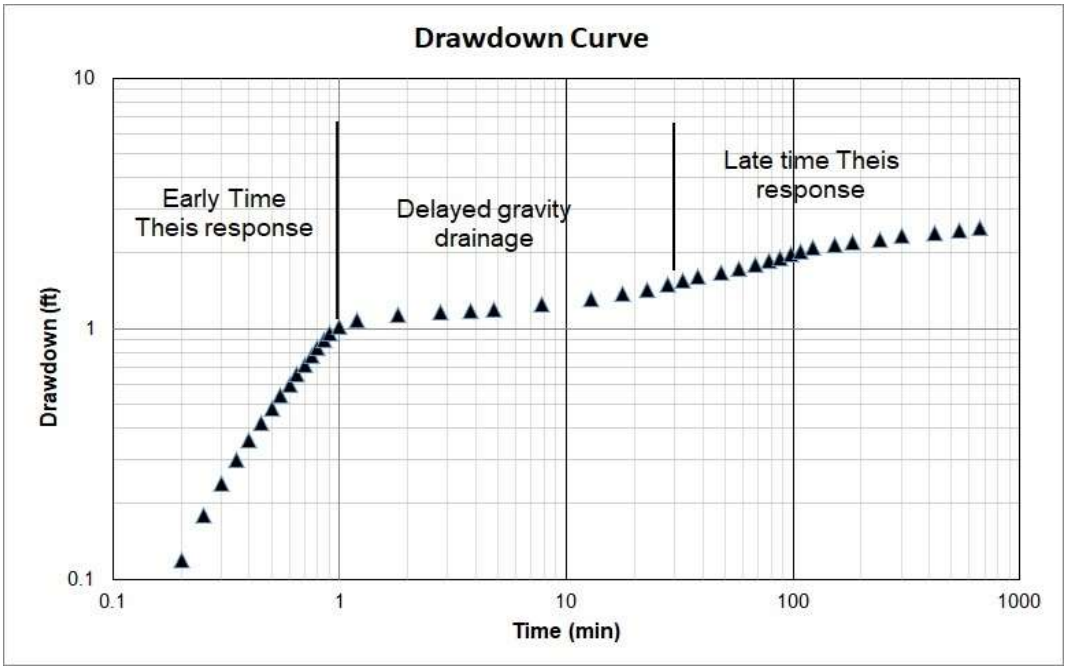


Figure 5.3.2: Characteristic "S" Shaped drawdown curve obtained from the test with unconfined aquifer.

For the study area, Pumping rate, Q = 75 m^3/hr.
Observation Well-1 is 10 m away from the pumping well.
Straight-line fitted through the data as shown from the basis for the calculation of hydraulic parameters.
The transmissivity (T) of the aquifer has been determined using equation (2).

$$T = \frac{2.3Q}{4\pi\Delta s} = \frac{2.3\times(75\times24)}{4\pi\times0.16} = 2060 m^2/day \ldots\ldots 2$$

The confined Storativity (S) has been determined using equation (4).

$$S = \frac{2.25Tt_{0s}}{r^2} = \frac{2.25\times2100\times8}{10^2\times60\times24} = 0.26\ldots\ldots\ldots 4$$

The **Radius of Influence** (R) has been determined by the following equation (5).

$$Q = \frac{2\pi Ts_d}{ln\left(\frac{R}{r}\right)} = \frac{2\times\pi\times2100\times0.278}{ln\ \frac{R}{10}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

$$R \approx 77 \text{ m}$$

The calculation for the rest of the observation wells for constant discharge and different distances from the pumping well is the same as above.



Photograph 5.3.3: Water level measurement in main well using in situ TLC meter with the sensor.



Photograph 5.3.4: Water level measurement in observation well-1 in situ digital water level meter with the sensor.



Photograph 5.3.5: Measurement of pumping well discharge using volumetric method (left image) for the calibration of pumping well discharge data measured using ultrasonic flow meter (right image) on 17.03.2024.

Having carefully identified these target areas, it is initiated a rigorous and systematic campaign for the collection of water samples. These samples were sourced from a multitude of locations within the chosen blocks, ensuring a diverse and representative cross-section of the water sources in the region. An essential component of this process was the assignment of unique sample IDs to each collected specimen. This step was pivotal in ensuring efficient identification and systematic organization during subsequent analyses. Sample collecting point is depicted in 5.3.6

This meticulous approach was instrumental in anchoring our study in comprehensive and representative data from the selected areas. It set the stage for a thorough evaluation of water quality in Bardhamān, laying the foundation for informed decision-making and potential remediation efforts in the region.

Following photograph are depicted the sample collecting point.



Photograph 5.3.6: Sample Collection at Damodar River



Photograph 5.3.7: Sample Collection of Pond near Damodar River



Photograph 5.3.8: Sample Collection of pond.



Photograph 5.3.9: Sample Collection of Groundwater near Damodar River



Photograph 5.3.10: Sample Collection of ponds.

5.4. Water quality test:

The collected water samples underwent a rigorous testing process. Physical parameters, such as turbidity and temperature, were measured. Chemical composition, including pH, dissolved oxygen, and chemical contaminants, was analysed. Pesticide and Bacteriological levels in the water samples were also assessed.

5.4.1 Analysis of water

In order to ascertain the quality of water, it is subjected to various tests. These tests can be divided into the following three categories:

- **Physical tests**
- **Chemical tests**
- **Bacteriological test**

Before discussing the various tests, it will be important to mention the safety measures that must be taken when gathering the water sample that will be subjected to analysis. In reality, sampling is the most crucial step in any analysis because if the samples used for the analysis are not typical of the substances being evaluated, even the most accurate analysis would produce deceptive results. In fact, it will be best to complete all of the analysis right away following the collection of samples, as the faster the analysis, the more accurate the results will be for the liquid at the time the samples are obtained. These precautions are as follows:

1.The water should be collected in bottles, especially of white glass, having well-fitted stoppers. Bottles having holding capacity of about 2litres of water are necessary for chemical analysis. For bacteriological examination, bottles with smaller capacities will be sufficient

2.Bottles should be thoroughly cleansed, filled thrice with water and thrice emptied before collecting the sample. However, it will not be necessary to carry out such process, if the sealed bottles are directly obtained from the laboratories.

3.When the sample of water is to be collected from a pipe, the water tap should be turned on and the water should be allowed to go waste for at least two minutes so as to prevent the entry of impurities of the pipe in the sample of water. If the sample is to be collected for conducting a bacteriological analysis, the nozzle of the tap should be flamed and made unbearably hot and then cooled by the running water before the bottle is filled.

4.For collecting the sample of water from lake, streams, spring or well the whole bottled with stopper closed should be immersed deep into the surface of water and then only the stopper of the bottle should be removed by means of a clean piece of string and the bottle is filled. Thus, the entry of floating materials will be prevented in the bottle.

5.The bottle should be held as far away from its neck as possible. In no case, the water entering the bottle should come into contact with the hand.

6.After collecting the sample, the stopper of bottle should be well secured and the bottles containing samples of water should be labelled stating the source, date and time of collection.

5.4.1.1 Physical Test

Under this category, tests are carried out to examine water from the following:

1. Temperature

The test for temperature of water has no meaning in the sense that it is not possible to give any treatment to control the temperature in any water supply project. The temperature of water to be supplied from storage reservoir depends on the depth from which it is drawn. The desirable temperature of potable water is 10°C while temperature of 25°C is considered to be objectionable.

The multiplication of bacteria in the waters is more rapid at higher temperatures than in the waters at lower temperature. Hence, when waters with a temperature of about 15°C are collected for bacteriological analysis, they should be cooled down as quickly as possible. It should further be remembered that the air temperature at the time of taking the water sample should always be recorded.

Test is conducted by HM-200 instrument.

2. **Turbidity**

The colloidal matter present in water imparts turbidity to water. The turbidity in water may also be due to clay and silt particles, discharges of sewage or industrial wastes, presence of large numbers of micro-organisms etc., and the cloudy appearance developed in water due to turbidity is aesthetically unattractive and it may also be harmful to the consumers.

The turbidity is expressed in terms of parts of suspended matter per million parts of water or shortly written as ppm. It is to be noted that the expression ppm is equivalent to mg per litre. The standard unit of turbidity is the form of finely divided silica in a million parts of distilled water. As per IS10500:2012 refer that the turbidity of drinking water should not be more than 5 NTU, and should ideally be below 1 NTU. Turbidity of the water is conducted by HACH 2100Q instrument is use.photograph **5.** is depicted the instrument of HACH 2100Q.



photograph 5.4.1: HACH 2100Q Turbidity meter



Photograph:5.4.2: Physical test of Samples

5.4.1.2 Chemical tests:

Under this category, tests are carried out to examine water for the following

1. Dissolved Oxygen

The water contains various gases from its contact with the atmosphere and ground surfaces. The usual gases are nitrogen, methane, hydrogen sulphide, carbon dioxide and oxygen. The contents of these dissolved gases in a sample of water are suitably worked out.

Oxygen in the dissolved state is obtained from atmosphere and pure natural surface water is usually saturated with it. The simple test to determine the amount of dissolved oxygen present in a sample of water is to expose water for 4 hours at a temperature of 27°C with 10% acid solution of potassium permanganate. The quantity of oxygen absorbed can then be calculated. This amount, for potable water, should be about 5 to 10 ppm. Dissolved Oxygen is measured by DO meter. The test is conducted by HACH HQ40d instrument.

2. Hydrogen ion concentration (pH)

The acidity or alkalinity of water is measured in terms of its pH value or H-ion concentration. It is desirable to maintain pH value of water very close to 7. The acidic water causes tuberculation and the alkaline water causes incrustation. For potable water, the pH value should be between 7 and 8.50 Following are the two methods which are employed to measure the pH value of water:

- **Electrometric method:** In this method, potentiometer is used to measure the electrical pressure exerted by positively charged H-ions. The pH value is then correspondingly expressed. Instrument use for this test is HM-200.

3. Total dissolved solids

In this test, the amounts of dissolved in water is determined. The highest desirable level of total solids is 500 mg/l and its maximum permissible level is 2000 mg/l. TDS is measured by HM-200 instrument as shown in Photograph:5..

	
Photograph:5.4.2: HM-200	Photograph 5.4.3: HACH HQ40d

4. Iron

The test quantifies the iron concentration in water, measured in mg/l, using the HACH DR 2800 Spectrophotometer. This instrument ensures precise and dependable assessment of iron levels in water samples for various applications.

Table5.4 : Items to collect for Iron test

Description	Quantity
Ferro Ver Iron Reagent Powder Pillows, 10-ml	1
Sample cells.	2

- **Procedure**

1. Start program **265 Iron, Ferro Ver**. For information about sample cells, adapters or light shields
2. **Prepare the sample:** Fill a sample cell with 10 ml of sample.

3. Add the contents of one Ferro Ver Iron Reagent Powder Pillow to the sample cell.
4. Swirl the sample cell to mix. Undissolved powder will not affect accuracy.
5. Start the instrument timer. A 3-minute reaction time starts. An orange Colour will show if iron is present. Let samples that contain rust react for 5 minutes or more.
6. **Prepare the blank:** Fill a second sample cell with 10 ml of sample.
7. Clean the blank sample cell.
8. When the timer expires, insert the blank into the cell holder
9. Push **ZERO**. The display shows 0.00 mg/l Fe.
10. Clean the prepared sample cell.
11. Insert the prepared sample into the cell holder.
12. Push **READ**. Results show in mg/l Fe.

5. Sulphate

This test focuses on determining the sulfate concentration in water, expressed in milligrams per liter (mg/l), and it employs the HACH DR 2800 Spectrophotometer instrument for precise analysis. The spectrophotometer employs a photometric technique to measure the absorbance of specific wavelengths of light by sulfate ions in the water sample. By comparing this absorbance to a standard curve, the instrument calculates the sulfate concentration. This analysis is crucial for assessing water quality, particularly in industrial and environmental contexts, as excessive sulfate levels can lead to adverse effects like corrosion and environmental contamination. The HACH DR 2800 Spectrophotometer ensures accurate and dependable results for informed decision-making and regulatory compliance.

Table 5.4.1: Items to collect for Sulphate test

Description	**Quantity**
SulfaVer 4 Reagent Powder Pillows, 10-ml	1
Sample cells.	2

- **Procedure**

1. Start program **680 Sulfate**. For information about sample cells, adapters or light shields
2. **Prepare the sample:** Fill a sample cell with 10 ml of sample.
3. Add the contents of one SulfaVer 4 powder pillow to the sample cell.
4. Swirl the sample cell to mix. Undissolved powder will not affect accuracy. White turbidity will form if Sulfate is present.
5. Start the instrument timer. A 5-minute reaction time starts. Do not disturb the cell during this time.

6. **Prepare the blank:** Fill a second sample cell with 10 ml of sample.
7. When the timer expires, clean the blank sample cell.
8. Insert the blank into the cell holder.
9. Push **ZERO**. The display shows 0 mg/l $SO4^{2-}$.
10. Clean the prepared sample cell.
11. Within 5 minutes after the timer expires, insert the sample into the cell holder.
12. Push **READ**. Results show in mg/l $SO4^{2-}$.

6. Phosphate

This test quantifies phosphate levels in water, measured in mg/l, utilizing the HACH DR 2800 Spectrophotometer. The spectrophotometer employs a photometric method to assess phosphate concentration by measuring light absorbance at specific wavelengths. By comparing the absorbance with a standard curve, the instrument calculates phosphate levels accurately. This analysis is vital for environmental and water quality assessments, as phosphate excess can cause water pollution and ecological imbalances. The HACH DR 2800 Spectrophotometer ensures precise and reliable results, essential for informed decision-making and regulatory compliance.

Table 5.4.2: Items to collect for Phosphate test

Description	Quantity
PhosVer 3 Phosphate Reagent powder pillow, 10-ml	1
Sample cells.	2

- **Procedure**

1. Start program **490 P React. PP**. For information about sample cells, adapters or light shields.
2. **Prepare the sample:** Fill a sample cell with 10 ml of sample.
3. Add the contents of one PhosVer 3 Phosphate Reagent Powder Pillow to the cell. A blue Colour develops if phosphorus is in the sample.
4. Immediately close the sample cell. Shake vigorously for 20–30 seconds.
5. Start the instrument timer. A 2-minute reaction time starts. If the sample was digested using the Acid Persulfate digestion, a 10-minute reaction period is necessary.
6. **Prepare the blank:** Fill a second sample cell with 10 ml of sample.
7. When the timer expires, clean the blank sample cell.
8. Insert the blank into the cell holder.
9. Push **ZERO**. The display shows 0.00 mg/l $PO4^{3-}$.

10. Clean the prepared sample cell.
11. Insert the prepared sample into the cell holder.
12. Push **READ**. Results show in mg/l $PO4^{3-}$.

7. Nitrate

This test measures the concentration of nitrate in water, expressed in mg/l, utilizing the HACH DR 2800 Spectrophotometer. The spectrophotometer employs a photometric technique, assessing the absorbance of specific wavelengths of light to determine nitrate levels. By comparing the absorbance to a standard curve, the instrument calculates nitrate concentration accurately. This analysis is critical for assessing water quality, particularly in drinking contexts, where excessive nitrate levels can lead to contamination and health concerns. The HACH DR 2800 Spectrophotometer ensures precise and dependable results, crucial for informed decision-making and regulatory compliance.

Table 5.1.3: Items to collect for Nitrate test

Description	**Quantity**
NitraVer 5 Nitrate Reagent Powder Pillow, 10-ml	1
Sample cells.	2

- **Procedure**

1. Start program **355 N, Nitrate HR PP**. For information about sample cells, adapters or light shields.
2. **Prepare the sample:** Fill a sample cell with 10 ml of sample.
3. Add the contents of one Nitra Ver 5 Nitrate Reagent Powder Pillow. Put the stopper on the sample cell.
4. Start the instrument timer. A 1-minute reaction time starts.
5. Put the stopper on the sample cell. Shake the cell vigorously until the timer expires. Some powder may not dissolve. Undissolved powder will not affect results.
6. Start the instrument timer. A 5-minute reaction time starts. An amber Colour shows if nitrate is present.
7. **Prepare the blank:** When the second timer expires, fill a second sample cell with 10 ml of sample.
8. Clean the blank sample cell.
9. Insert the blank into the cell holder.
10. Push **ZERO**. The display shows 0.0 mg/l $NO3^{-}$.

11. Clean the prepared sample cell.
12. Within 1 minute after the timer expires, insert the prepared sample into the cell holder.
13. Push **READ**. Results show in mg/l $NO3^-$

8. Ammonia

This test quantifies the concentration of ammonia in water, measured in mg/l, utilizing the HACH DR 2800 Spectrophotometer shown Fig5.4.4. The spectrophotometer employs a photometric technique to measure the absorbance of specific wavelengths of light by ammonia in the water sample. By comparing this absorbance to a standard curve, the instrument calculates the ammonia concentration with precision. This analysis is essential for assessing water quality, particularly in environmental and industrial contexts, where excessive ammonia levels can indicate contamination and have detrimental impacts. The HACH DR 2800 Spectrophotometer provides accurate and reliable results, crucial for informed decision-making and regulatory compliance.

Table 5.4.4: Items to collect for Ammonia test

Description	Quantity
Ammonia Nitrogen Reagent Set	1
Water, deionized	25 ml
Pipet, serological, 1-ml	1
Mixing cylinder, graduated, 25 ml, glass stopper	2
Sample cells	2

- **Procedure**

1. Start program **380 N, Ammonia, Ness**. For information about sample cells, adapters or light shields.
2. **Prepare the sample:** Fill a mixing cylinder to the 25- ml line with sample.
3. **Prepare the blank:** Fill a mixing cylinder to the 25-ml line with deionized water.
4. Add 3 drops of Mineral Stabilizer to each mixing cylinder.
5. Put the stopper on the mixing cylinders. Invert the mixing cylinders several times to mix.
6. Add 3 drops of Polyvinyl Alcohol Dispersing Agent to each mixing cylinder.

7. Put the stopper on the mixing cylinders. Invert the mixing cylinders several times to mix.
8. Use a pipet to add 1.0 ml of Nessler Reagent to each mixing cylinder.
9. Put the stopper on the mixing cylinders. Invert the mixing cylinders several times to mix.
10. Start the instrument timer. A 1-minute reaction time starts.
11. Pour 10 ml from the blank cylinder into a sample cell.
12. When the timer expires, clean the blank sample cell.
13. Insert the blank into the cell holder.
14. Push **ZERO**. The display shows 0.00 mg/l NH3.
15. Pour 10 ml from the sample cylinder into a second sample cell.
16. Clean the prepared sample cell.
17. Insert the prepared sample into the cell holder.
18. Push **READ**. Results show in mg/l NH_3



Figure 5.4.4: HACH DR2800 Spectrophotometer

5.4.1.3 Bacteriological test:

- **Most Probable Number (MPN) Test for Water Quality (IS:1622-1981)**

A statistical approach test called the most probable number (MPN) test is based on the randomly distributed distribution of microorganisms per volume in a particular sample.

- In this procedure, a series of tubes holding a liquid indicator growth medium are filled with measured amounts of water.
- The media that have been exposed to one or more indicator bacteria exhibit growth and a distinctive Colour change. Those that merely receive an inoculum of water devoid of indicator bacteria do not see the Colour change.
- The MPN of indicator organisms in the sample may be determined by making use of statistical tables based on the quantity and distribution of positive and negative reactions.
- MPN test is completed in three steps:
    1. Presumptive test
    2. Confirmed test
    3. Completed tes

- **Procedure of MPN test:**

(I) Presumptive Test

1. Prepare and autoclave Durham's tube-equipped test tubes with single- and double-strength Mac Conkey purple medium.
2. Consider three sets of test tubes, each with five tubes; one set has 10 ml of double strength (DS), whereas the other two have 10 ml of single strength (SS).
3. Transfer 10 ml of water with sterile pipettes into each DS broth tube. Transfer 0.1 ml of water to the remaining five tubes in the last set of SS broth tubes and 1 ml of water sample to each of the five tubes in the first set of SS broth.
4. Incubate the tubes at 37°C for 24 hours.
5. After incubation, check out the media's Colour change and the gas generation in Durham's tube.
6. Count the positive results from each batch and compare them to the norm to determine the coliform count per 100 ml of water.

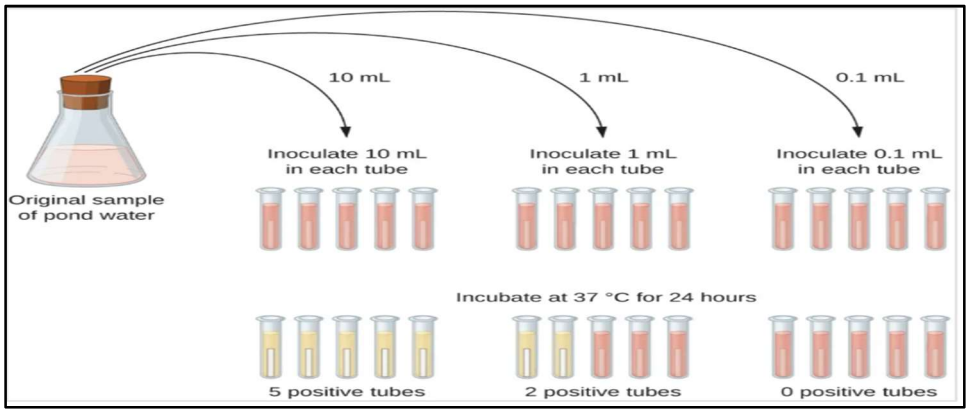


Figure 5.4.5: Preparation of sample in Durham's tube

(II) Confirmed Test

In addition to coliforms, some additional microbes use lactose fermentation to produce acid and gas. A confirmatory test is performed to confirm the presence of coliform. For this, a loopful of suspension from a positive tube is added to an agar plate (EMB agar or Endo Agar) or slant, as well as a 3 ml lactose-broth or brilliant green lactose fermentation tube.



Figure 5.4.6: Brilliant Green Lactose Fermentation Tube

A. Inoculation of the lactose-broth

1. Incubate the inoculated lactose-broth fermentation tubes at 37°C and inspect gas formation after 24 ± 2 hours.
2. If no gas production is seen, further incubate up to a maximum of 48 ±3 hours to check gas production.

B. Inoculation in media slants

1. Take a loopful of suspension from a positive tube and inoculate it on the agar surface.
2. The agar slants should be incubated at 37°C for 24± 2 hours.
3. Colonies must be examined macroscopically.

(III)Completed Test

1. Transform a typical coliform colony from the agar plate into a tube of brilliant green bile broth with placed Durham's tube and on the surface of a nutrient agar slant.
2. Incubate at 35°C for 24 hours.
3. After 24 hours, check the broth for the production of gas, and perform Gram staining for organisms on the nutrient agar slant.

5.4.1.4. Pesticides Test:

The term "pesticide" is a composite term that includes all chemicals that are used to kill or control pests. Pesticides are used to protect crops against insects, weeds, fungi, and other pests. They also play a significant role in food production. They protect or increase yields, and the number of times per year a crop can be grown on the same land.

Pesticides are potentially toxic to humans and can have both acute and chronic health effects, depending on the quantity and the ways in which a person is exposed. Some of the older, cheaper pesticides can remain in the soil and water for years. They have been banned in developed countries for agricultural use but are still used in many developing countries. There are more than 1,000 pesticides used around the world to ensure food is not damaged or destroyed by pests. Each pesticide has different properties and toxicological effects (and the toxicological effects of multiple pesticides can be greater than the sum of their parts). As per IS 10500:2012 there are 17 types of pesticides are described and the test was conduct by Gas Chromatography-Mass Spectrometry machine. There are some procedures which have done before testing the sample

Method of sample extraction for Test:

1. 500 ml of sample water + 5 gm of NaCl in separatory funnel ⟶ Shake well for proper mixing ⟶ Add 50 ml of CH_2Cl_2 and shake well with continuous air venting.
2. Adjust the separatory funnel with clamp and stand ⟶ Set a conical flux below it with Na_2SO_4** in a funnel for filtration ⟶ Wait for 1-2 mins for formation of organic layer and collect it in conical flux. Repeat the whole step for at least 3 times to proper separation of organic layer.

** Set the funnel with conical flux. Close the opening of the pipe with cotton to prevent leakage of Na_2SO_4. Add CH_2Cl_2 to check leakage.

3. Put the conical flux on water bath** for vaporization ⟶ Wait till the volume comes to at least 1-2 ml ⟶ Transfer the volume to 5 ml volumetric flux and make up the remaining with Ethyl Acetate ($CH_3COOC_2H_5$).

** Prepare the water bath before starting of sample extraction. Set the temperature to desirable limit and let the water starts heating.

4. Take 1-2 ml of prepared sample to the GC vial and start analysis.



Photograph:5.4.1.4.1 Separatory funnel along with required apparatus



Photograph 5.4.1.4.2: Chemicals used for sample extraction

After preparation sample, sample poured in to a small ampul and put this at GCMS. Detection of concentration of Pesticides in water with GC-MS. **Figure 5.4.1.4.3**depicted the steps followed for conducted the pesticide test. **Figure5.4.1.4.4** depicted the photograph of ISQ 7000-Trace 1300 Single Quadrupole Mass Spectrometer

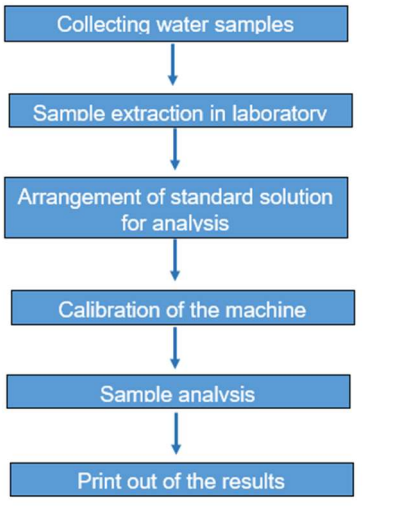


Figure 5.4.1.4.3: Steps to follow during pesticide analysis



Photograph:5.4.1.4.4: ISQ 7000-Trace 1300 Single Quadrupole Mass Spectrometer

5.4.2 Well field design concept:

In areas where groundwater is a source of public water supply, well fields must be designed with a variety of constraints, such as pumpage from the individual well must not produce excessive drawdown and the rate of pumpage must be sustainable (Chin et al. 2013). The impact of the well field on the environment such as reduced water availability to plants caused by lower water tables and decreased surface water inflows caused by well captures must generally be assessed.

Estimation of sustainable withdrawal with well field design concept:

The objective of well field design is to determine the number and location of production wells required to supply water at a specific rate. For large housing complexes, pumping rate requirements are typically increasing with rapid urbanization. The primary constraint in well field design is the maximum allowable drawdown in the aquifer by well field operation. To accommodate this constraint, the following design procedure is adopted.

Step-I

Assume that each well in the well field causes a drawdown (at the well) equal to 1/2 the allowable drawdown, with the other half of the allowable drawdown caused by interference from other wells, boundary effects and well losses. Determine the pumping rate Q, at each well that would cause a drawdown (at the well) equal to one half the allowable drawdown. This can be done using Theis equation (1935) with a pumping time equal to 1 year.

Step-II

The number of wells required in the well field is equal to the required water supply rate, Q_r, divided by the pumping rate from each well Q. This ratio is rounded upward nearest integer.

Step-III

Arrange the well in such a way that the total drawdown such that total drawdown at each will does not exceed the allowable drawdown selecting the relative locations of the well will depend on the individual site characteristics, such as property boundaries, and existing pipe network, but the well should generally be aligned parallel to end and close as possible to the surface recharge boundaries.

On the basis of the above-mentioned aspect, the well field design concept is adopted for the evaluation of groundwater sustainability assessment in the site.

The pumping rate from a single well that would cause a drawdown of 1.5 m, equal to one-half of the allowable drawdown of 3.0 m is estimated. The drawdown, s_w, resulting from the operation of each well can be estimated using the Theis equation which is as follows:

$$s_w = \frac{Q}{4\pi T} W(u) \text{…….5.4.2.1}$$

where, Q is the pumping rate from the well, T is the transmissivity of the aquifer, $W(u)$ is the well function, and u is defined by the relation

$$u = \frac{r^2 S_y}{4Tt}$$

where 'r' is the distance from the well, 'S_y' is the specific yield of the aquifer, and 't' is the time since the beginning of pumping, Since the drawdown in the wellfield will vary between zero and 2.55 m, the average transmissivity, T, to be used in the well field design obtained from the field experiment is 1980 m^2/day. But for the critical condition in the summer season, we consider average T = 2100 m^2/day. For a single well with t = 365 days,

$$u_w = \frac{r_w^2 S_y}{4Tt} = \frac{(0.1)^2 \times 0.2}{4 \times 2100 \times 365} = 6.523 \times 10^{-10}$$

Since $u_w \leq 0.004$, with less than 0.1% error

$$W(u_w) = -0.5772 - \ln u_w \text{…….(5.4.2.2)}$$

And therefore, $W(u_w) = -0.5772 - \ln (6.523 \times 10^{-10}) = 20.57$

According to the Theis (1935) equation, the pumping rate Q, required to provide a drawdown, s_w, is given by the following equation:

$$Q = \frac{4\pi T s_w}{W(u_w)} \text{…….5.4.2.3}$$

For s_w = 1.257 m (one-half the allowable drawdown),

$$Qw = \frac{4\pi \times 2100 \times 1.05}{20.57} = 1347 \text{ m}^3\text{/day}$$

Hence the sustainable allowable withdrawal is 1350 m^3/day

Thus, comparing the allowable Q as obtained above from the Well Field Design Concept, the estimated value from the data provided by PHED, Q = 5600 m^3/day is a safer value of withdrawal from this study area.

The number of wells required is given by

Number of wells = $\frac{5600}{1350}$ =4.15 ≈5

Considering further sustainability and critical conditions in the summer season, the number of wells to be adopted is 7 numbers.

Considering the five well fields with the arrangement shown in Fig5.4.7

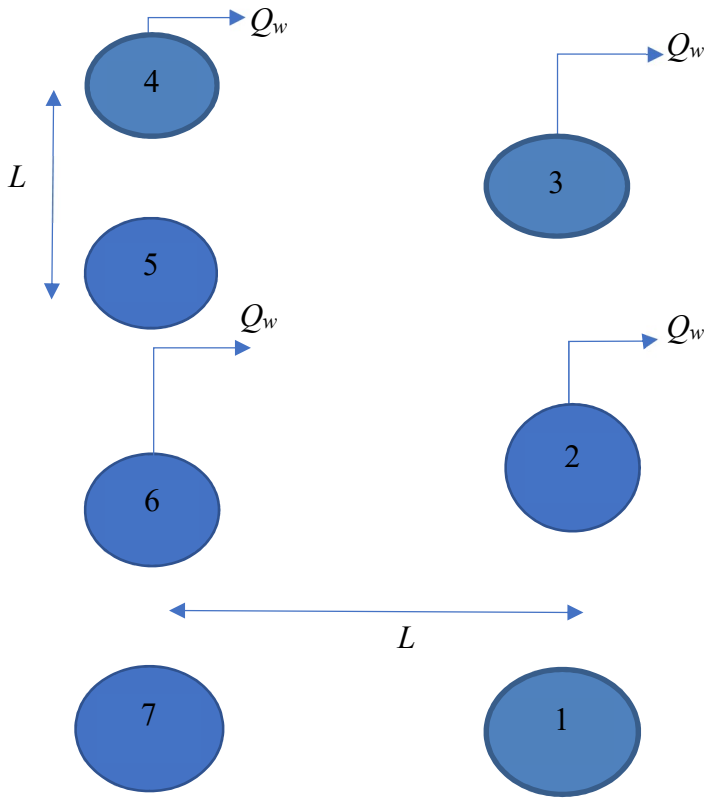


Figure5.4.7: Conceptual arrangement of Wells

Each of the five wells is to operate at the same pumping rate $Q_w = \frac{5600}{7}$ = 800 m^3/day.

The arrangement consists of the wells (numbers.1, 2, 3, 4, 5, 6, 7,) at a distance from the central well. Clearly, when all five wells are in operation, the drawdown will be greatest at the central well (no.1).

According to the principle of superposition

$S_1 = \frac{Q_w}{4\pi T} \sum_{i=1}^{10} W(u_i)$; where u_i are given by $u_1 = \frac{r_w^2 S_y}{4T} = \frac{0.1^2 \times 0.2}{4 \times 2100 \times 365} = 6.523 \times 10^{-10}$

and $u_2 = u_3 = u_4 = u_5 \ldots\ldots\ldots\ldots = u_7 = \frac{R^2 S_y}{4Tt} = \frac{0.2}{4 \times 2100 \times 365} R^2 = 6.523 \times 10^{-8} \times R^2$ ……(5.4.2.4)

So, $W(u_1) = -0.5772 - \ln(6.523 \times 10^{-10}) = 20.57$

$W(u_2) = W(u_3) = W(u_4) = W(u_5) \ldots\ldots\ldots\ldots W(u_7)$

In the present study, considering critical conditions in the summer season maximum drawdown is 0.45m for the pumping rate from the well 1200 m^3/day and the total demand is 5600 m^3/day, the projected allowable drawdown will be

$$\frac{Q_1}{Q_2} = \frac{s_{w1}}{s_{w2}}$$

$$\frac{1200}{5600} = \frac{0.45}{s_{w2}}$$

$$s_{w2} = 2.1\text{m}$$

$$2.1 = \frac{800}{4\pi \times 2100}\,[20.57 + 6\,W(u_2)]$$

$$W(u_2) = 8.1 = W(u_3) = W(u_4) = W(u_5) \ldots\ldots\ldots = W(u_7)$$

$$W(u_2) = -0.5772 - \ln(u_2)$$

$$8.1 = -0.5772 - \ln(u_2)$$

$$u_2 = 1.7 \times 10^{-4}$$

From equation 5 we get,

$$1.7 \times 10^{-4} = 6.523 \times 10^{-8} \times R^2$$

$$R = 51.05\text{ m} \approx 52m$$

Therefore, a well field consisting of seven wells is arranged as shown in figure 5.4.7with each well pumping 800 m^3/day and spaced 52 m apart from the each well, will yield the required amount of water and produce a drawdown that will not exceed the specified maximum of 2.1 m. The arrangement of 7 wells are considered.

5.4.2.1. Sieve Analysis Test Procedure:

1.Take a representative oven dried (at 1050C for 24 hours) sample of soil that weighs about 500 gm. (this is normally used for soil samples the greatest particle size of which is 4.75 mm).

2.If soil particles are lumped or conglomerated crush the lumped and not the particles using the pestle and mortar.

3.Determine the mass of sample accurately. Wt. (gm)

4.Prepare a stack of sieves. Sieves having larger opening sizes (i.e. lower numbers) are placed above the ones having smaller opening sizes (i.e. higher numbers). In case of sandy soil, the very last sieve, is 0.075 mm and a pan are placed under it to collect the portion of soil passing 0.075 mm sieves. Here is a full set of sieves. 4.75mm and 0.075 mm should always be included).

5.Make sure sieves are clean; if many soil particles are stuck in the openings try to poke them out using brush.

6. Weigh all sieves and the pan separately. (Fill in column 3)

7.Pour the soil from step 3 into the stack of sieves from the top and place the cover, put the stack in the sieve shaker and fix the clamps, adjust the time on 5 minutes (Theoretically 10 minutes) and get the shaker going.

8.Stop the sieve shaker and measure the mass of each sieve + retained soil. (Fill in column 4)

9.Weigh the sand retained by each sieve to the nearest 0.01 gm. This is done in a cumulative way – this means that you add what is remaining on the coarsest sieve on top to the container on the scales, and measure the weight. Following this, you add the material from the second sieve down, and again note the combined weight of both samples. Continue in this way for the whole set. When finished, check that the final weight corresponds to the initial weight of the sample.

10.Clean each sieve as it is emptied and returns the soil to the stock.

11.Enter the results in Table. From this, you can calculate the percentage retained on each sieve, and correspondingly, the percentage passing.

12.Plot the results on 3 cycle logarithm graph paper



Photograph:5.4.2.1: Analysis of grain-size distribution in the Laboratory of the School of Water Resources Engineering, Jadavpur University.

5.4.3 Flow Diagram of Multistage Filtration:

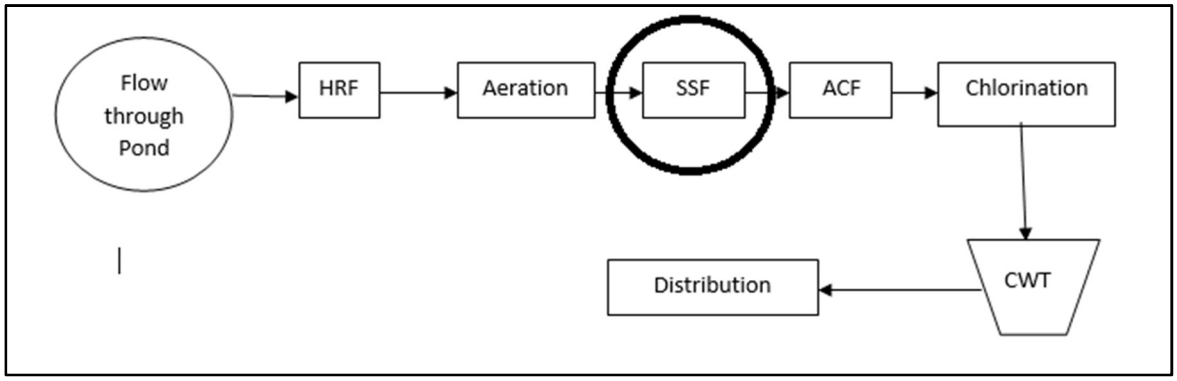


Figure 5.4.3: Flow procedure of MSF

- **Flow Procedure:**

The water will be pumped out of the pond and stored in a Raw Water Tank (RWT) in order to provide sufficient head pressure for the gravity-based treatment process. From there the raw water flows through a Horizontal Roughing Filter (HRF) that serves as a pre-treatment step. In the following, the water is aerated by means of a cascade Aeration process before being treated through a Slow Sand Filter (SSF). After treatment with SSF, the water flows through an Activated Carbon Filter (ACF) and is collected in the Clear Water Tank (CWT). Figure 5..3 flow diagram of MSF unit is depicted.

5.4.3.1: The Basic Design of Slow Sand Filters:

The Stages in a Slow Sand Filtration System

There are several important stages in a slow sand filtration system:

- Pre-treatment – one or more of the following:
    a) sedimentation tank
    b) roughing filter
    c) aeration
- The sand beds
- ·Under drainage, protected by a gravel pack
- A flow-regulating valve
- Weir
- Chlorination (if applicable)
- Storage Tank

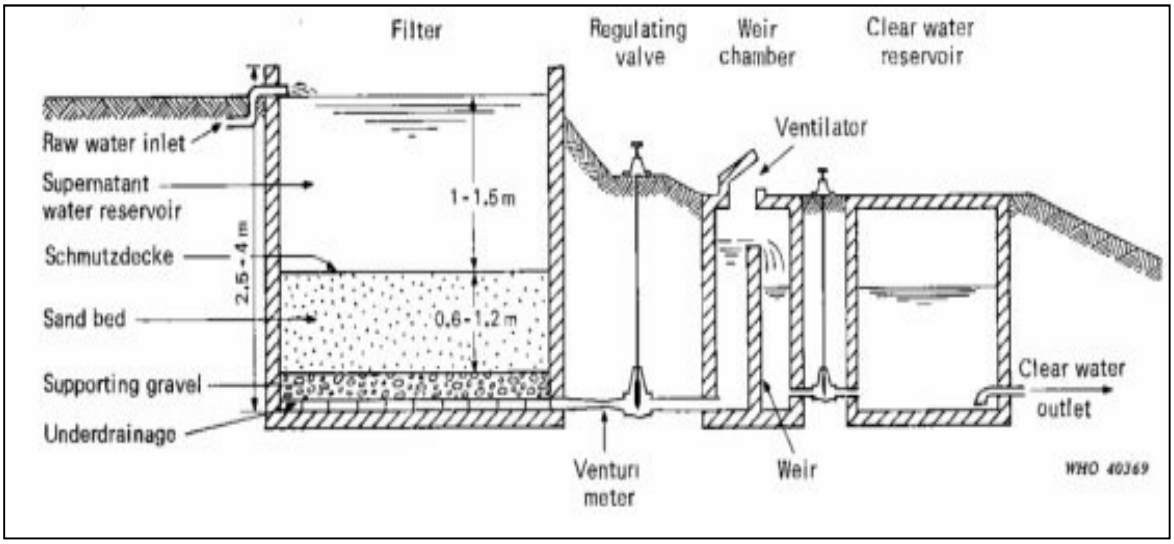


Figure 5.4.3.1: Show the basic design principles used in a slow sand filter

5.4.3.2 Design characteristics of the slow sand filtration units

In an SSF treatment plant, at least two units should operate in parallel for continuous supply. A unit basically consists of a structure that contains the following components: Flow control and drainage systems, supernatant water layer, and filter bed.

- **Flow control systems:** Controlling the flow in SSF units is necessary to maintain the proper filtration rate through the filter bed and the submergence of the media under all conditions of operation. Abrupt filtration rate increases should be avoided. Two types of flow rate control are used outlet and Inlet. In an outlet, the controlled filter supernatant water level is kept close to the maximum desired level above the filter bed. To control the flow rate, the outlet valve is gradually opened to compensate for the increase in the head loss over the filter media. This is the usual control method in Europe and has been adopted in some of the units built in the Americas (Pardón and Lloyd, 1994; Tanner and Baker, 1994). The storage capacity above the sand bed provides for some equalization of the influent water quality, sedimentation of heavier particles, and time for some biological activity (Fox et al, 1994), as well as some buffer capacity. In inlet-controlled filters, the increase in head loss is compensated by an increase in the height of the supernatant water. Di Bernardo and Alcocer (1996) found similar performance in terms of effluent water quality, head loss in the filtering bed and filter run times for inlet and outlet control SSF units run in parallel, with filtration velocities in the range of 0.13 to 0.5 mh^{-1}. In the inlet flow control option, the inlet box should allow flow control, and excess energy dissipation to protect the filtering bed from scouring; facilitate flow distribution to the SSF units filtering in parallel, and permit possible overflow.

The drainage system consists of a principal drain with lateral branches usually constructed in perforated pipes; brickwork or tiles and covered with a layer of graded gravel and a layer of course sand. The drainage system of SSF has to comply with the following functions:

- To support the filter material and prevent it from being drained from the filter;
- To ensure uniform abstraction of the water over the filter unit;
- To allow for the backfilling of the filter and drive out possible air pockets.

The main drain should discharge the filtered water freely at atmospheric pressure in the outlet box. A flow indicator is required at both inlet and outlet sides of the units to facilitate operational procedures and to verify water balance, as an indication of possible water losses in the main filtering boxes. The outlet weir is also necessary to maintain the supernatant water layer above the maximum level of sand, protecting biological activity, preventing pressure drops in the filter bed, and ensuring the functioning of the units independently of the level fluctuations in the contact or storage tanks.

❖ **Supernatant water layer:** The layer of supernatant water provides the static head necessary for the passage of water through the sand bed. In a clean bed the initial head loss is usually below 0.1 m and gradually increases until the maximum level is reached. In units with outlet control, the variations of the supernatant depth for small systems have been reported in the range of 0.6 to 1.2 m (Pyper and Logsdon, 1991). At the Westerkamp plant in Amsterdam, where the SSF units deal with highly pre-treated water, the average supernatant water height is 2 m (Kors et al, 1996). Filter shading may contribute to improving filter runs if significant production of filter blocking algae is happening on the filter skin or in the supernatant water layer (Haarhoff and Cleasby (1991), but few definitive advantages in terms of filtrate quality have been reported (Di Bernardo, 1993).

❖ **Filter bed:** The adequate selection of sand includes size grading, characterized by the effective size diameter d10, and the uniformity coefficient, $U_c=d_{60}/d_{10}$. Huisman and Wood (1974) advise that d10 should be small enough to produce safe water and to prevent penetration of clogging matter to such depth that it can't be removed by surface scraping. 30 Bellamy (1985) reports a total coliform removal reduction from 99.4% at d_{10} of 0.1mm to 96% at d_{10} of 0.6mm. Di Bernardo and Escobar (1996) studied four pilot units in parallel having sand with d10 values in the range of 0.21 to 0.23 mm, and u_c values of 2.24, 2.85, 4.20, and 4.29. The tested filtration rates were 0.1, 0.2 and 0.25 mh^{-1}. For the lower velocities (0.1 and 0.2 mh^{-1}), the pilot units with higher u_c values had longer filter runs, deeper dirty penetration, and better effluent quality in terms of turbidity, apparent Colour, total iron and number of particles. The higher quality seems to be associated with a greater amount of data after the maturation period in the filters having sand with greater u_c values. Van der Hoek et al (1996) studied the impact of grain size and filtration rate on operation and performance in SSFs in Amsterdam. They fed four pilot units with highly pre-treated surface waters. Two different filter rates were applied to two different filter sand types (d_{10-90}=0.19-0.35 mm and d_{10-90}=0.25-0.84 mm). All the units were producing water within the Amsterdam Water Supply standards. The filters with the smaller grain size showed slightly better performance with respect to the filtrate, and presented a shorter filtration rate, as predicted by filtration theory. However, these results also show that pre-treatment in this

case practically overrides the effect of grain size and filtration rate on the SSF performance. Deeper sand beds should result in improved removal of particles. However, due to the development of the filter skin and the biological activity concentrated mainly in the upper sand layers, particle removal is more effectively accomplished in this part of the SSF units. After a field survey Lloyd (1974) found evidence showing the significance of the uppermost 5-10 cm of SSF as the functional zone in purification at a filtration rate of 0.15 mh^{-1}, where around 1 log reduction of mesophilic and thermophilic bacteria usually takes place. For the same grain size grading, this functional zone increases with higher filtration rates, although population quantities and densities tend to decrease for the most active protozoa predators. Bellamy et al (1985) found in their pilot units that 93 per cent of the total coliforms were removed in the top 0.5m bed depth and 95 per cent above 1.0m bed depth. Experimental evidence like this supports the practice of having a minimum sand depth above 0.3 to 0.5 m in the SSF units to achieve more than one log reduction of indicator bacteria. This is relevant for small systems working with low flow rates (0.1 to 0.2 mh^{-1}), but having to filter at higher rates during short periods due to their lower buffering capacity when one of the units is out of operation. The sand to be put into the SSF units should be clean, and free of clay, earth and organic material (Visscher et al 1987; Ives, 1990). The presence of dust or fine material produces high initial head losses and seems to limit the essential development of an active and effective microbial population in the filter bed. Placing dirty sand in the filter may interfere with the treatment process and makes it necessary to remove the sand earlier for correct washing.There are several important elements that should be observed when constructing slow sand filters:

- The raw water supply feeding the filter should be able to maintain a constant head of water above the filter bed, thus there will be a constant pressure pushing water through the filter. The raw water source must therefore be able to supply a flow rate greater than the flow rate through the filter.
- The filter bed (normally sand) should be at least 0.6 m deep and should contain sand of an appropriate size and size distribution.
- The under-drainage system must support the filter bed while providing the minimum resistance to flow.
- The resistance of the filter bed will increase during use as the pores between sand grains become blocked by the material being removed from the raw water. The flow rate through the bed should be controlled by a regulating value placed in a pipe after the filter. The amount of head above the filter should not be used to regulate flow.
- A weir should be placed in the system between the filter and the storage tank. The weir ensures that if the raw water supply fails the filter bed can’t run dry. As the filter is used the resistance of the sand bed surface increase due to clogging, the weir ensures that it is impossible for the top of the sand bed to run dry even if water can drain out of the bottom of the bed faster than it can pass through the surfac

5.4.3.3 Design of Slow Sand Filter Model:

Required Output flow (Q_{SO}): 6L=6*24=144*3=432l/day = 0.432 m^3/day
Consider Loss= 10% =0.1
Input Flow (Q_{si}) = 0.4321 + (0.4321*0.1) = 0.45m^3/day = (0.45/24) m^3/hr = 0.02 m^3/hr
Consider Filtration Rate (V_{SF})= 0.15 m/hr (Range: 0.1-0.2 m/hr)
Cross Sectional Area (A_F) = Q_{si} / V_{SF} = 0.02/0.15 m^2
=0.133 m^2=0.15m^2(provided)
Providing 3 chambers area of each 0.05 m^2
Filter Length (L_S) =0.5 m
Filter Width (W_S) = 0.05/0.5 = 0.1 m
Height of Sand Layer (h_S) = 0.5 m
Sand volume in filter= (0.5*0.1*0.5) = 0.025 m^3 for each chamber
Height of Gravel layer under Sand (h_{sg}) = 0.07 m
Gravel Volume in Filter= 0.5×0.1 × 0.07 m^3 = **0.0035m^3** for each chamber
Maximum height of supernatant water over sand layer=0.4m
Total Depth (H) = h_S + h_g + H_s +Freeboard = (0.5+ 0.07+ 0.5 + 0.03) = 1.1 m
Slow Sand Filter Dimension (Inner) = (L×B×H) **= (0.5 × 0.1× 1.1)** m^3 for each chamber

Sand Selection

Uniform Coefficient (C_U)= 3-5
Effective particle size(d_s)=0.2-0.35 mm

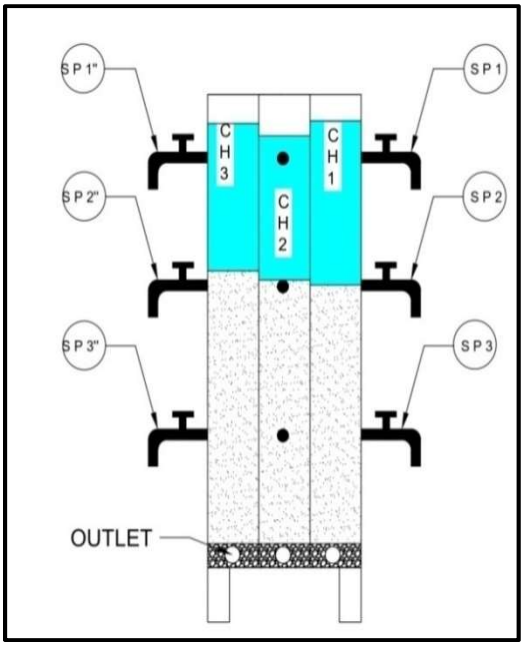


Figure 5.4.3.2.: Elevation view from front side

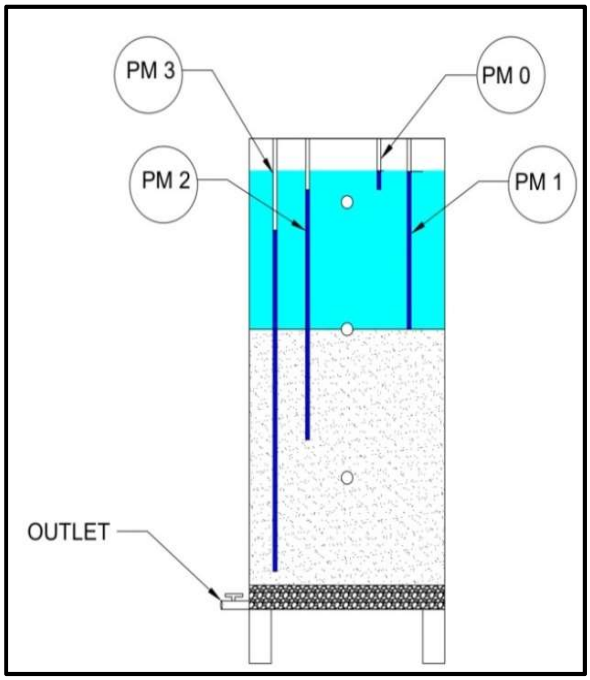


Figure 5.4.3.3: Elevation view from Chamber 1

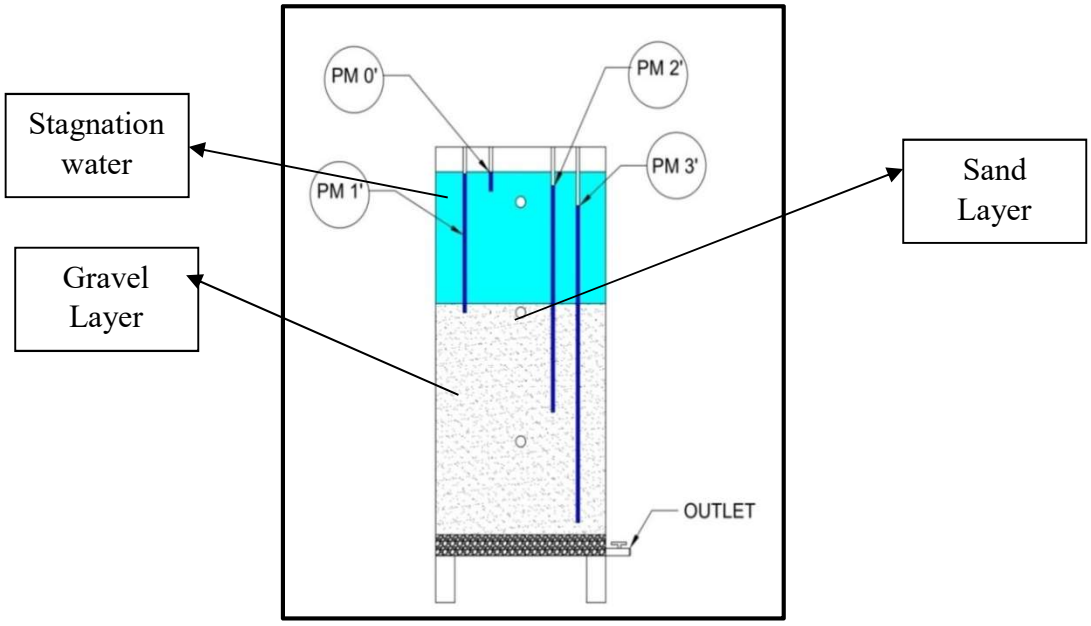


Figure 5.4.3.4: Elevation view from Chamber 3

CH1-CHAMBER 1
CH2-CHAMBER 2
CH3-CHAMBER 3

SP 1- SAMPLING POINT AT TOP IN CHAMBER 1.
SP 2- SAMPLING POINT AT MIDDILE IN CHAMBER 1.
SP 3- SAMPLING POINT AT BOTTOM IN CHAMBER 1.

SP 1'- SAMPLING POINT AT TOP IN CHAMBER 3.
SP 2'- SAMPLING POINT AT MIDDILE IN CHAMBER 3.
SP 3'- SAMPLING POINT AT BOTTOM IN CHAMBER 3.

PM 0-PIEZOMETER AT SUPERNATENT WATER IN CHABER 1.
PM 1- PIEZOMETER AT TOP OF SAND BED IN CHABER 1.
PM 2- PIEZOMETER AT MIDDLE OF SAND BED IN CHABER 1.
PM 3 PIEZOMETER AT BOTTOM OF SAND BED IN CHABER 1

PM 0'-PIEZOMETER AT SUPERNATENT WATER IN CHABER 3.
PM 1'- PIEZOMETER AT TOP OF SAND BED IN CHABER 3.
PM 2'- PIEZOMETER AT MIDDLE OF SAND BED IN CHABER 3.
PM 3' PIEZOMETER AT BOTTOM OF SAND BED IN CHABER 3.

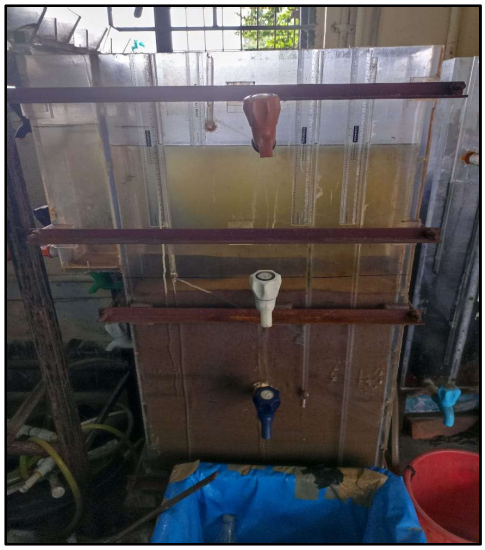
5.4.3.4 Lab Scale Model Setup:

Set up a lab scale model in our lab which consists of an overhead storage tank, aeration tank and a multi stage filter. The aeration process is used a cascade-type aerator. The filter consists of three chambers filled with different sizes of sand medium. At bottom of each chamber have a gravel layer of height up to 0.06m, and above this layer have a sand layer height of height 0.50m, 0.55m and 0.60m are provided in chamber 1, chamber 2 and chamber 3 respectively. After that installed a reciprocating pump for supplying water from the pond to the storage tank. Set up a storage tank of volume 300 Lit. from which water will first go to the cascade aerator and then into the sand filter. Photograph5. shows the MSF model and **Error! Reference source not found.** depicted the SSF model.

- **Gravel Specification:** gravel used in the bottom layer up to 0.07m of size varies from 4.75mm to 30mm. after sieving with a different sieve which is retained in 4.75mm and passing through 30mm sieve is used. At the bottom layer grave size 20-30 mm is used. In the 2^{nd} layer 10-20 mm is used then in the 3^{rd} layer 5-10mm gravel size is used.
- **Sand specification:** sand used in SSF has a uniformity coefficient generally in the range of 2-3. Effective particle size varies between 0.2-0.35mm. At first, sieving with different sieve sizes of ranges 150µm to 450µm. The sand is used which is retained in 150µm and passed through 450µm.Then filled into the sand filter for 0.6m depth above the gravel layer.



Photograph5.4.3.5: Lab scale MSF model



Photograph5.4.3.6: Lab scale SSF

5.4.3.5 Model Water Sample Testing and Monitoring:

During the lab-scale model trial for water treatment simulation, systematically collected water samples from multiple points within the model setup. These samples were meticulously monitored throughout the testing phase. This comprehensive approach allowed us to assess the model's performance accurately and evaluate its effectiveness in treating water. By closely tracking the water quality at different stages of treatment, it could identify any variations or improvements, providing valuable insights for potential real-world applications and refinements in water treatment processes.



Photograph5.4.3.7: Monitoring of the SSF model

5.4.3.6 Discussion of Results:

The findings from our rigorous examination of physical, chemical, bacteriological test analysis and discussion. Specifically focusing on bacteriological test and its efficacy in eliminating turbidity, chemical components, and total coliform from the tested substances. This comprehensive assessment played a pivotal role in evaluating the overall functionality of our system for water treatment and quality enhancement. By scrutinizing head loss development, gained crucial insights into potential flow restrictions and their implications. Furthermore, our investigation into the model's ability to remove turbidity and various contaminants underscored its importance in ensuring safe and clean water supplies. These results will be instrumental in refining and optimizing our water treatment processes for enhanced environmental and public health outcomes.

5.4.3.7 Optimization of SSF System:

With insights from the model data and field data, it can proceed to optimize a Slow Sand Filtration (SSF) system. The focus was on addressing the most critical water quality parameters identified in our study area. In conclusion, our study employed a multidisciplinary approach to tackle water quality issues in the Bardhhaman district of West Bengal. By combining field data collection, laboratory experiments, and the design of a specialized treatment model, the aimed to provide a holistic solution. The optimization of an SSF system holds promise for improving water quality and ensuring access to clean and safe drinking water in the region. This integrated

approach underscores the importance of addressing water quality concerns in a systematic and sustainable manner, benefiting both the environment and public health.

5.4.3.8. Design of Slow Sand Filter in Field:

From lab scale model, consider that the velocity, material use, pollution load, sand depth, bio layer formation is similar in the SSF at field, and then design the SSF at field. After than design an SSF unit at Puratangram village in Bardhhaman district as it found most critical point from our study. Surveyed in that village and found population and other required data related to our study.

Population of the village =3000

Drinking Water Demand= 5 lpcd (As per**IS 1172: 1993**)

Output flow (Q_{SO}): 3000x5 L/D = 15 m^3/day

Consider loss=10%=0.1

Input Flow (Q_{si}) =15+0.1x15=16.5 m^3/day = (16.5 /24) m^3/hr =0.6875 m^3/hr

Filtration Rate (V_{SF})= 0.15 m/hr (Range: 0.1-0.2 m/hr)

Cross Sectional Area (A_F) = Q_{si} / V_{SF} = 0.6875/0.15 m^2 =4.6 m^2=5 m^2 (provided)

As per IS 11401 (Part 2): 1990 General Requirements for Slow Sand Filters

A rough indication of suitable number (n) is given by the formula $\boldsymbol{n = \sqrt[3]{A_F}}$

A = total area of the filter's beds in m^2

$$\boldsymbol{n = 0.5\sqrt[3]{A_F} = 0.5\sqrt[3]{5} = 0.85 \simeq 1}$$

So, provided 2 no of chamber.

Now as per IS 11401 (Part 2): 1990, economical length (L) and width (B) of rectangular filter of chamber is,

$$\boldsymbol{L = \sqrt{\frac{2A_F}{n} + 1} = \sqrt{\frac{2 * 5}{2} + 1} = 3.23 \simeq 4\ m}$$

$$\boldsymbol{B = \frac{(n+1)L}{2n} = \frac{(1+1) * 4}{2 * 1} = 4\ m} \simeq 4.5$$

Height of Sand Layer (h_S) = 0.9m

Sand volume in filter= (4*4.5*0.9)/2 = 8.1 m^3 for each chamber

Height of Gravel layer under Sand (h_{sg}) = 0.3 m (As per IS code)

Gravel Volume in Filter= 4×4.5 × 0.3/2 m^3 =2.7 m^3 for each chamber

Maximum height of supernatant water over sand layer (H_s)=0.9 m

Total Depth (H) = h_S + h_g + H_s +Freeboard = (0.9+ 0.3+ 0.9 + 0.1) = 2.2 m

Slow Sand Filter Dimension (Inner) = (L×B×H) = **(4× 2.25× 2.2)** m^3 for each chamber

Sand Selection

Uniform Coefficient (C_U)= 3-5

Effective particle size(d_s)=0.2-0.35 mm

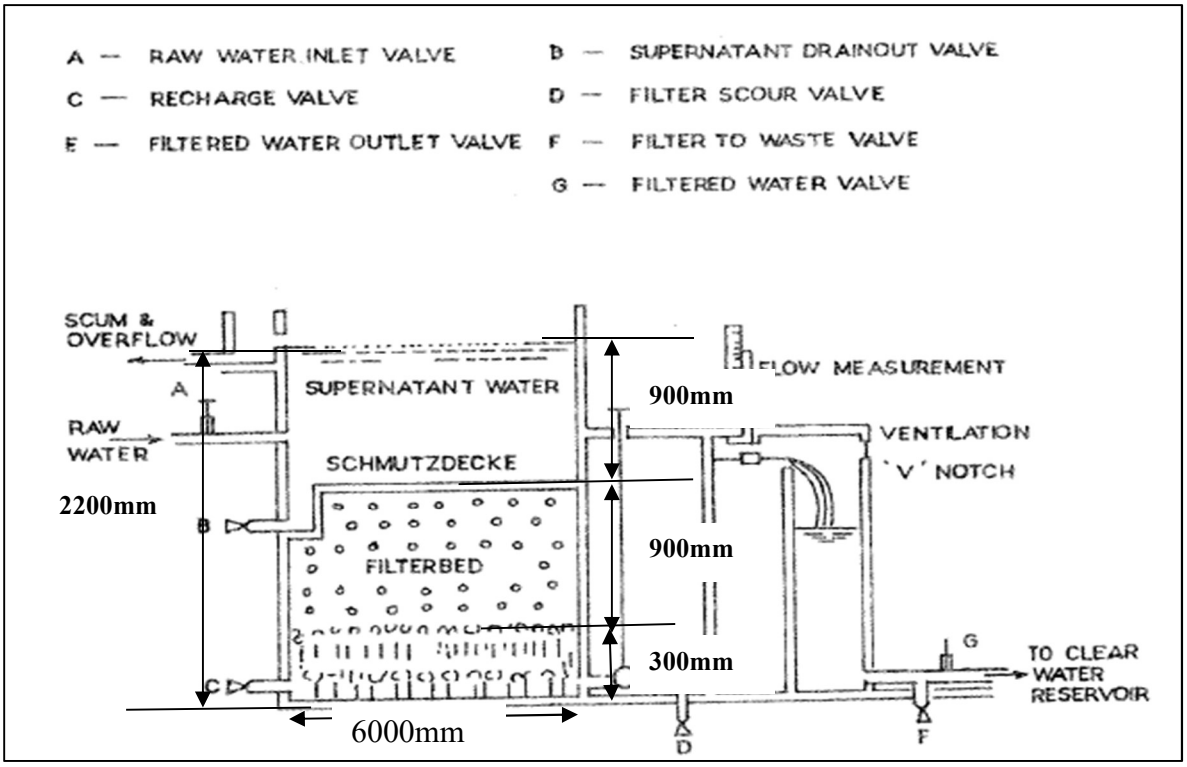


Figure 5.4.3.8: Elevation view of SSF unit in Field

6.RESULT & DISCUSSION:

The integration of well field design and multistage filtration with riverbank filtration (RBF) for sustainable water supply in rural areas of Bardhamān, West Bengal, demonstrates significant advancements in water treatment methodologies. Through comprehensive pumping tests and well field design, the study effectively evaluated the sustainable withdrawal quantity of sub-surface water in the riverbank, ensuring long-term viability and minimal ecological disruption. The combined use of RBF with multistage filtration techniques—encompassing roughing filters, slow sand filters, and activated carbon-proved highly effective in removing emerging contaminants from raw water sources, surpassing the performance of each method when used in isolation. This synergy not only enhanced the removal efficiency but also mitigated potential fouling, a common issue in filtration systems. The study also explored novel natural filtration methods, further improving water quality and reducing operational complexities. These findings highlight the potential of integrated filtration systems to provide a sustainable and reliable water supply in geogenically contaminated rural areas, offering a scalable solution adaptable to varying environmental conditions. The detailed results discussed below elaborate on the specific contaminant removal rates, the operational parameters optimized for maximum efficiency, and the overall sustainability of the proposed system.

6.1. Pumping Tests& Recuperation Test result:

Table 6.1.1: Initial Data recorded just before starting the Pumping Test:

Well Name	Distance from the main well	Duration of monitoring	Depth of water from Datum / Static Water table	MSL of bed level	Discharge of pump
	(m)	(hr)	(m)	(m)	(m^3/hr)
Main Well	--	45	8.16	99.925	75
OBS-1	10	45	4.815	99.743	--
OBS-2	20	45	7.24	98.861	--
OBS-3	55	45	2.58	99.973	--

The pump started at 03:25 pm on 16th March, 2024 and the readings of the drawdown in the main well and three observation wells were taken as depicted in the following graphs –

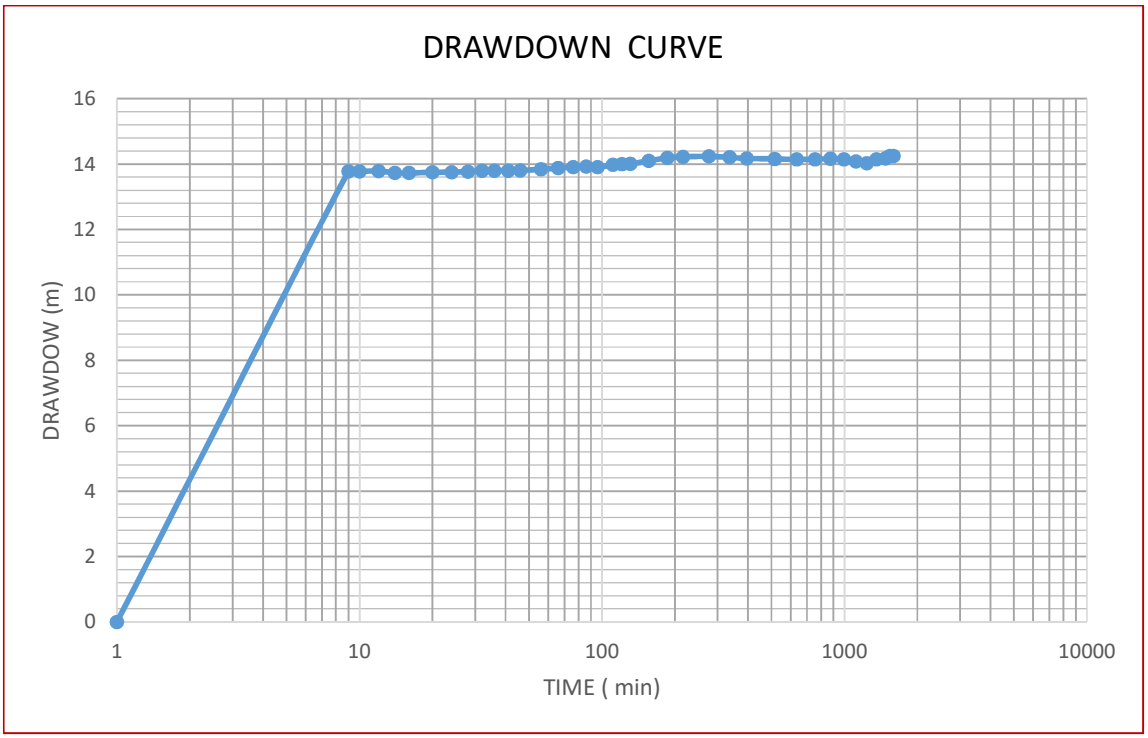


Figure 6.1.1: Variation of Drawdown (*s*) at the main well with varying time (*t*) for pumping out water from the main well.

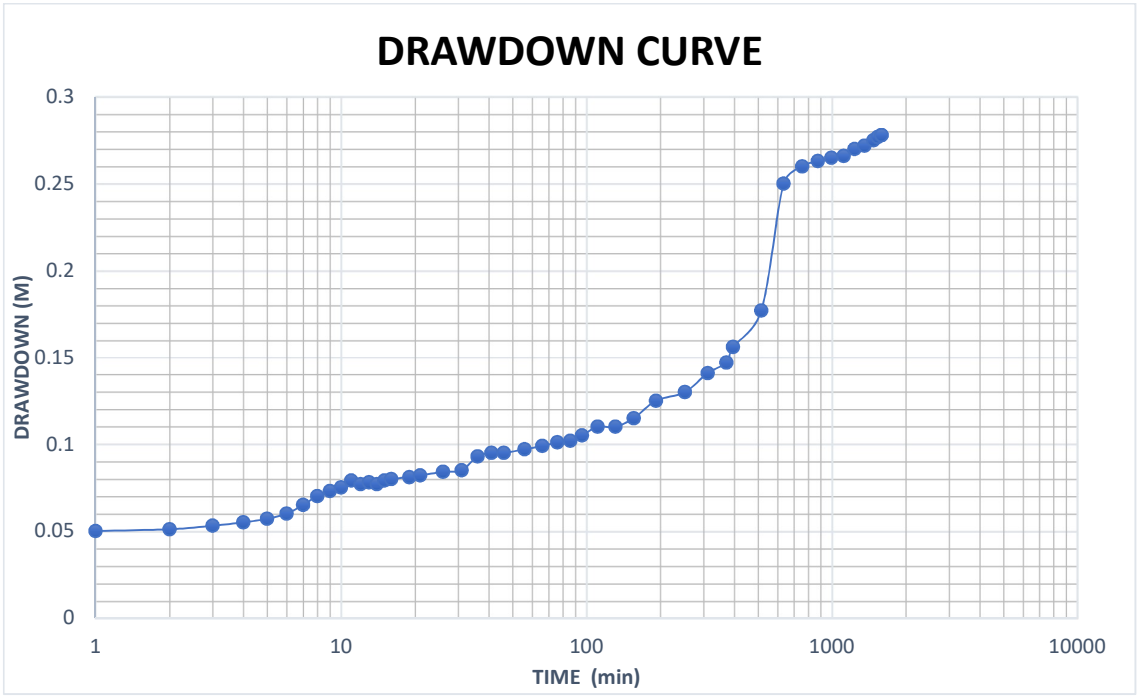


Figure 6.1.2**:** Drawdown (*s*) versus time (*t*) data plotted for observation well-1.

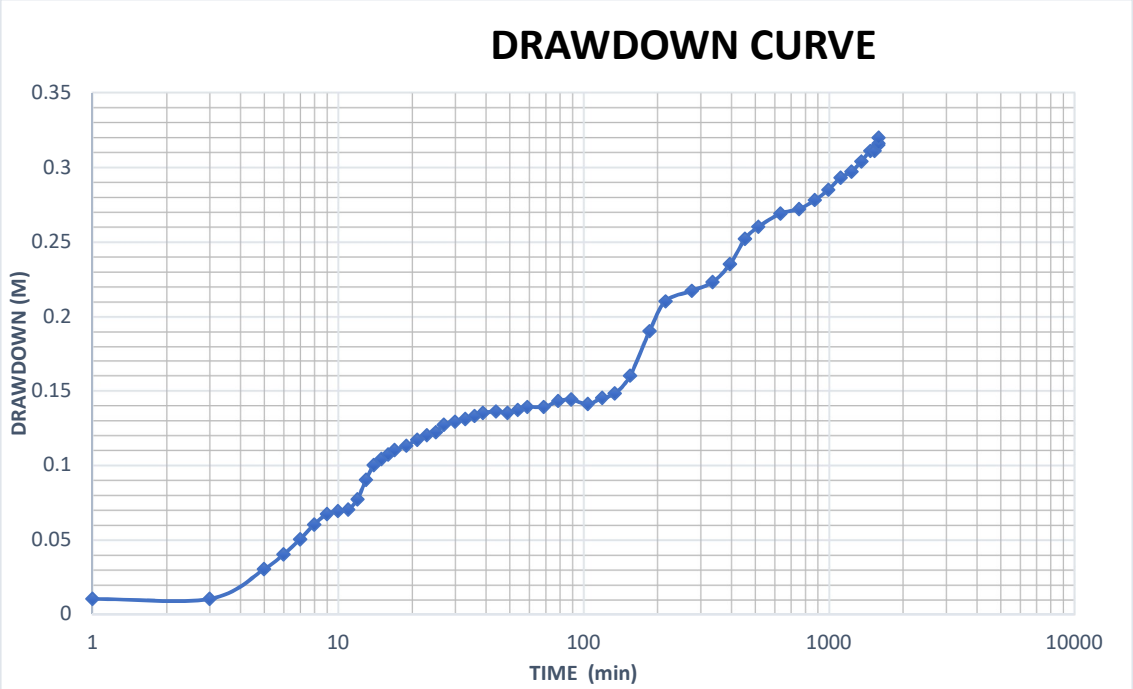


Figure 6.1.3: Drawdown (*s*) versus time (*t*) data for observation well-2.

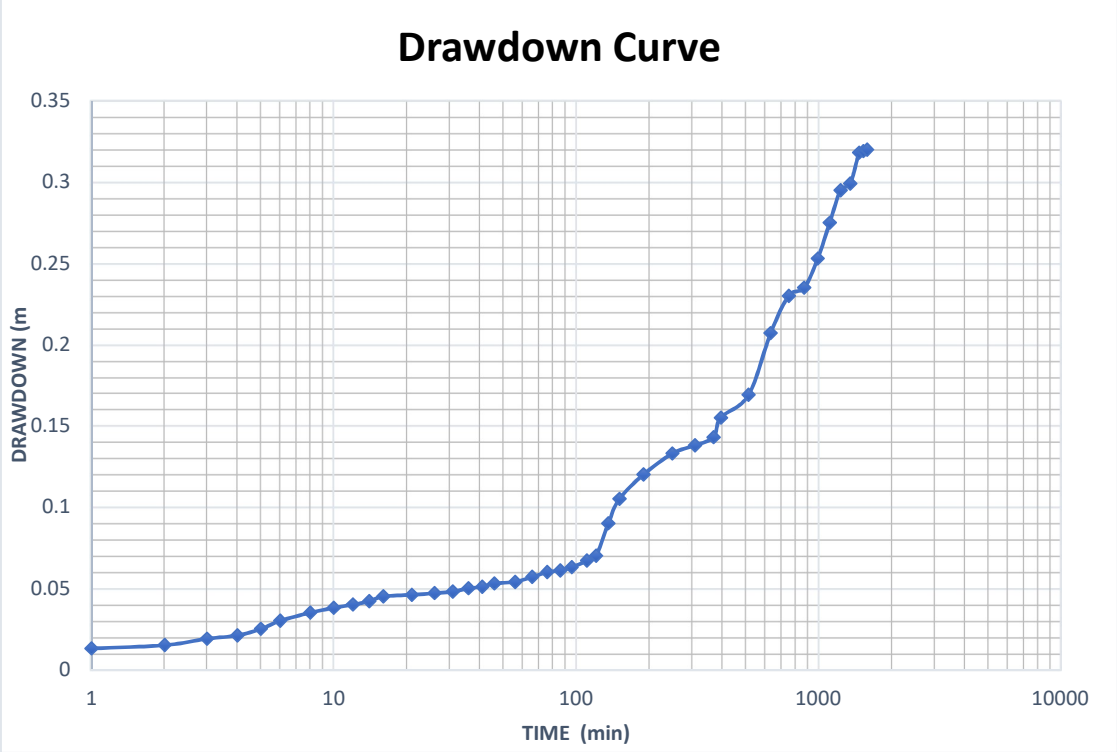


Figure 6.1.4: Drawdown (*s*) versus time (*t*) data for observation well-3.

A summary of observation data of Drawdown, Transmissivity, and Storativity of observation wells with respect to the main well (10 m from the left bank) is given in 6.1.2

Table 6.1.2: Results of pumping Test at a Glance**:**

Well Name	Distance from Main Well	Storativity	Discharge	Transmissivity	Maximum Drawdown
	(m)		**(m^3/hr)**	**(m^2/day)**	**(m)**
Main Well (10 m from the left bank)	-	-	75		14.24
OBS-1	10	0.241	-	1979.9	0.278
OBS-2	20	0.013	-	2199.99	0.32
OBS-3	55	0.034	-	1667.36	0.32
Average Transmissivity = 1956 m^2/day Critical Value of Transmissivity=1980m^2/day					

All the distances of the observation wells were measured with respect to the respective main wells. The diameter of the main well was 200 mm and the depth of boring was 45 m. The diameter of the three observation wells was 50 mm each and their depth of boring was 45 m.

- **Recuperation Test:**

At the end of the pumping test when the pump is stopped, the water level in the pumping well and three observation wells will begin to rise. This is referred to as recovery of groundwater level, while measurements of drawdown below the original static water level (prior to pumping) during this recovery period are known as residual drawdowns. In the present study, the maximum drawdown in the main well was measured 14.24m and the residual drawdown was measured 0.0 m which suggests 100% recovery.

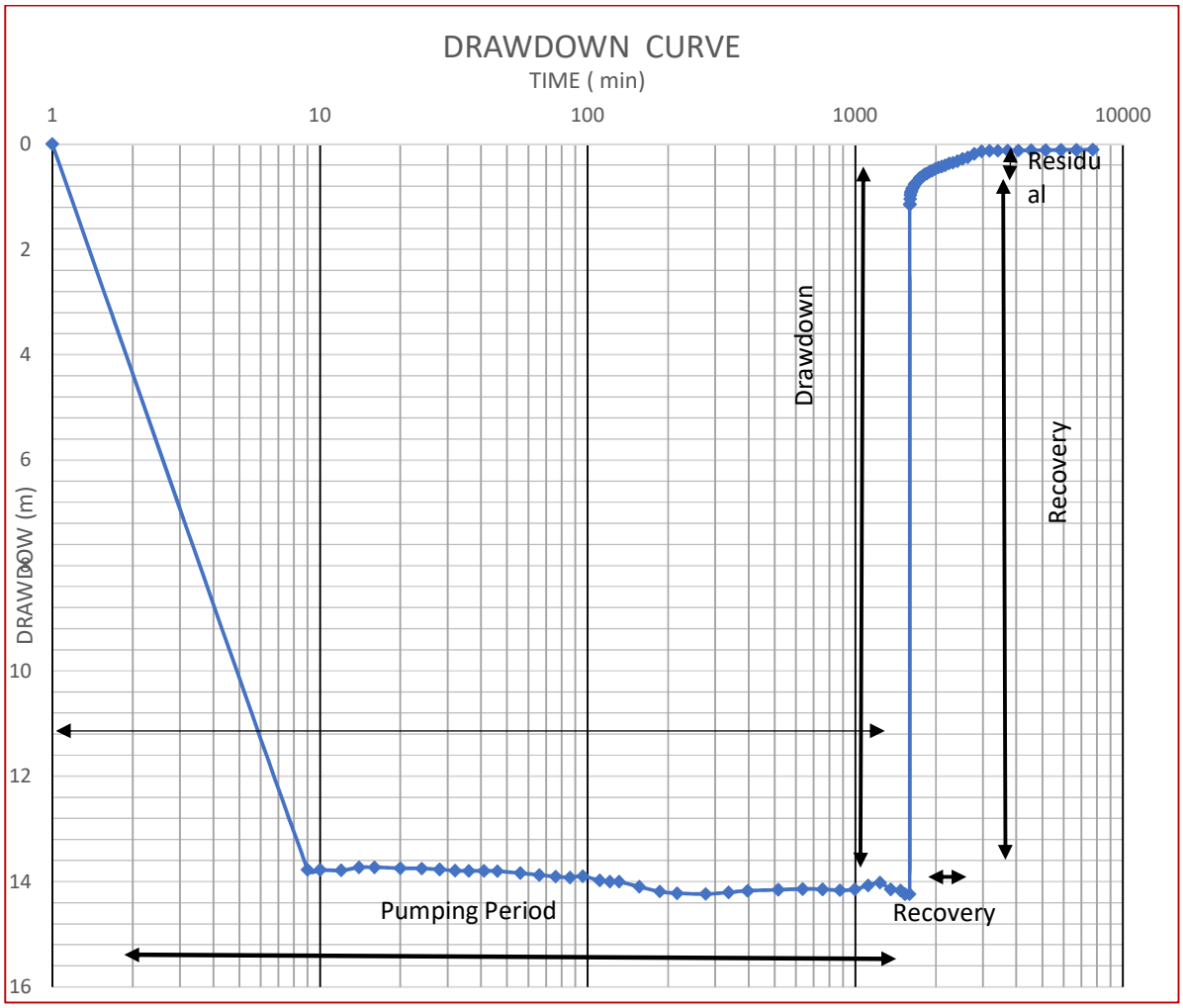


Figure 6.1.5: Drawdown versus time curve representing recuperation data for Main well

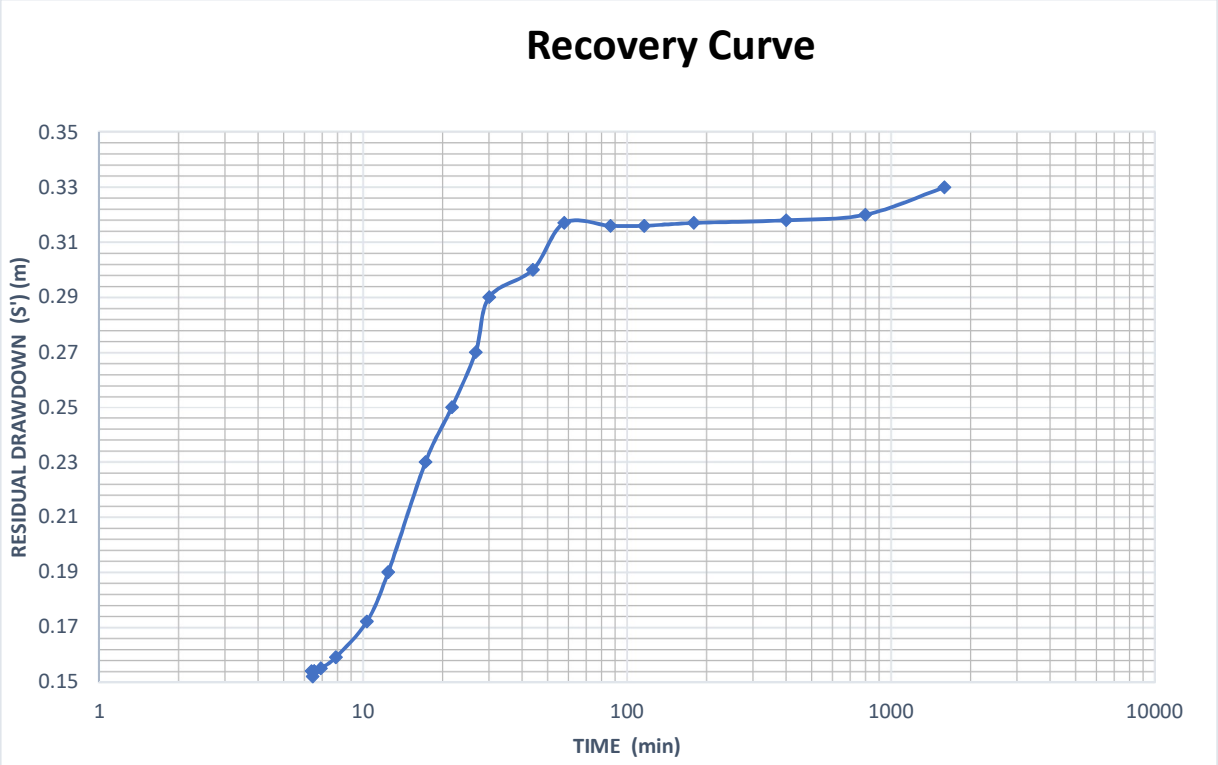


Figure 6.1.6: Time drawdown curve, Theis recovery for observation well-1.

The values of *S*' versus *t/t'* are plotted on semi-log paper and using the following equation, transmissivity and storage coefficient have been determined.

$$T = \frac{2.3Q}{4\pi\Delta s'} = \frac{2.3\times75\times24}{4\pi(0.114)} = 3012 \text{ m}^2/\text{day}$$

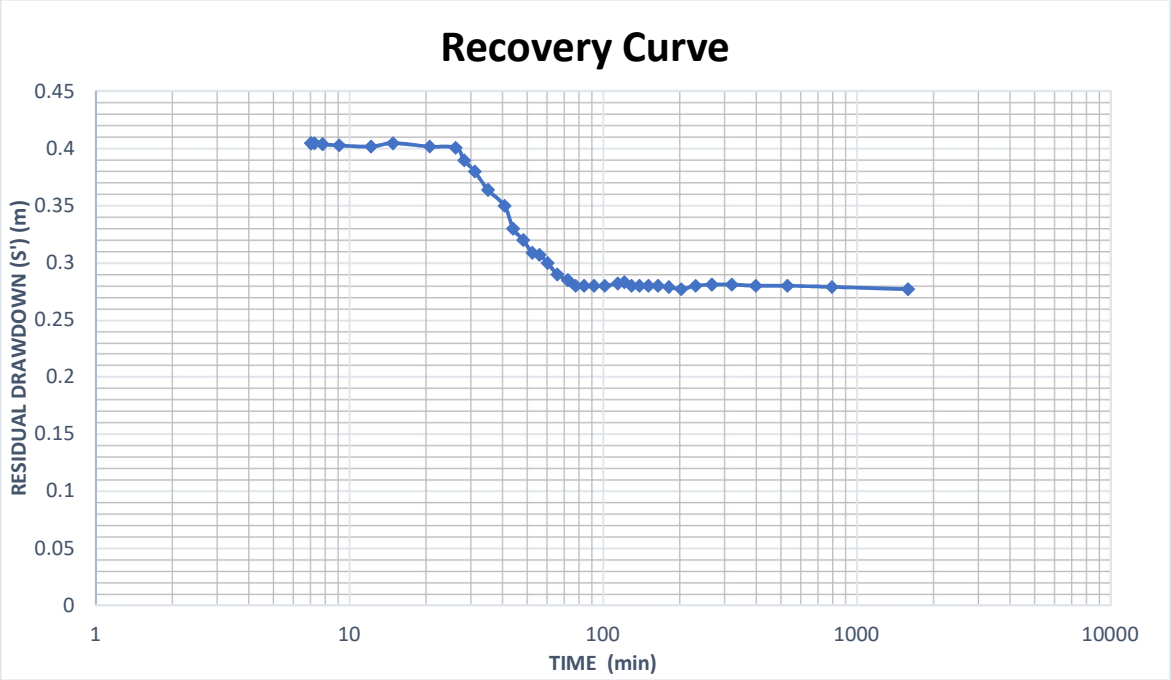


Figure 6.1.7**:** Time drawdown curve, Theis recovery for observation well-2.

Table 6.1.3: Results of recuperation or recovery test at a glance:

Well Name	Distance from Main Well	Discharge	Transmissivity	Maximum Drawdown
	(m)	(m^3/hr)	(m^2/day)	(m)
Main 1 (10 m from the left bank)	-	75	-	14.24
OBS-1	10	-	2778.94	0.278
OBS-2	20	-	2639.99	0.32

6.2. WELL FIELD DESIGN RESULT:

Therefore, a well field consisting of seven wells is arranged as shown in Fig:6.2 with each well pumping 800 m^3/day and spaced 52 m apart from the each well, will yield the required amount of water and produce a drawdown that will not exceed the specified maximum of 2.1 m. The arrangement of 7 wells are considered.

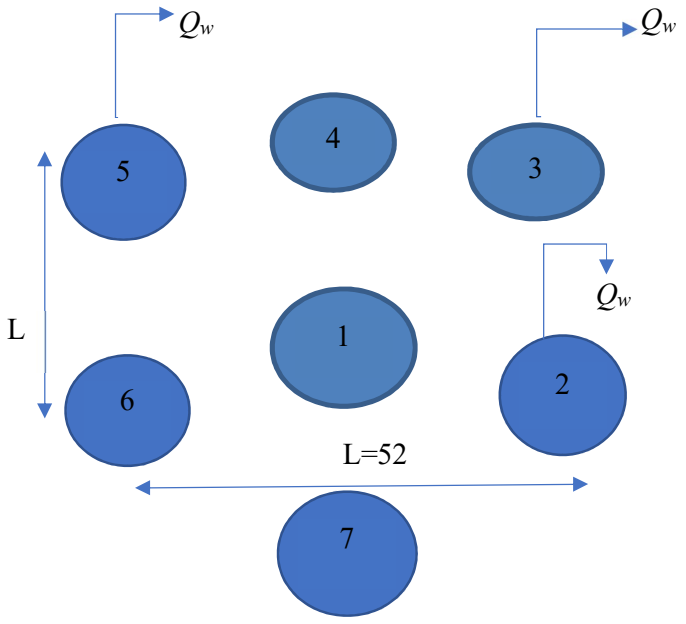


Figure 6.2: Proposed Well Field.

6.3. Mechanical Sieve analysis data:

A mechanical analysis is done with the bore well log material and from that the material size is determined.

Table 6.3.1: Mechanical Analysis of Main Well (depth 10m to 30m)

Sieve Size (mm)	Weight Retained (gm)	Cumulative Weight Retained (gm)	% of Cum. Wt. Retained	% Finer
11.2	1.6	1.6	0.16	99.84
4.75	12.86	14.46	1.45	98.55
3.35	6.82	21.28	2.14	97.86
2.3	14.36	35.64	3.57	96.43
1.7	56.79	92.43	9.29	90.71
0.85	381.26	473.69	47.49	52.51
0.5	327.93	801.62	80.57	19.43
0.3	192.74	994.36	99.94	0.06
0.12	0.05	994.41	99.94	0.06
0.09	0.03	994.44	99.95	0.05
Pan	0.54	994.98	100	0
CALCULATION				
D_{30}= 0.61 mm, D_{50} = 0.82 mm, D_{60} = 1.0 mm, D_{10} = 0.41 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.4				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 1.0				

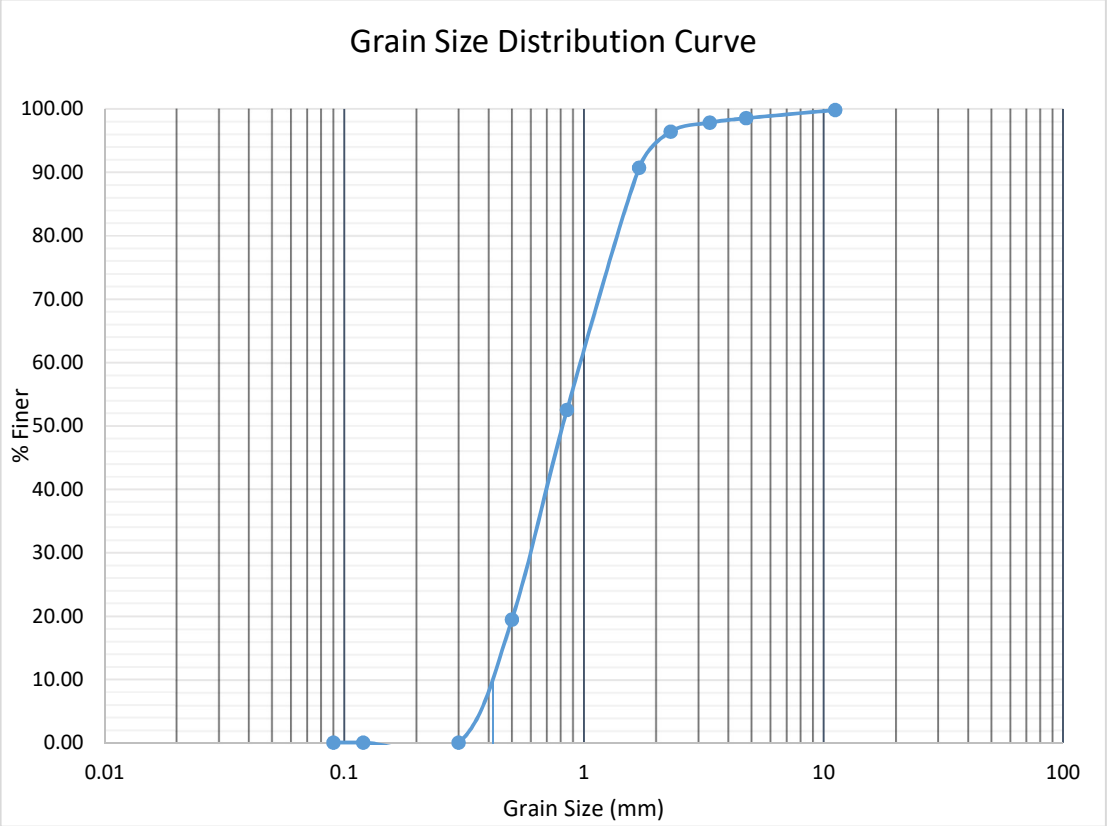


Figure6.3.1: IS sieve aperture dimension (mm) vs Cumulative % passing as per Sieve analysis for the main well (depth 10m to 30m)

Table 6.3.2: Mechanical Analysis of Main Well (depth 30m to 50m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	0	0	0	100
4.75	35.8	35.8	3.59	96.41
3.35	25.17	60.97	6.11	93.89
2.3	31.44	92.41	9.26	90.74
1.7	31.57	123.98	12.64	87.36
0.85	150.04	274.02	27.95	72.05
0.5	172.25	446.27	45.52	54.48
0.3	528.9	975.17	99.46	0.54
0.12	0.82	975.99	99.54	0.46
0.09	0.31	976.3	99.57	0.43
Pan	4.18	980.48	100.00	0.00
CALCULATION				
D_{30}= 0.41 mm, D_{50}= .49 mm, D_{60}= 0.60 mm, D_{10}= 0.35 mm				
Coefficient of Uniformity, $C_u = D_{60}/D_{10}$ = 1.82				
Coefficient of Curvature, $Cc = D_{30}^2/(D_{60} \times D_{10})$= 0.81				

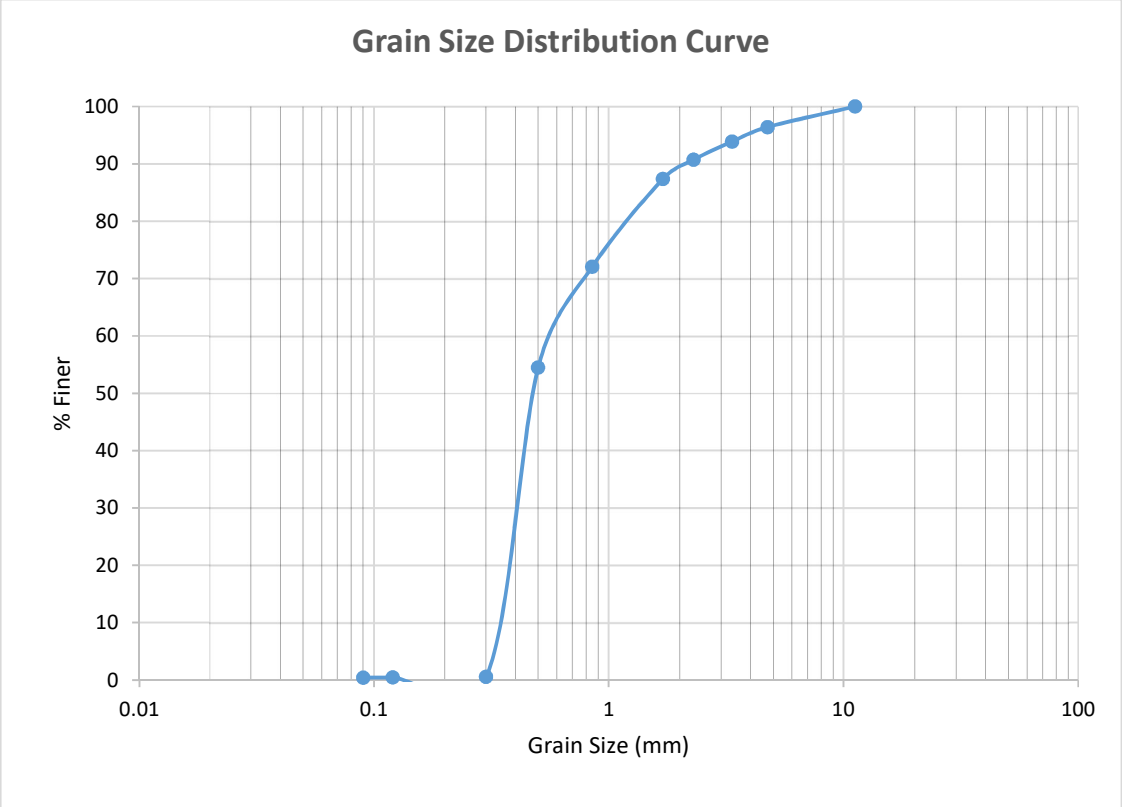


Figure 6.3.2: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for Main Well (depth 30m to 50m)

Table 6.3.3: Mechanical Analysis of Observation Well-1 (depth 10m to 18m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	4.23	4.23	0.39	99.61
4.75	27.03	31.26	2.90	97.10
3.35	99.99	131.25	12.17	87.83
2.3	31.56	162.81	15.10	84.90
1.7	43.85	206.66	19.17	80.83
0.85	168.16	374.82	34.77	65.23
0.5	388.12	762.94	70.77	29.23
0.3	313.41	1076.35	99.84	0.16
0.12	0.16	1076.51	99.86	0.14
0.09	0.04	1076.55	99.86	0.14
Pan	1.52	1078.07	100.00	0.00
CALCULATION				
D_{30}= 0.51 mm, D_{50}=0.67 mm, D_{60}= 0.79 mm, D_{10}= 0.38 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.17				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.868				

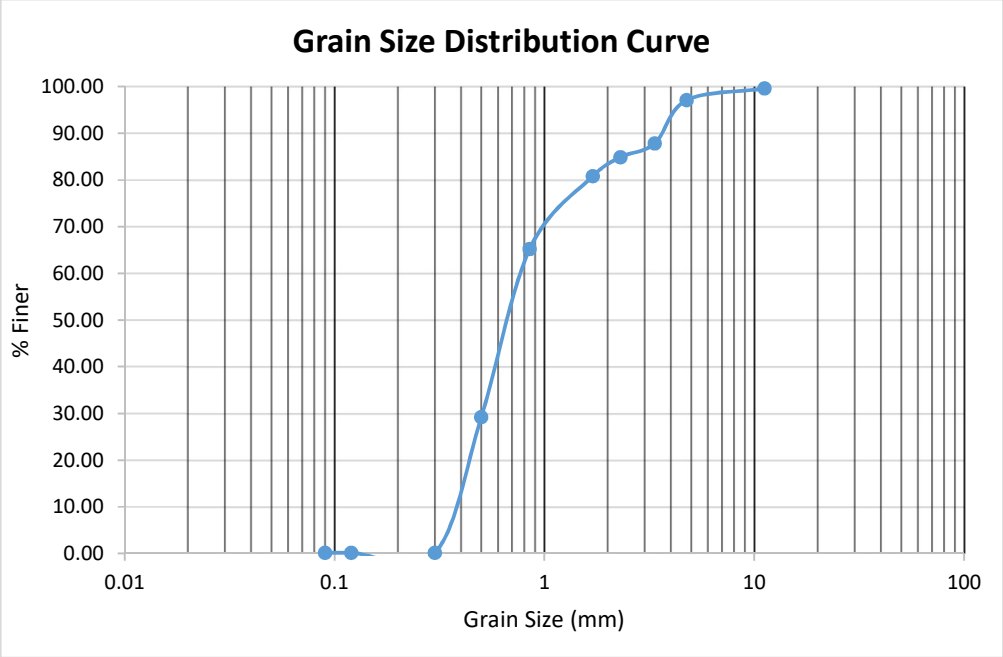


Figure6.3.3: IS sieve aperture dimension (mm) versus cumulative % passing as per sieve analysis for observation well-1(depth 10m to 18m)

Table 6.3.4: Mechanical Analysis of Observation Well-1 (depth 18m to 30m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	6.38	6.38	0.64	99.36
4.75	25.76	32.14	3.22	96.78
3.35	22.51	54.65	5.47	94.53
2.3	32.65	87.3	8.74	91.26
1.7	57.55	144.85	14.50	85.50
0.85	278.15	423	42.33	57.67
0.5	327.79	750.79	75.13	24.87
0.3	247.08	997.87	99.86	0.14
0.12	0.56	998.43	99.91	0.09
0.09	0.09	998.52	99.92	0.08
Pan	0.77	999.29	100.00	0.00
CALCULATION				
D_{30}= 0.55 mm, D_{50}= 0.768 mm, D_{60}= 0.92 mm, D_{10}=0.38 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.42				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.884				

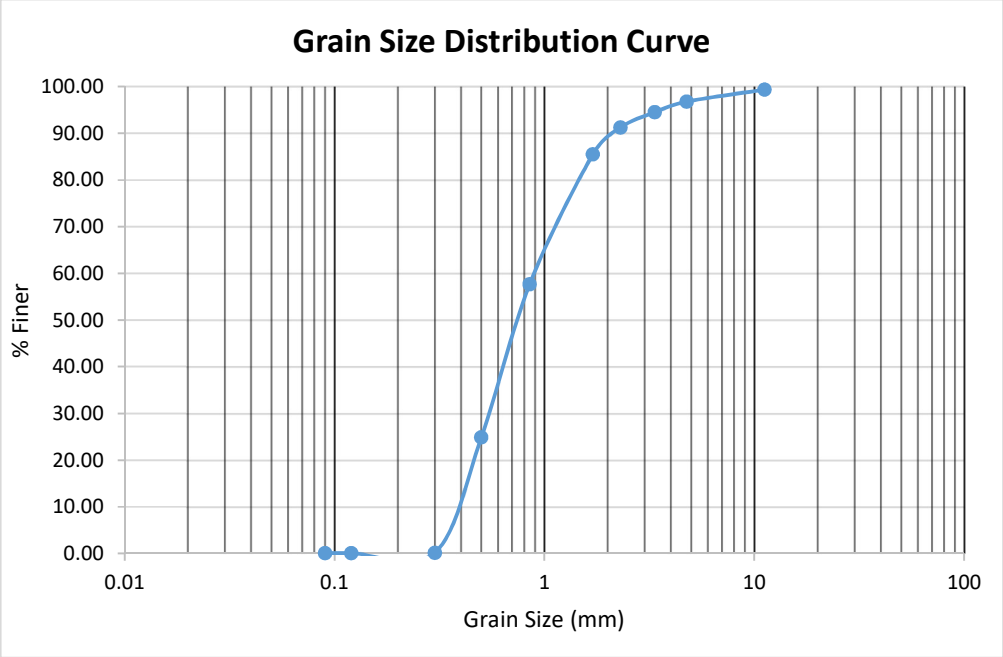


Figure6.3.4: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for observation well-1 (depth 18m to 30m)

Table 6.3.5: Mechanical Analysis of Observation Well-1 (depth 30m to 45m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	15.52	15.52	1.56	98.44
4.75	61.6	77.12	7.74	92.26
3.35	15.98	93.1	9.34	90.66
2.3	38.41	131.51	13.20	86.80
1.7	63.2	194.71	19.54	80.46
0.85	213.39	408.1	40.95	59.05
0.5	284.22	692.32	69.47	30.53
0.3	301.93	994.25	99.76	0.24
0.12	1.02	995.27	99.86	0.14
0.09	0.11	995.38	99.87	0.13
Pan	1.25	996.63	100.00	0.00
CALCULATION				
D_{30}= 0.5 mm, D_{50}= 0.738 mm, D_{60}= 0.91 mm, D_{10}=0.38 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.43				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.76				

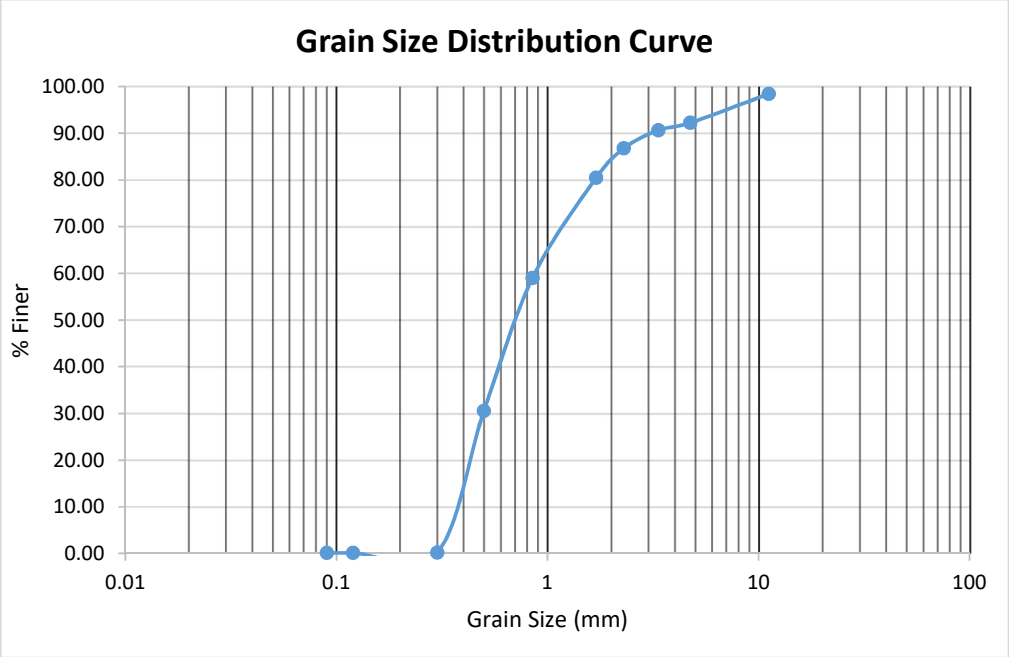


Figure6.3.5: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for observation well-1 (depth 30m to 45m)

Table 6.3.6: Mechanical Analysis of Observation Well-2 (depth 10m to 25m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	2.47	2.47	0.25	99.75
4.75	84.1	86.57	8.71	91.29
3.35	46.02	132.59	13.34	86.66
2.3	78.45	211.04	21.23	78.77
1.7	87.36	298.4	30.02	69.98
0.85	260.98	559.38	56.28	43.72
0.5	275.89	835.27	84.03	15.97
0.3	157.36	992.63	99.86	0.14
0.12	0.34	992.97	99.90	0.10
0.09	0.01	992.98	99.90	0.10
Pan	1.02	994	100.00	0.00
CALCULATION				
D_{30}= 0.676 mm, D_{50}=1.05mm, D_{60}= 1.37 mm, D_{10}= 0.43 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 3.24				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.78				

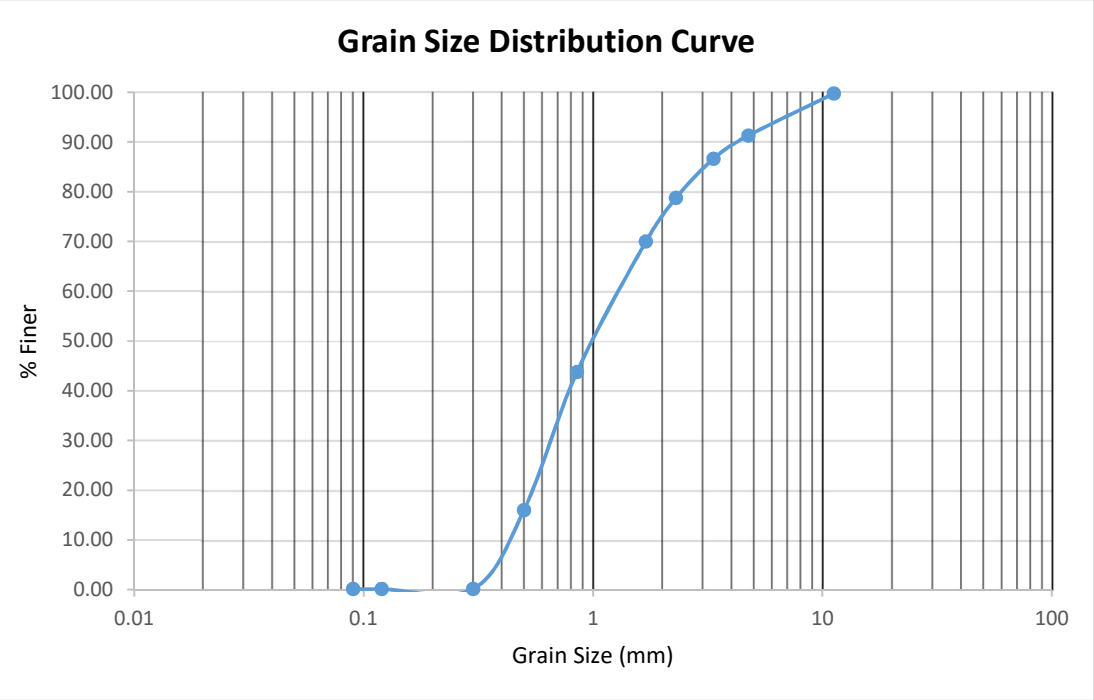


Figure6.3.6: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for observation well-2 (depth 10m to 25m)

Table 6.3.7: Mechanical Analysis of Observation Well-2 (depth 25m to 40m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	0	0	0.00	100.00
4.75	19.28	19.28	1.94	98.06
3.35	26.09	45.37	4.57	95.43
2.3	58.28	103.65	10.43	89.57
1.7	92.32	195.97	19.73	80.27
0.85	324.76	520.73	52.42	47.58
0.5	303.59	824.32	82.98	17.02
0.3	167.15	991.47	99.80	0.20
0.12	0.35	991.82	99.84	0.16
0.09	0.09	991.91	99.85	0.15
Pan	1.5	993.41	100.00	0.00
CALCULATION				
D_{30}= 0.648 mm, D_{50}=0.91mm, D_{60}= 1.17 mm, D_{10}= 0.43 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.81				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.86				

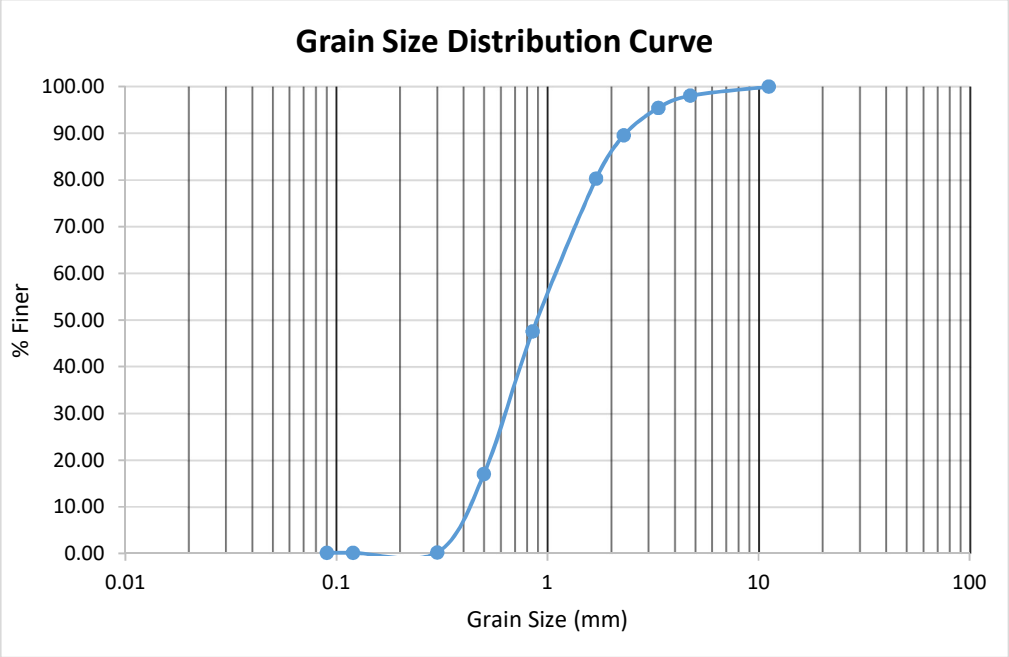


Figure6.3.7: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for observation well-2 (depth 25m to 40m)

Table 6.3.8: Mechanical Analysis of Observation Well-3 (depth 6m to 25m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	1.7	1.7	0.17	99.83
4.75	21.53	23.23	2.33	97.67
3.35	14.3	37.53	3.77	96.23
2.3	27.85	65.38	6.56	93.44
1.7	44.13	109.51	10.99	89.01
0.85	238.24	347.75	34.90	65.10
0.5	406.4	754.15	75.69	24.31
0.3	241.19	995.34	99.90	0.10
0.12	0.04	995.38	99.91	0.09
0.09	0.04	995.42	99.91	0.09
Pan	0.9	996.32	100.00	0.00
CALCULATION				
D_{30}= 0.55 mm, D_{50}=0.72mm, D_{60}= 0.806mm, D_{10}= 0.40 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.11				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.97				

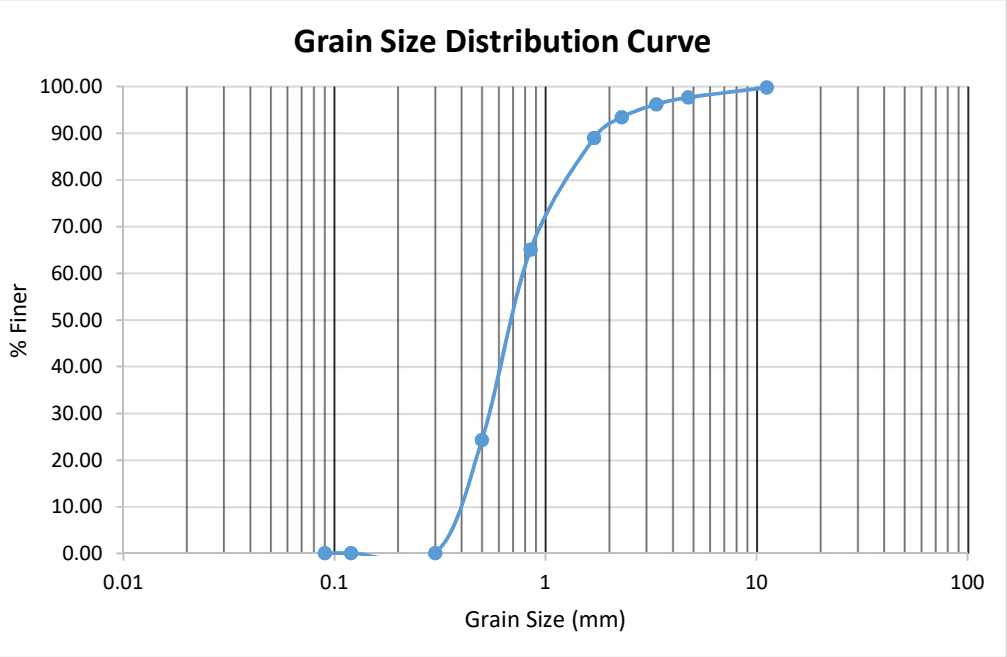


Figure6.3.8: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for observation well-3 (depth 6m to 25m)

Table 6.3.9: Mechanical Analysis of Observation Well-3 (depth 25m to 40m)

Sieve Size (mm)	**Weight Retained (gms)**	**Cumulative Weight Retained (gms)**	**% of Cum. Wt. Retained**	**% Finer**
11.2	0	0	0.00	100.00
4.75	17.52	17.52	1.77	98.23
3.35	22.66	40.18	4.05	95.95
2.3	54.18	94.36	9.51	90.49
1.7	82.25	176.61	17.81	82.19
0.85	290.45	467.06	47.09	52.91
0.5	274.29	741.35	74.74	25.26
0.3	247.97	989.32	99.74	0.26
0.12	0.22	989.54	99.77	0.23
0.09	0.1	989.64	99.78	0.22
Pan	2.22	991.86	100.00	0.00
CALCULATION				
D_{30}= 0.56 mm, D_{50}=0.81mm, D_{60}= 1.05mm, D_{10}= 0.38 mm				
Coefficient of Uniformity, Cu= D_{60}/D_{10} = 2.79				
Coefficient of Curvature, Cc= $D_{30}^2/(D_{60}\times D_{10})$ = 0.82				

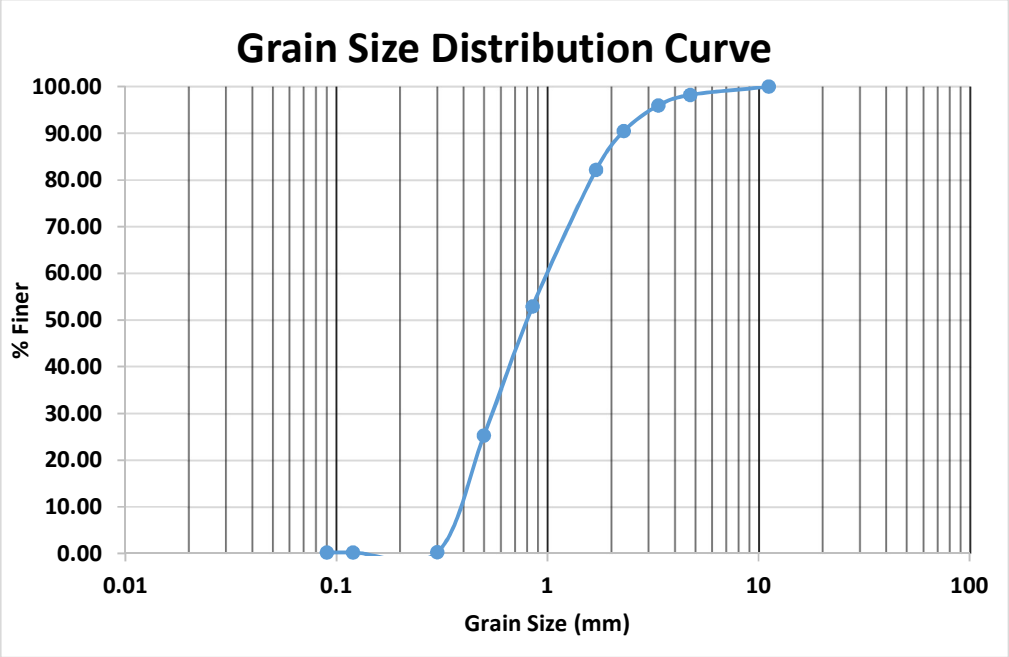


Figure6.3.9: IS sieve aperture dimension (mm) versus cumulative % passing as per Sieve analysis for observation well-3 (depth 25m to 40m)

Based on the grain size distribution data, it is observed that the Coefficient of Uniformity (C_u) mostly varies from 1.8 to 2.4 for main well. Based on the analysis, an artificial gravel pack around the pumping well is required as the Coefficient of Uniformity is found less than 3.0. The gravel pack materials should have a Coefficient of Uniformity less than 2.5. For determination of the gravel size, D_{30} can be considered and around 4 to 6 times of D_{30} can be selected for artificial gravel packing.

Table:6.4: Sample with their location:

Sl. No	Sample-ID	Turbidity (NTU)	pH	TDS (mg/l)	Phosphate (mg/l)	Nitrate (mg/l)	Sulphate (mg/l)	Iron (mg/l)	Ammonia (mg/l)
	Permissible value	**1**	**6.5 - 8.5**	**500**		**45**	**200**	**1**	**0.5**
1	**River Water (RW)**	**3.69**	**8.4**	**192**	**0.21**	**4.3**	**38**	**0.13**	**0**
2	**Ground Water (TW)**	**0.55**	**8.4**	**315**	**0.12**	**2.9**	**60**	**0.87**	**0**
3	**Pond Water (PW)**	**6.62**	**8.5**	**192**	**0.28**	**2.4**	**24**	**1.17**	**1.32**
4	**Pond Water (PW)**	**20.09**	**8.5**	**353**	**0.34**	**3.8**	**3**	**0.76**	**2.42**
5	**Ground Water (TW)**	**0.48**	**8.4**	**667**	**0.19**	**5.0**	**80**	**0.26**	**0**
6	**Ground Water (SP)**	**0.42**	**8.5**	**227**	**0.32**	**5.3**	**14**	**0.23**	**0**
7	**Pond Water (PW)**	**7.5**	**8.8**	**403**	**0.37**	**26**	**42**	**0.7**	**4.5**
8	**Ground Water (TW)**	**0.66**	**8.5**	**196**	**0.13**	**3.8**	**17**	**0.45**	**0**
9	**Ground Water (SP)**	**0.65**	**8.5**	**237**	**0.42**	**4.3**	**54**	**0.18**	**0**
10	**MAIN WELL**	**0.48**	**8.7**	**222**	**0.29**	**7.9**	**11**	**0.32**	**0**

Table:6.4.0: Various type of Name elaborated:

NAME	DESCRIBE
SWRE	SCHOOL OF WATER RESOURCES ENGINEERING
RW	RIVER WATER
PW	POND WATER
TW (HAND PUMP)	GROUND WATER
SP (SUBMERSIBLE PUMP)	GROUND WATER
S2, S3, S4, S5, S6, S7, S8, S10, S11,	SAMPLE ID NO
MAIN WELL	GROUND WATER

- Water collection in various places near Damodar River:



6.4. Figure: Water Sample collection in map

6.4.1 Physical Test:

- **Turbidity:**

Field samples of various part from Bardhhaman district was collected and tested in the laboratory of School of Water Resources Engineering. The measured turbidity (NTU) is shown in Figure 6.4.1 the data are shown by bar chart with sample ID. It is shown that turbidity value is under permissible limit for 4 out of 10 samples. Sample ID RW/S-3, PW/S-7, PW/S-5, PW/S-4, have more than desirable value of turbidity where PW/S-5 exhibit the maximum value of 20.09 NTU.

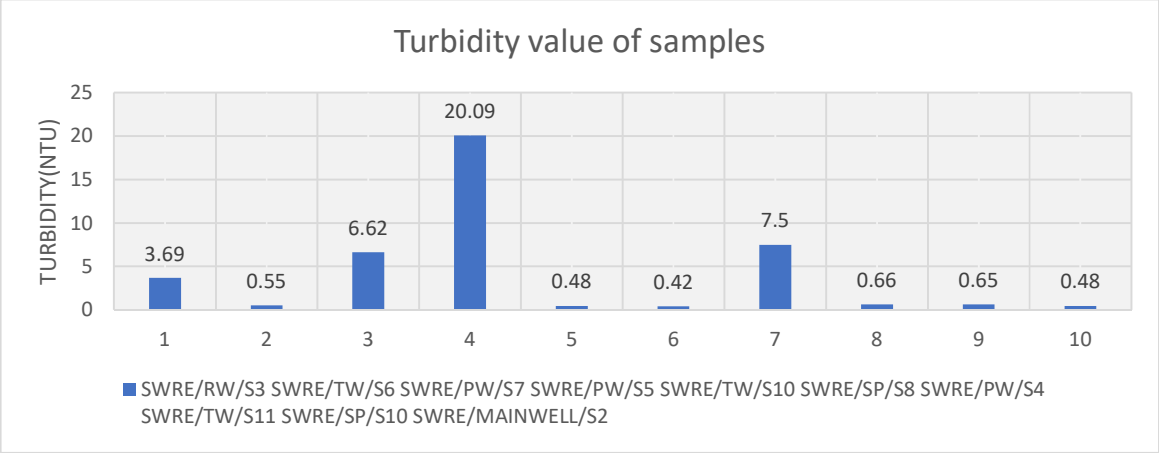


Figure 6.4.1: Turbidity of Collected Sample

6.4.2. Chemical Test

Chemical tests are done for all the samples collected from Bardhhaman district and discus it bellows,

- **pH:**

pH of all the samples is with in limit according to IS 10500:2012, that is 6.5 to 8.5. Highest pH level found in sample ID PW/S4. Figure 6.4.2 is depicted the pH value of the collected samples.

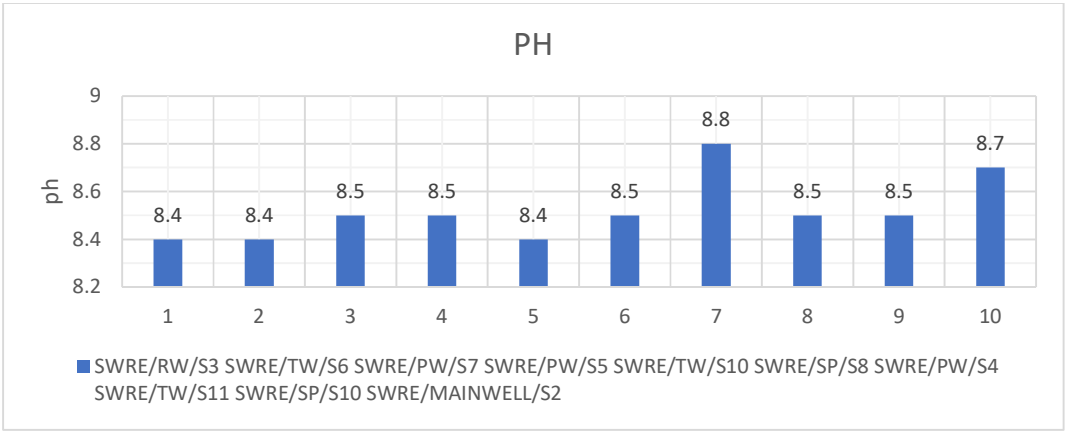


Figure 6.4.2.1: pH of Collected Samples

- **TDS:**

TDS of the samples are almost with in limit according to IS 10500:2012, that is 500 mg/l. Highest TDS level found in sample ID TW/S10 it is about 667 ppm which is greater than permissible limit and lowest in sample RW/S3,PW/S7 the value is 192 ppm.
Figure **6.4.** shows the variation of TDS of all collected samples.

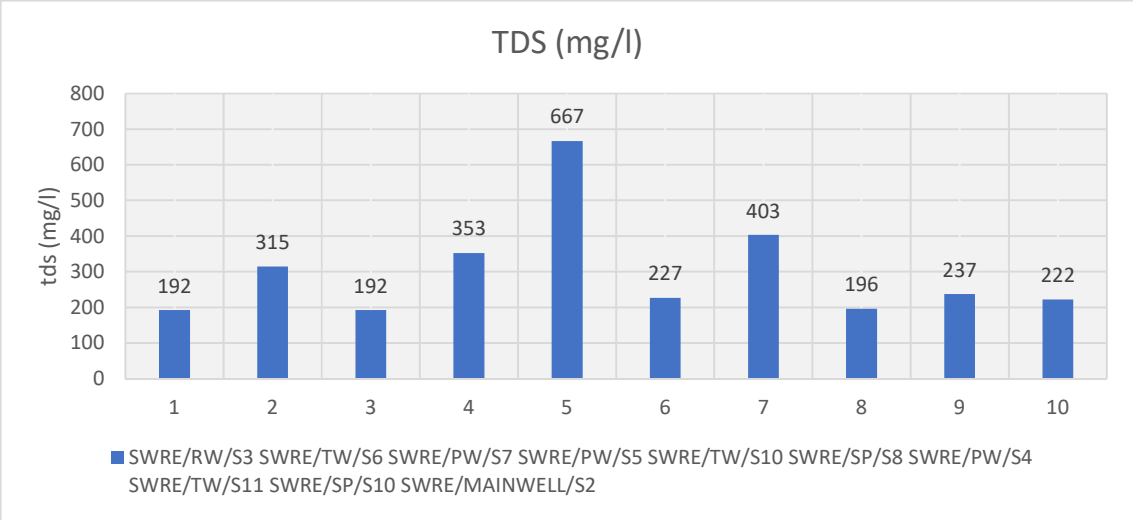


Figure 6.4.2.2: TDS of Collected Samples

- **Nitrate**

Nitrate is also in permissible limit in all samples and highest concentration in sample ID PW/S-4 is 26 ppm and lowest in sample PW/S-7 the value is 2.4 ppm. Figure 6.**3** depicted the Nitrate concentration of the samples.

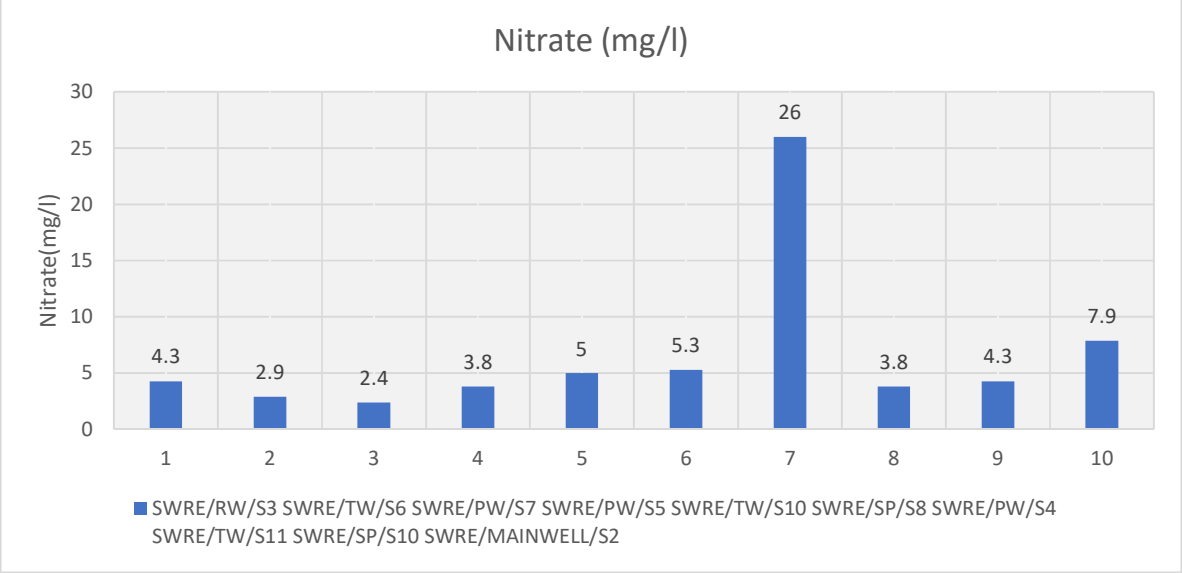


Figure 6.3.2.3: Nitrate of Collected Samples

Sulphate:

Permissible limit of sulphate is 200 ppm as per IS 10500:2012. All the samples are with in permissible limit. Figure 6.4.2.4 is depicted the value of sulphate of collected samples.

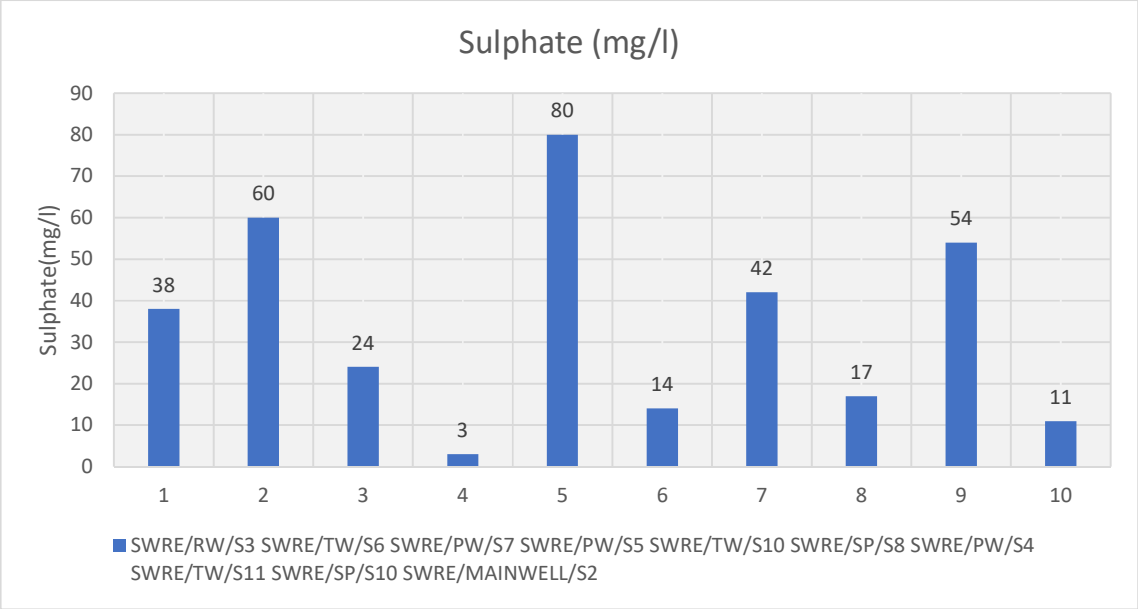


Figure 6.4.2.4: Sulphate of Collected Samples

- **Iron:**

Permissible limit of iron is 1.0 ppm as per IS 10500:2102. In following samples there is 1 sample which is more than permissible limit. The sample is PW/S-7, more than permissible value. The concentration of Iron is shows in Figure .

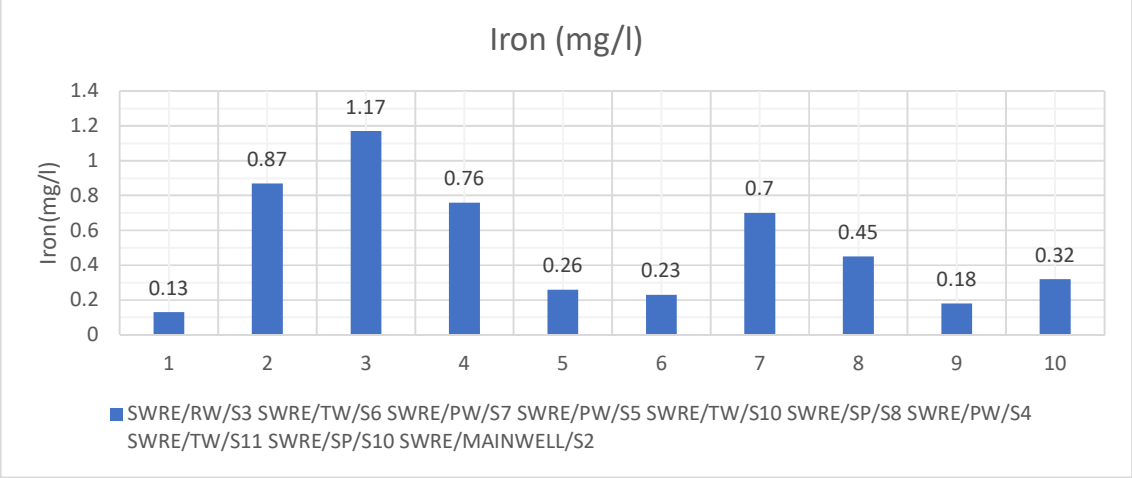


Figure 6.4.2.5: Iron of Collected Samples

- **Ammonia:**

Permissible limit of Ammonia is 0.5 ppm as per IS 10500:2102. In following samples there are four samples which are more than permissible limit. The samples are TW/S-6, PW/S-7, PW/S-5, PW/S-4 The level of Ammonia is shown in Figure .

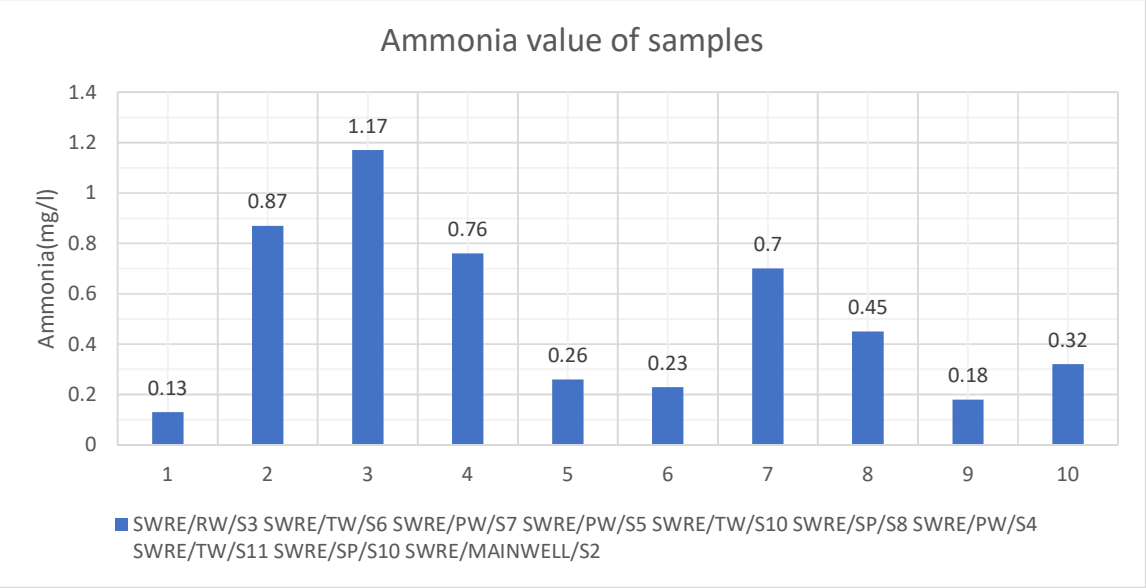


Figure 6.4.2.6: Ammonia of Collected Samples

- **Endosulfan Sulphate**:

In the river water, the concentration of endosulfan sulphate was found to be 0.12 µg/l. After 980 minutes of pumping, the concentration in the well water decreased to 0.01104 µg/l. Subsequently, when this well water was treated using the Multi-Stage Filtration (MSF) system, the concentration was further reduced to 0.0916 µg/l. The percentage removal of endosulfan sulphate in the well water and the MSF system were 8% and 23.64%, respectively, as shown in Figure 6.4.2.7 and Figure6.4.2.8 These results assume that the river water is infiltrating into the well through bank filtration, which is supported by the observed total dissolved solids (TDS) and bacteriological values.

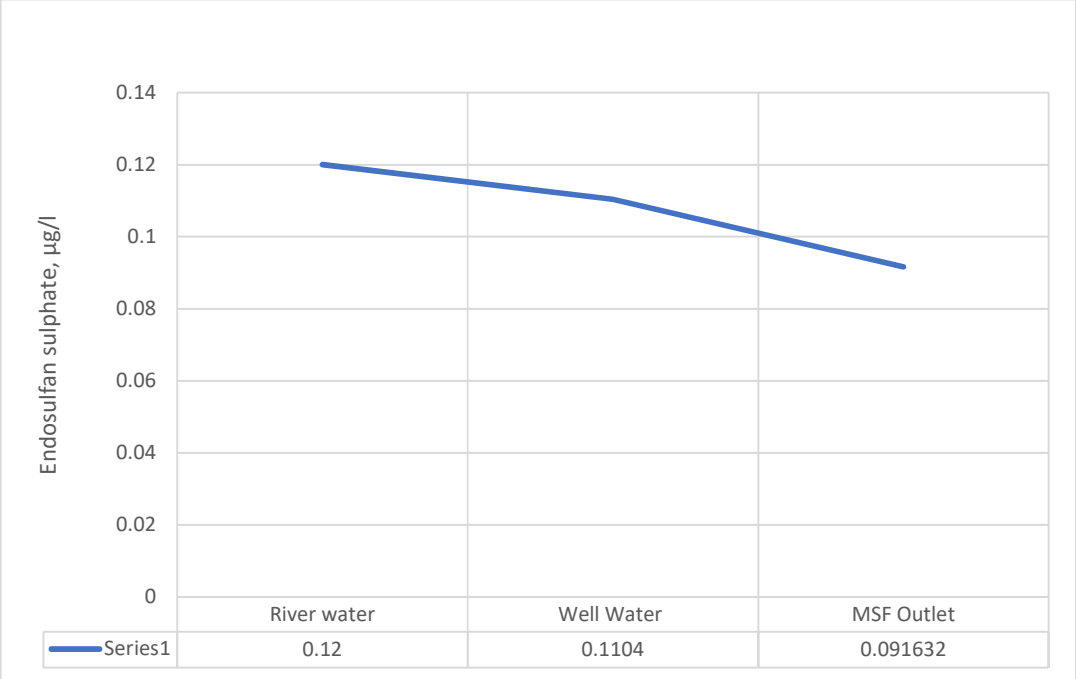
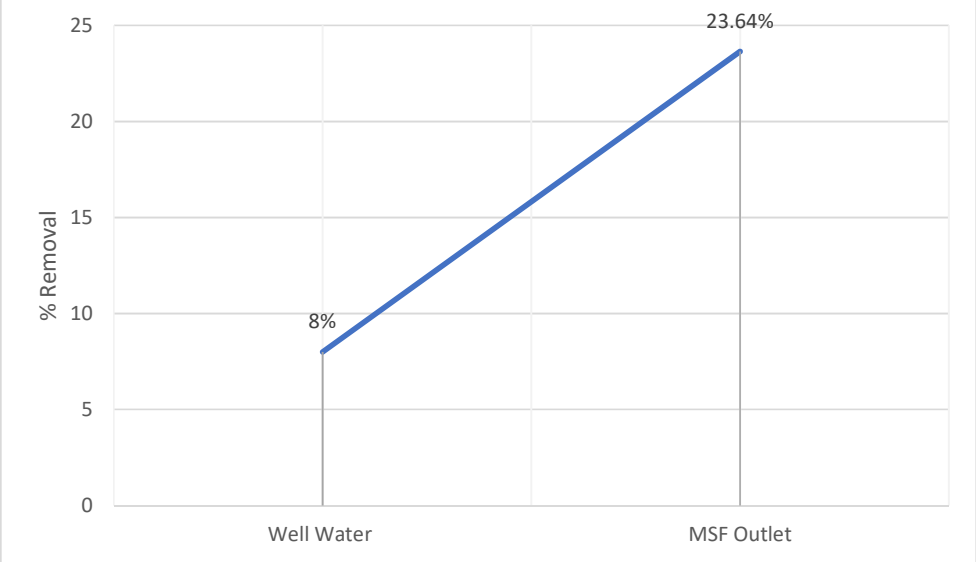


Figure6.4.2.7: Endosulfan Sulphate of Collected Samples



6.4.3. **Bacteriological Test of water**:

Table 6.4.3.1 Bacteriological lab Test Report:

Bacteriological Quality	TIME	TC (Total Coliform)	FC (Fecal Coliform)
WELL	-10	18	3.78
WELL	10	11	2.42
WELL	100	160	45
WELL	1000	750	172.5
WELL	1500	955	220

- Field Samples of Various Pumping well from Bardhhaman district was collected and tested in the laboratory. The measured of Total Coliform (TC)and Fecal Coliform (FC) are shown in Figure 6.4.3.1 and Figure 6.4.3.2

- **Total Coliform (TC**): Shows an initial decrease followed by a continuous and significant increase, indicating worsening water quality over time.

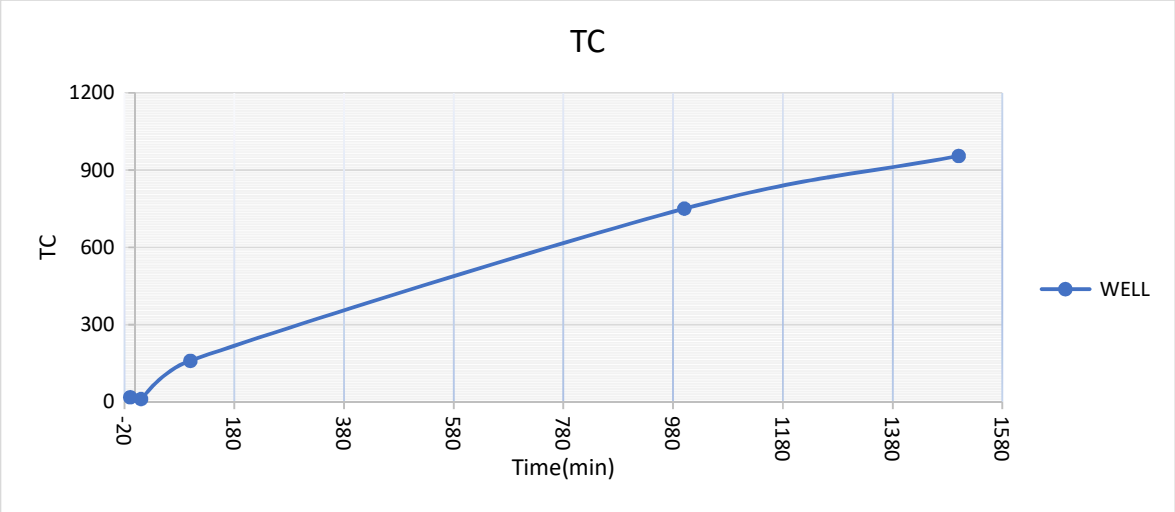


Figure: 6.4.3.1: Total Coliform

- **Fecal Coliform (FC):** Follows a similar pattern as TC, with initial reduction and subsequent significant increases, pointing to increasing fecal contamination.

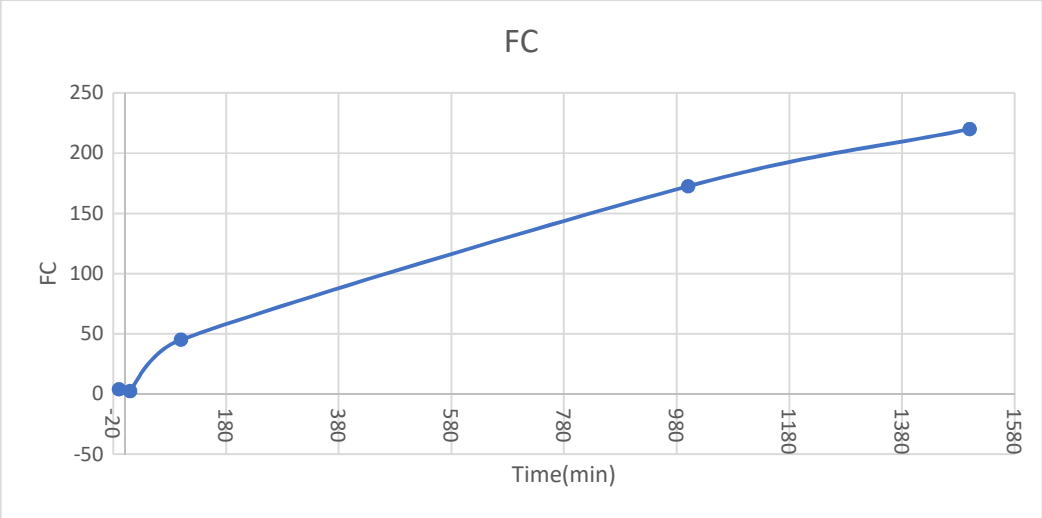


Figure:6.4.3.2: Fecal coliform

This analysis suggests that while there may have been an initial improvement in bacteriological quality, the overall trend indicates a significant and continuous increase in contamination levels, posing potential health risks. Further investigation and corrective actions are necessary to address this worsening water quality.

Table 6.5: SSF MODEL DATA TABLE:

The table below provides a detailed analysis of the total coliform (TC) and fecal coliform (FC) levels at different points in a treatment system over several weeks:

Date	Day	Inlet	Outlet -1	Outlet -2	Outlet -3	Outlet 1% (RE)	Outlet 2%(RE)	Outlet 3%(RE)
19-1-2024	1	1497	200	204	197	86.64	86.37	86.84
26-1-2024	8	1405	191	176	203	86.41	87.47	85.55
03-02-2024	16	1626	149	159	157	90.84	90.22	90.34
11-02-2024	24	1429	170	170	174	88.10	88.10	87.82
19-02-2024	32	1506	156	144	146	89.64	90.44	90.31
27-02-2024	40	1488	148	165	142	90.05	88.91	90.46
03-03-2024	47	1521	162	159	150	89.35	89.55	90.14
10-03-2024	54	1492	139	159	139	90.68	89.34	90.68
17-03-2024	61	1689	144	149	145	91.47	91.18	91.42

The SSF model demonstrates strong and consistent performance in reducing total coliform and fecal coliform levels. The treatment system maintains high efficiency, with reduction percentages consistently above 85% and often reaching above 90%. This indicates robust treatment capabilities, ensuring that the water quality meets safety standards.

7.CONCLUSION & RECOMMENDATION:

The integration of riverbank filtration (RBF) with multistage filtration techniques, including roughing filters, slow sand filters, and activated carbon, has proven to be highly effective in addressing the challenge of removing emerging contaminants in rural areas of West Bengal, India. The comprehensive study achieved its objectives and yielded significant results, as summarized below:

- **Sustainable Withdrawal Quantity Assessment:**

Pumping tests and well field design successfully evaluated the sustainable withdrawal quantity of sub-surface water in the riverbank, ensuring long-term viability and minimal ecological disruption.

Transmissivity and Storativity measurements indicated an average transmissivity of 1956 m^2/day, demonstrating ample water availability for extraction.

- **Well Field Design:**

The proposed well field design, consisting of seven wells spaced 52 meters apart and each pumping 800 m^3/day, ensures the required water supply while maintaining drawdown within acceptable limits.

- **Grain Size Distribution Analysis:**

Mechanical sieve analysis guided the selection of appropriate gravel pack materials for artificial packing around pumping wells, ensuring optimal filtration efficiency.

- **Effectiveness of Filtration Systems:**

The combined use of RBF with multistage filtration techniques demonstrated superior effectiveness in removing emerging contaminants from raw water sources.

Individual systems and their combination surpassed performance expectations, with notable contaminant removal rates and minimal fouling. Chemical tests indicated compliance with permissible limits for parameters such as pH, TDS, nitrate, sulphate, iron, and ammonia, with occasional exceptions.

Bacteriological tests revealed initial improvements but a subsequent increase in contamination levels over time, emphasizing the need for continuous monitoring and corrective actions.

The multistage filtration system effectively reduced endosulfan concentration from river water to well water, achieving a significant percentage removal, thereby enhancing water safety.

- **Novel Methods and Natural Filtration:**
  Exploration of novel natural filtration methods further enhanced water quality and reduced operational complexities, showcasing potential sustainable solutions for rural water treatment.

In conclusion, the study underscores the potential of integrated filtration systems to provide sustainable and reliable water supply in rural areas, offering scalable solutions adaptable to varying environmental conditions. Continued research and implementation efforts are essential to ensure long-term water quality and community well-being.

8. **LIMITATIONS OF THE STUDY**:

- Regional Specificity: The study's findings are largely based on conditions in rural areas of West Bengal, India, and may not be directly applicable to other geographical regions with different hydrogeological characteristics or contaminant profiles.

- Short-term Assessment: While the study provides insights into the effectiveness of the integrated filtration systems in the short term, long-term performance and sustainability need further evaluation. Monitoring over extended periods could reveal potential issues such as system degradation, unexpected contaminant breakthrough, or changes in water quality parameters.

- Limited Contaminant Scope: The study primarily focuses on addressing emerging contaminants and may not comprehensively cover all potential pollutants present in the water sources. Future research could expand the analysis to include a broader range of contaminants, including microbial pathogens and emerging pollutants not addressed in this study.

- Bacteriological Challenges: Despite initial improvements in bacteriological water quality, the observed increase in contamination levels over time highlights challenges in maintaining microbial control. Further investigation into the causes of bacterial regrowth and the development of effective mitigation strategies is necessary.

- Operational Scalability: While the integrated filtration systems show promise for rural areas, scalability to larger populations or different infrastructure settings may pose challenges. Future studies should address the scalability of these systems and potential modifications needed for implementation in various contexts.

9.**FUTURE SCOPE OF THE STUDY**:

- Long-term Monitoring: Continued monitoring of water quality and system performance over an extended period will provide valuable insights into the sustainability and resilience of integrated filtration systems. Longitudinal studies can help identify trends, anticipate challenges, and inform adaptive management strategies.

- Expanded Contaminant Analysis: Future research should explore additional contaminants of concern, including emerging pollutants, microbial pathogens, and contaminants specific to regional or local sources. This comprehensive approach will enhance the effectiveness of filtration systems and ensure the safety of drinking water supplies.

- Technological Innovations: Continued research and development efforts should focus on exploring new technologies and innovations to improve the efficiency, reliability, and affordability of integrated filtration systems. This includes advancements in filtration media, sensor technologies for real-time monitoring, and automation for optimized system operation.

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