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Sustainable Water Management

Editors:
Prof. M. L. Meena
Prof. Yashodhara Varale
Dr. Krishan Kant Upadhyay
Dr. Prasenjit Talukdar

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Editors

Prof. M. L. Meena

Department of Geography,

School of Basic Sciences,

Central University of Haryana,

Mahendragarh (HR)

Prof. (Dr.) Yashodhara Varale

I/C Principal and Head,

Department of Environmental Studies,

Dr. Ambedkar College of Commerce and

Economics, Wadala, Mumbai

Dr. Krishan Kant Upadhyay

Department of Chemistry,

Kamla PG College,

Dholpur, Rajasthan

Dr. Prasenjit Talukdar

Department of Petroleum Engineering,

Dibrugarh University Institute of

Engineering and Technology (DUIET),

Dibrugarh University, Assam

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PREFACE

Water is one of the most vital resources for life on Earth, yet its sustainable management remains a significant global challenge. The growing demands of an expanding population, coupled with the adverse effects of climate change, urbanization, and industrialization, have placed unprecedented pressure on water resources. Addressing these challenges requires innovative strategies, interdisciplinary collaboration, and a commitment to preserving this invaluable resource for future generations.

The book Sustainable Water Management is an effort to explore and present a wide spectrum of insights, research findings, and practical solutions related to the sustainable use and management of water resources. It brings together contributions from researchers, practitioners, and experts from diverse fields, offering a holistic perspective on water management practices, technologies, and policies.

This book is structured to address both foundational and advanced concepts. It covers topics such as water conservation techniques, the role of technology in water treatment, the impact of governance and policy frameworks, and the integration of traditional knowledge with modern practices. By including case studies from various regions, the book highlights the successes and challenges faced in implementing sustainable water management solutions in different socio-economic and environmental contexts.

Our aim as editors is to provide a platform that fosters dialogue and inspires action. We believe that sustainable water management is not merely a technical challenge but a shared responsibility that requires collective effort across sectors and disciplines. This book is intended to serve as a valuable resource for policymakers, researchers, educators, students, and all those committed to ensuring water security and environmental sustainability.

We extend our gratitude to the contributors whose expertise and dedication have enriched the content of this book. We also thank the institutions and organizations that support research and initiatives in sustainable water management, as their efforts play a pivotal role in shaping a better future.

It is our hope that this book will spark new ideas, promote collaboration, and encourage readers to take meaningful steps toward sustainable water management practices. Together, we can work toward safeguarding this precious resource for generations to come.

- Editors

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Prasenjit Talukdar*[1], Gaurav Himanta Khaklari[2],
Kishan Kumar Dey[1] and Sabiha Swavnam[1]
[1]Department of Petroleum Engineering, DUIET,
[2]Department of Petroleum Technology,
Dibrugarh University, Dibrugarh, Assam 786004
*Corresponding author E-mail: prasenjit_duiet@dibru.ac.in

Abstract:

Today fossil fuels contribute more than 80% of the world's energy. To meet the global energy demand, the Exploration and Production (EandP) companies are facing pressure to increase production every year. But the repercussion of the rapidly increasing petroleum industry is the generation of a large volume of produced water (PW) /wastewater during drilling and production operations. In a drilling operation, two major wastes are produced i.e., produced water (PW) and drilling waste (drill cuttings etc.). So, drilling waste must be properly managed before disposal or reuse to ensure no impact to the environment. In production operation the main waste is the PW during the production of hydrocarbon. PW associated with petroleum industry can contain various organic and inorganic chemicals, metals, total dissolved solids (TDS) etc., which have adverse impact on human health, aquatic life and the environment. Due to all these negative impacts to living organisms many countries have stringent their wastewater disposal laws, so selecting an efficient and environment friendly PW treatment process has become the main focus for the oil and gas industry. PW treatment can be done using different physical, chemical, and biological methods. Many chemical and biological methods were found to be very effective for removing most of the pollutants from PW, but they were not eco-friendly these methods were found to produce secondary pollution harmful for the environment, so they required further treatment before disposal making them very expensive. So, the industry is trying to shift towards eco-friendly physical and some novel treatment technologies like membrane separation technologies, advanced oxidation processes (AOPs) etc. This study focusses on giving an idea of the different types of pollutants that are produced along with the

wastewater, their environmental impact and lastly discuss some of the treatment technologies along with some of the eco-friendly management technologies for wastewater produced during drilling and production operation in the oil and gas industry.

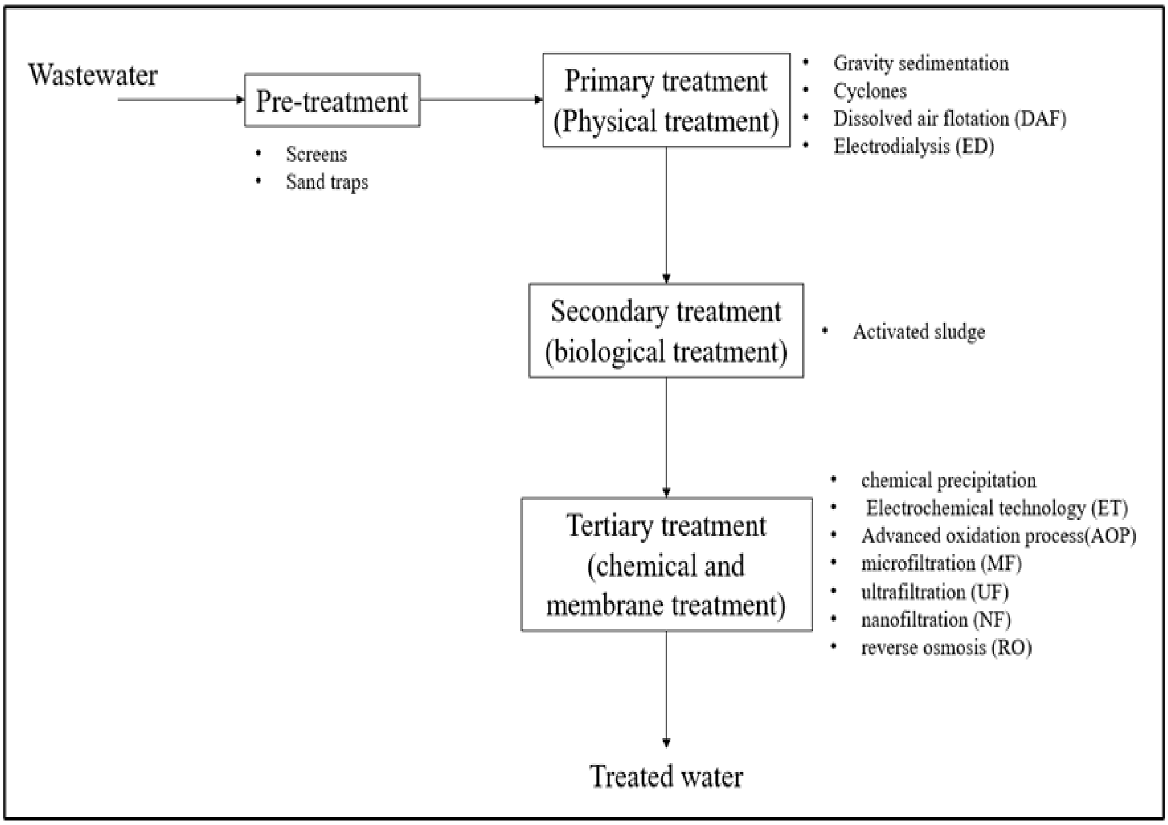

Figure 1: Flowchart of the processes for PW treatment

Keywords: Environment-Friendly Management; Produced Water; Drilling Waste; Organic/Inorganic Compounds; Eco-Friendly Treatment

Introduction:

The production of oil and gas in the modern era began from the year 1859 in Titusville, Pennsylvania. Since then, several wells have been drilled all over the world to extract the oil and gas. But with the production of oil and gas certain byproducts are also produced like the produced water and drilled cuttings. This produced water (PW) is considered as the major source of waste that is generated during the operational lifetime of a well, and the second source of waste is the drill cuttings that are produced during the drilling operation (Hao *et al.,* 2019)(Olajire, 2020). With the growing demand for energy and the discovery of new petroleum reservoirs every year, the EandP companies are facing new challenges of pollution prevention and waste management to not cause more straining damage to nature. The petroleum industry is a complex and integrated industry that includes a large variety of activities starting with oil and gas exploration. The first task of upstream petroleum companies is to drill holes in the targeted area. But it has a great repercussion on the environment. From exploratory drilling to development and expansion all drilling projects have long term environmental consequences(Ite *et al.,* 2013)(Hazard, 2018). Drilling fluid waste and drill cuttings from large-scale drilling projects release a variety of pollutants into water streams. Drilling fluid is a mixture of mud, clay, and chemical additives, which aid drilling but contains toxic and hazardous components. It often gets contaminated with formation fluids, BTEX, acid gases, PAHs, and toxic metals, increasing turbidity, salinity, and sedimentation, thereby degrading water quality. Until the mid-1990s, oil hydrocarbons from offshore drilling mud cuttings were a significant pollutant of marine environments. Drilling activities are also believed to interfere with surface and groundwater flows, according to research (Ahmadun *et al.,* 2009). Another by-product is produced water, which contains organic and inorganic contaminants such as BTEX, NPD, PAHs, phenols, heavy metals, and radioactive materials. It therefore has high pH, salinity, and pollution of natural water bodies, thereby affecting ecosystems and human health if not well managed. Further increase in demand and development of technologies like hydraulic fracturing has also lead to the huge increase in the quantity of PW (Silva *et al.,* 2017). This huge quantity cannot be dicharged entirely into different water bodies, instead reuseing a portion of this PW in different activities like reinjection (waterflooding), cleaning in refineries, household use etc. would be more economical (Gray, 2020). But before reusing or discharging the PW proper treatment of the PW is essential. This paper aims at reviewing different traditional and novel technologies that can be used to treat the wastewater produced during the oil and gas exploration operation. Also, to compare different treatment technologies to find the most environment friendly technology.

Sources of wastewater in the oil and gas industry:

There can be many sources of wastewater in the oil and gas industry. The two main sources of wastewater are drilling fluid wastewater produced during drilling operation and the water produced during production operation which is commonly referred to as produced wastewater/produced water (PW).

Drilling fluid wastewater:

There are two types of waste produced in drilling operation- drilling fluid waste and drill cuttings. Drilling mud—also called drilling fluid—is an essential component of the drilling process. Mud aids in the process of drilling a borehole into the earth. During drilling process numerous chemicals and additives are added into the mud system. These chemicals always have high toxicity. Also, during processing muds become saturated with components like (i) hydrogen sulphide, (ii) diesel fuel, (iii) methane, (iv) benzene, toluene, ethylbenzene, and xylenes (BTEX) (v) nitrogen oxides, (vi) toxic metals, (vii) polycyclic aromatic hydrocarbons, (viii) sulphur dioxide. Impacts to water resources could occur due to water quality degradation from increases in turbidity, sedimentation, and salinity; spills; cross-aquifer mixing; and water quantity depletion. Moreover, the drilling activities may affect surface and groundwater flows. So, the adverse impact on environment and human health could results if hazardous wastes are not properly handled and directly release to the environment.

Ensuring safe management of drilling wastewater:

Generally waste management practice is "compliant, cost-effective management of the minimum waste''(Qin *et al.,* 2009). The management practices can be categorized into three groups: waste minimization, recycle/reuse, and disposal.

Waste Minimization:

The most effective method to treat waste is to reduce its creation at the drilling site. Various technologies like directional drilling, small hole sizes, and low-fluid drilling techniques reduce waste generation. Environment-friendly drilling fluids, such as Synthetic-Based Muds (SBM), also significantly decrease environmental impacts. Although invented in the 1990s, SBM can boast of a performance equivalent to oil-based muds (OBM) with a quicker rate of penetration and fewer non-productive time (NPT). Though expensive, SBM is inexpensive in offshore applications since it has a higher biodegradability level, a low toxicity rate, and environmental acceptability. These factors have made it superior to conventional OBM. (Bakhtyar and Gagnon, 2012).

Some of the techniques to minimize the environmental impact of drilling include pneumatic drilling, slim hole drilling, solids control, and mud system monitoring. Pneumatic drilling uses compressed air or gas instead of fluids and has fewer wastes and space requirements but needs special equipment. Slim hole drilling involves wellbores of 6 inches or smaller and reduces waste and wastewater drastically. Solids control methods such as shale shakers, hydrocyclones, and centrifuges clean drilling fluids, preserve mud properties, and reduce waste. Proper monitoring of the mud system ensures optimal fluid selection, which improves performance and safety while minimizing environmental risks and costs (Mellott and Co, 2006)(Javad *et al.,* 2014)(Bose *et al.,* 2019).

Recycling and reuse of Muds:

Reusing drilling mud helps the operator to meet up with the environmental regulations and concerns. Reusing drilling fluid from well to well is highly dependent on the condition of the fluid at the end of the previous well. Not all drilling fluid can be re-used. In some cases, OBM and SBM can be reused or recalculated after the completion of the drilling operation. This helps in the reduction of the generation of drilling wastewater. Currently, various techniques are there to clean the used mud for reuse. Then the base fluid as well as any leftover mud from the previous well is stored for the next wells. Generally drilling mud operators either go for the approach of reusing the whole mud or closed-loop drilling system. In closed loop system mud are captured from drilling rig. After that drill cuttings are removed and with the help of some specified chemical quality of mud are maintained. When mud degraded entirely and can't be recycled, they can be used for making cement. Reusing/recycling drilling mud is gaining much attention lately due to cost-effectiveness and environmental factor.

Treatment and disposal:

Operators are being increasingly restrained in the handling and discharge of drilling wastewater, which contains dissolved solids, metals, NORM, oil, grease, and organics. All these require treatment for surface disposal, depending on the type and concentration of contaminants present. Common treatments include primary treatments such as gravity separation, dissolved or induced air flotation; secondary treatments (coagulation, flocculation, biological process); and tertiary treatments (advanced oxidation, membranes, electrocoagulation, thermal processes). Treated water may be released to waters, but in very sensitive environments, there is strict requirement for injection underground or into commercial facilities.

Produced water:

Produced water (PW) is a byproduct of hydrocarbon production, which comes from formation water or injected fluids used to maintain reservoir pressure or enhance recovery. PW production has increased globally to 250 million barrels per day, three times that of oil (Ahmadun *et al.,* 2009). PW is known to have harmful materials such as dissolved solids, including sodium, chloride, and phosphate; hydrocarbons; and NORMs, which could harm the environment and wildlife (Chittick and Srebotnjak, 2017). Thus, proper treatment of PW should be carried out, either for reinjection into formations or to avoid causing harm to the environment.

Characteristics of the produced water:

A basic understanding of the characteristics of the PW is essential before undergoing any further treatment. Although the overall characteristics of the PW are the same which is mainly due to the mixture of organic and inorganic compounds, but depending on the geological location, formation, reservoir age, reservoir history, type of HC produced, or types of chemical additives used to enhance HC production some characteristics may vary (Olajire, 2020)(Ahmadun *et al.,* 2009). *Olajire (2020)* mentioned that this can make properties of PW differ in different regions. The organic compounds that are generally found mixed with PW are HC chains like benzene, toluene, ethylbenzene, xylene (BTEX), naphthalene, phenanthrene, polycyclic aromatic hydrocarbons (PAHs), and apart from these HC compounds, organic substances like carboxylic acids, alcohols, aldehydes, ketones, phenols, organic oxygenate, heterocyclic compounds containing nitrogen or other elements waxes, surfactants, biocides are also found. According to *Liu et al. (2021)* this HC compounds mixed with PW is considered to the most hazardous component (Hazard, 2018). PW also contains inorganic compounds like calcium, magnesium, potassium, bicarbonate, bromide, barium, iron, zinc etc., also anions and cations of various minerals out of which chloride and sodium concentrations are generally on the higher side (Ahmadun *et al.,* 2009). *Ahmadun et al. (2009)* categorized PW components into: (1) dissolved/dispersed oil compounds, (2) dissolved formation minerals, (3) production chemicals, (4) produced solids, and (5) dissolved gases. Dissolved oils include water-soluble organics like formic acid, BTEX, and phenols, while dispersed oils include PAHs and heavier alkyl phenols (C_6–C_9). Dissolved minerals include cations such as Na^+, Ca^{2+}, Mg^{2+}, and Fe^{2+}; anions include Cl^- and SO_4^{2-}; heavy metals include Cd, Pb, and Hg; and NORMs such as Ra226 and Ra228. Production chemicals include polar compounds like LAS and imidazolines. Produced solids include formation solids, scale, bacteria, waxes, and suspended inorganics like SiO2 and BaSO4. Dissolved gases include CO_2, O_2, and H_2S (Ahmadun *et al.,* 2009).

Sun *et al.* (2019) reported that hydraulic fracturing (HF) shale wells produce 210,000–2,100,000 gallons of wastewater over their lifetime, with daily flow rates of 200–800 gallons (Chittick and Srebotnjak, 2017). HF produced water (PW) contains high organic compound concentrations, raising total organic carbon levels to 1530 mg/L. Hazardous volatile organics, including benzene, carbon tetrachloride, and vinyl chloride, persist even after 250 days. Synthetic organics like dibromochloromethane and hexachlorobenzene also exceed safe levels, while compounds like naphthalene and diethylhexyl phthalate show risk quotients above 1. Inorganics include high levels of chloride, sodium, and iron (up to 1390 mg/L), while NORMs such as Ra^{226}, U^{238}, and Sr^{90} are commonly present, with Ra^{226} being the most prevalent (Sun *et al.,* 2019).

Management of produced water:

As mentioned in the earlier sections produced water (PW) contains a variety of hazardous compounds which are needed to be removed from the PW so that it could be used for different purposes. Ahmadun *et al.* (2009) in their paper mention that management of PW can be done in 4 ways: (1) injecting the PW in the same or other formation. (2) discharge of the PW into water bodies. (3) reuse for industrial operations, and (4) civil usage (Ahmadun *et al.,* 2009). All this usage of PW is only possible after the removal of all the hazardous compounds so proper treatment technology depending on the subsequent use of the PW and PW characteristics meeting all the necessary regulatory standards and environmental regulations should be adopted (Olajire, 2020). The main aim of PW treatment is to remove the dispersed oil, soluble organic, suspended particles, dissolved gases like CO_2 etc., salts, water hardness, NORMs, and disinfection of the PW. Physical, chemical, biological or the most recent membrane treatment technologies can be used for wastewater treatment (Ahmadun *et al.,* 2009). *Amit Sonune and Rupali Ghate (2004)* mentioned that the treatment process takes place in steps with the preliminary treatment at the beginning where coarse solids and other large materials like sand, metals, glass etc. are removed, next comes the primary treatment where physical methods are used to remove 50-70% of the suspended solids, 65% of oil and some amount of nitrogen, phosphorus, and heavy metals. The effluent from primary treatment mainly contains the colloidal and dissolved organic and inorganic solids which are further removed in the next step i.e., the secondary treatment where biological treatment is used to remove the dissolved organic compounds (Sonune and Ghate, 2004). Membrane technology which generally comes under the tertiary treatment process can also be combined with the biological treatment for better removal and it is referred to as the membrane bioreactor(MBR) technology (Olajire, 2020). After a proper primary and secondary treatment, 85% to 95% of the influent biochemical oxygen demand and total suspended solids could be removed from the wastewater but this number is not sufficient if the water has to be used in purposes like irrigation, drinking etc. So further advanced tertiary treatments are required to remove the remaining organic and inorganic materials (Sonune and Ghate, 2004). In tertiary treatment conventional chemical treatments like oxidation of the organic compounds by chemical oxidants, chemical precipitation, electrochemical process, or novel technique like advanced oxidation processes (AOPs) etc. are used (Crini and Lichtfouse, 2020)(Sonune and Ghate, 2004).

Primary treatment (Physical treatment technology):

Mentioned below are some of the physical treatment technologies that are currently used in the oil and gas industry:

Gravity sedimentation:

Gravity sedimentation is one of the most affordable and simple technology that can be used in the beginning of the separation treatment process to separate the dispersed and floating oil in water by using the difference in densities between them (Methods and Opportunities, 2021). *Liu et al. (2021)* in their paper mentioned that the using chemical agents, ultrasonic waves, microwaves, electric fields, and temperature fields can increase the efficiency of the separation process (Hazard, 2018). The study also mentioned about the enhanced gravity sedimentation technology where corrugated, inclined, parallel plates and other internal components with coalescing functions are coupled with the principle of the shallow pool that increases the efficiency of the separation process. According to *Liu et al. (2021)* gravity sedimentation and enhanced gravity sedimentation technology technologies would be very beneficial for offshore wells (Y. Liu *et al.,* 2021).

Abuhasel et al. (2021) mentioned that gravity sedimentation can be employed for the separation of oily wastewater, but it has some disadvantages like limited separation capacity, requires a large area for setup and complex management and operation.

Cyclones:

Cyclones can be of different types ofhydro cyclone is one of them, it is a static device that uses the centrifugal field for the separation process. The wastewater is injected into the cyclone at a relatively high speed through the inlet. The wastewater is subjected to a strong centrifugal field which is 100-1000 times stronger than the gravitational field, utilizing the density difference between oil and water. The light component i.e., oil is exerted out from the upper ports and heavy component i.e., water is exerted from the lower ports (Y. Liu *et al.,* 2021). Compact floatation unit (CFU) is a vertical separator vessel which is capable of separating three-phase water-oil-gas using centrifugal force and gas-flotation with an efficiency of about 50-70% dispersed oil removal. The treated water is collected at the bottom and oil/gas are removed from the top of the vessel.In offshore well rigs because of space constraints, compact systems with small and light characteristics are favourable, so CFU becomes a great option for offshore facilities to remove solids and oil from offshore-produced water (Ahmadun *et al.,* 2009). In the offshore conventional air flotation equipment and CFUs are the two most used cyclones. But due to small area requirement of CFUs it is preferred over conventional air flotation equipment (Y. Liu *et al.,* 2021). *S. Liu et al. (2005)* in their paper mentioned about a double cone air sparged hydro cyclone (DCASH) which was able to give a separation efficiency of around 90% when used for the treatment of produced water (PW) by during polymer flooding which is difficult to treat with other methods due to high viscosity and very small oil droplet size present in the PW (S. Liu *et al.,* 2005).

Dissolved Air Flotation (DAF):

Abuhasel *et al. (2021)* mentioned dissolved air flotation (DAF) technology to be one of the best physical separationtechnologies for the treatment of oily wastewater. The principle of DAF is to inject air under a particular pressure at the bottom of an open chamber, and as the air bubbles rise to the top of the chamber the oil or suspended solid pollutants are attached to the air bubbles. DAF is of 2 types and based on the method of bubble generation DAF can be classified into dissolved and induced (diffused) DAF (Y. Liu *et al.,* 2021). DAF generates microbubbles with sizes ranging from 20–100 microns. The microbubbles attach to the oil droplets to form agglomerates and increase the droplet's buoyancy to move upward. Pressure, and saturation of air in the wastewater the major parameters to be considered during this process. The pressure required for the process must be reduced to the atmospheric pressure condition along with excess gas dissolved in the system (Methods and Opportunities, 2021). The separation of oil and water by DAF technique is based on the Stokes' law (Olajire, 2020).

Electrodialysis (ED):

Electrodialysis (ED) a membrane and a pair of electrodes are used to separate the dissolved salts i.e., the cations and anions of calcium, magnesium etc. The membranes allows either cations or anions to pass through them and the ions are attached to the electrodes with a separate charge. This treatment technology is beneficial for PW having low concentration of dissolved solids (Ahmadun *et al.,* 2009).

Secondary treatment (Biological treatment technology):

Biological treatment technologies can be used to separate biodegradable organic matter contained in wastewater by converting them into simpler substances and additional mass (biomass)by adding a wide variety of microorganisms, and then the biomasswhich is formed from the biosynthetic transformation of the colloidal and dissolved organic matter can be separated from treated wastewater through sedimentation. The added microorganisms consume the dissolve contaminants in the wastewater in a tank called bioreactor tank to form additional biomass (sludge). The water is washed out of the reactor for clarification leaving behind the sludge (solid waste) containing both live and dead bacteria, at the bottom of reactor. *Olajire (2020*) in his paper also found that bioreactor-based methods were more suitable than the traditional activated sludge systems for the biological treatment of PW because of some inherent advantages like precise management and control of the biodegradation parameters, toxic resistant of the immobilized biomass, increased mass transfer between all phases in the bioreactor (Olajire, 2020).

Ahmadun *et al. (2009)* in their mentioned about the use of aerobic and anaerobic microorganisms for biological treatment of produced wastewater. Activated sludge which is used for aerobic biological treatment is one of the common methods for treating wastewater.

In their experiment they used atotal petroleum hydrocarbon (TPH) removal efficiency of 98-99% for 20 days. Their paper also discussed about the biological oxidation treatment where harmless bacteria, algae, fungi, and protozoa were used to convert dissolved organics and ammonia compounds into water and CO_2, nitrates/nitrites, respectively (Ahmadun *et al.,* 2009). When the wastewater is highly concentrated with pollutants than anaerobic degradation of pollutants rather than aerobic degradation would be a cost-effective alternative (Tchobanoglous *et al.,* 2003).

Tertiary treatment:

Tertiary treatment of PW is generally divided into two types: chemical treatment technology and membrane technology.

Chemical treatment technology:

Chemical treatment technologies for example chemical precipitation involve dosing oily water with flocculants to neutralize the charge and help in flocculation which is based on the kind of flocculant added, its dosing quantity, the level of concentration of oil and temperature besides pH. In organic or inorganic flocculants, Abuhasel *et al.,* (2021) mentioned electrochemical technologies among which the electroflotation, electrocoagulation and electroflocculation are included. ETs is usually combined with the other method for effective operations. The electrochemical cells of ET systems make use of the applied potential, which allows for direct oxidation or indirect electro-oxidation of oil into CO_2, H_2O, or biodegradable by-products. (Methods and Opportunities, 2021). Although conventional chemical methods were found to be quite efficient in removing the pollutants in PW but most of the process involved production of non-biodegradable by-products causing secondary pollution.

Olajire *(2020)* in his paper mentioned about a eco-friendly chemical treatment named advanced oxidation processes (AOPs) where extremely reactive hydroxyl radicals (HO•) are generated to attack the electron-rich recalcitrant organic compounds like BTEX, phenols and acetic for the complete oxidation of such pollutants in PW and produce a less toxic intermediate product. This technology was also found to be highly cost effective and had the ability to mineralize a wide range of organic pollutants (Olajire, 2020).

Membrane technology:

Although there are several efficient biological and chemical treatment technologies for the treatment of PW but due to high cost for the treatment process, use of toxic chemicals for the treatment which causes secondary pollution research are going on to find efficient and eco-friendly treatment alternatives. Physical and membrane-based separation treatment became the promising technology for the 21st century. The membrane treatment relies on the pore size of the membrane to separate the components in PW according to their pore size (Sonune and Ghate, 2004).

Madaeni (1999) mentioned in his paper that membranes are capable of removing a wide range of biological and non-biological substances from PW. Membranes were also found capable of eliminating viruses, bacteria, and other microorganisms from wastewater either completely or most of it. There are different types of membrane separation processes namely microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) membrane processes. Membranes are made up of thin films of synthetic organic or inorganic materials having different pore sizes which selectively separate the pollutants from the fluid. MF can be used for separation of suspended particles, UF for the separation of macromolecules, and RO for the separation of dissolved and ionic components (Mellott and Co, 2006). And NF membranes can be used for separation of multivalent ions (Ahmadun *et al.,* 2009).

Olajire (2020) described microfiltration (MF) membranes with pore sizes ranging from 0.1 to 10 μm, which enable water, metal ions, and viruses to pass but reject bacteria, protozoa, and suspended solids. MF membranes are applied to remove color, odor, viruses, and colloidal organic matter. However, the efficiency is lowered due to biofouling and clogging caused by the buildup of microorganisms, which necessitates periodic backwashing and chemical cleaning (Olajire, 2020). Several research has been conducted to reduce the membrane fouling and it was found that combining the MF process with pre and posttreatment steps can reduce membrane fouling (Ebrahimi *et al.,* 2010).

Ultrafiltration (UF) membranes, with pore sizes of 0.01–0.1 μm, can efficiently remove bacteria, viruses, silica, proteins, plastics, and hydrocarbons. Compared to microfiltration (MF). UF membranes operate at slightly higher pressure for the efficient removal of oil, suspended solids, and dissolved constituents from produced water (PW). Kong *et al.* (2017) noted that the UF membrane, with added coagulation, successfully removed 32.5–83.3% of the dissolved organics from the hydraulic fracturing wastewater of Fuling Shale in China. (Kong *et al.,* 2017)(Olajire, 2020). The pores in NF membranes have diameters of 0.001–0.01 μm, retaining all the divalent ions and particles that are larger than that diameter while rejecting more than 99% of them, yet they can pass monovalent ions, like sodium chloride. NF is effective in removing metals and other contaminants of that size but is unsuitable for desalination. Sadrzadeh *et al. (2018)* reported that NF membranes could remove up to 98% of TDS, TOC, and dissolved silica, this is superior to the conventional treatment processes for SAGD-produced water. (Sadrzadeh *et al.,* n.d.). Their finding further indicated that more than 99% removal efficiency of divalent ions was achieved with the use of tight NF membranes. Riley *et al. (2018)* evaluated the use of close circuit desalination with nanofiltration (NF) and reverse osmosis (RO) to remove the total dissolved solids (TDS) and organic matter from pre-treated PW (Riley *et al.,* 2018). Their results showed removal efficiencies of 99.6% and 89% for TDS and dissolved organic carbon (DOC), respectively from PW to produce high quality water, thus suggesting close circuit desalination as a promising method to facilitate the reuse of PW. Reverse osmosis (RO) is another type of membrane separation technology which has a pore sizeless than 0.001 μm, smaller than that of NF. It can be used for effective removal of contaminants as small as 0.0001 μm. RO membrane technology with adequate pre-treatment has been reported to be efficient for PW treatment, with a life expectancy of 3–7 years. RO was found to remove all ionic compounds and only water molecules pass through the membrane and rejection of solutes from PW was mostly more than 99% (Olajire, 2020). *Ebrahimi et al. (2009)* investigated ceramic membranes combined with pre-treatment (MF or DAF) and post-treatment (UF and NF) processes for oilfield produced water (PW). Their study showed oil removal efficiency reached 93% with MF pre-treatment and up to 99.5% using UF followed by NF. Backflushing was found more effective than chemical cleaning for fouled ceramic membranes. (Ebrahimi *et al.,* 2010).

Conclusion:

This review paper has been written to give an idea about the sources, characteristics and the how the waste produced during the drilling and production operations can affect the health of the living organisms. The paper starts with the different methods and technologies available to reduce, reuse (after treatment) and recycle the waste produced during the drilling operation. Different wastewater treatment technologies starting from the traditional primary, secondary, and tertiary technologies are discussed along with the novel treatment technologies like the advanced oxidation technology (AOP) and membrane technology. After studying the different technologies available for treatment, it was found that primary technology combined with AOP, or membrane technology could be the most effective and environment friendly way of treating the PW.

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DIFFERENT SOURCES OF WATER POLLUTION IN OIL AND GAS INDUSTRIES AND THEIR REMEDIAL MEASURES

Prasenjit Talukdar*[1], Gaurav Himanta Khaklari[2],

Nabanita Hazarika[1], Nitisha Das[1] and Mayuree Kashyap[1]

[1] Department of Petroleum Engineering, DUIET,

[2] Department of Petroleum Technology,

Dibrugarh University, Dibrugarh, Assam 786004

*Corresponding author E-mail: prasenjit_duiet@dibru.ac.in

Abstract:

Crude oil accounts for 33% of the world's energy consumption, and rising energy demand has intensified oil and gas drilling operations, significantly affecting the environment. Exploration and production activities generate various aqueous wastes, including produced water, drilling fluids, cuttings, well treatment chemicals, cooling water, process drainage, spills, and domestic wastewater. Drilling fluids, cuttings, and produced water are persistent sources of contamination that negatively impact water quality, human health, and aquatic ecosystems. With an annual input of 1.7–8.8 million metric tons of petroleum hydrocarbons into the marine environment, it leads to catastrophic damage. To reduce these effects, wastewater and other chemical by-products should be treated before discharge. Biological methods like bioelectrochemical systems, hydraulic plumes, phytostabilization, and biosparging use microorganisms or plants to remove contaminants. Physical methods include containment booms, skimmers, air stripping, and steam stripping. Chemical treatments like emulsification, ultraviolet oxidation, photocatalytic oxidation, and activated carbon treatment remove the contaminants. Electrokinetic remediation is an electrical process, which removes hazardous materials. Floating treatment wetlands are a cost-effective approach for the removal of COD, BOD, pH, and metal toxicity in wastewater. Wastewater treatment encompasses three steps: primary, secondary, and tertiary, ensuring that the discharge limits are met and allowing reuse of water. Advanced pressure-driven membrane technologies, namely microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), are more commonly applied based on contaminant size and charge. Forward osmosis is also becoming popular through optimized draw solutions and new membranes. For drilling fluids, synthetic-based muds form an environmentally safer alternative to oil-based fluids. This paper gives an overview of sources of water pollution in the oil and gas industry, with emphasis on diverse remedial measures towards environmental challenges in varied contexts.

Keywords: Water Pollution; Produced/Waste Water; Drilling Cuttings; Oil Spill; Environment Protection.

Introduction:

Oil is the backbone of many countries in the world and it is one of the main sources of income for oil-based industries. With increase in human civilization energy demand for oil is increasing for different purposes (Singh *et al.,* 2020). Based on the demand continuous exploration and production of oil resource is done by the countries to grow their economy. According to organization of the petroleum exporting countries (OPEC) report from 2018 it was expected that the demand for oil would be increased by 97 million barrels per day (mbpd) from 2017 to 111.7 mbpd by 2040 (Singh *et al.,* 2020). More than 65,000 onshore and offshore oil and gas fields are discovered in the world (Peng *et al.,* 2020).

Crude oil consists of mainly hydrocarbons like polycyclic aromatic hydrocarbons, alkanes also sulfur, nitrogen, metals. Some hydrocarbons are carcinogenic and neurotoxic which caused destruction in aquatic life as well as human health (Afzal *et al.,* 2019). Due to oil exploration and production operations of oil resources environmental pollution is raising accordingly. Operational discharges from drilling and production operations are continuous sources of water pollution. Fresh water content in the world is only 3.5% where 96.5% water is present in oceans (Singh *et al.,* 2020). The oil extraction processes produce large volumes of oil contaminated water around 33.6 million per day (Afzal *et al.,* 2019).

Different types of drilling fluids and cuttings, produced water, well treatment chemicals, cooling water, wash and drainages water, spills and leakages, and domestic water are the main sources of aqueous waste in exploration and production activities(Jafarinejad, 2017). Billions of gallons of produced water and processes water are produced annually as waste products in the oil and gas industry. From 1970 to 2017, more than 5.7 million tons of crude oil was found to be spilled into the oceans. In 2017 alone, the oil lost in marine water was around 7,000 tons (ITOPF, 2018). Since 1940s, the oceans has suffered more than 25 major oil spill destroying the lives and livelihood (Singh *et al.,* 2020).

Around 1.7-8.8 million metric tons of petroleum hydrocarbon is released into the marine environment globally which affect the marine environment badly(Ossai *et al.,* 2020). Different remediation methods are developed to minimize the contamination of water from different sources of oil and gas industries but they are not sufficient to manage it. This paper mostly focused on the different sources of water pollution from oil and gas industries and some already developed remedial measures to minimize the impact of water pollution on environment.

Sources of water pollution:

Watson *et al.* investigated that offshore upstream oil and gas operations comprise a range of activities including the combustion of fuels for electricity generation and equipment running, and excess hydrocarbon flaring that emit greenhouse gases (GHGs) like carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), oxides of nitrogen (NO_x), nitrous oxide (N_2O), and sulfur oxides (SO_x). In addition, process emissions are generated from physical and chemical processing activities, and loading and venting of tanks release CO_2, CO, CH_4, NO_x, N_2O, SO_x, and VOCs. The largest sources of fugitive emissions are leaks from seals, gaskets, and valves. Incineration from waste gives off VOCs, CH_4, and CO_2. Refrig-erant systems and fire-fighting apparatuses generate halons and chlorofluorocarbons through incidental discharges. Of all of these, the highest proportion of GHG emissions through combustion, venting, and flaring in the offshore oil and gas upstream operations contributes to harming the marine environment through ocean acidification, eutrophication, and higher temperatures in the ocean. Gases like CO_2, CO, NO_x, N_2O, and SO_x react with rainwater, causing the formation of acidic precipitation. Acid rain pollutes the marine ecosystem, degrading the quality of marine water further (Watson, 2020).

S. Bathrinath *et al.* studied that due to the spills of petroleum industry during the transportation, coastal and marine biological resources are highly disturbed. In some areas decreased fish catch and declining coastal livelihood are the results of adverse oil spills environmental impact (Bathrinath *et al.,* 2021).

S. Jafarinejad (2017) estimated that oil and gas operations, from extraction to processing and consumption, produce waste that adversely affects the environment. The main pollutant in upstream operations is produced water, which has hydrocarbons, inorganic salts, heavy metals, solids, organic compounds, sulfides, corrosion inhibitors, and biocides. Process water, such as cooling and wash water, also has similar impurities. Drilling fluids and cuttings introduce hydrocarbons, drilling chemicals, solids, and heavy metals into the environment. Stimulation fluids used during production consist of acids, methanol, naturally occurring radioactive materials (NORM), and gelling agents. Historically, the disposal of oil-based muds and cuttings into marine environments was one of the major sources of hydrocarbon pollution in offshore oilfields. However, stricter regulations implemented in the mid-1990s have significantly reduced this practice (Jafarinejad, 2017).

A. Sidhu *et al.* studied that production of brine water is a result of conventional and Enhanced oil recovery. The brine water is recovered with oil and separated at the surface. If the brine seeps into shallow ground water formations or flows into local stream, it pollutes the water. The amount of produced brine water increased as the well becomes exhausted. Also insufficient surface casing, unplugged abandoned and leaky oil wells, and leakage from surface holding pits are responsible for pollution of ground and surface water (Sidhu and Mitsch, 1987).

M. Lubrecht *et al.* studied that for infiltration or reinjection of reclaimed or processed water from remediation projects into affected aquifers, horizontal directional wells are ideal as they can diffuse reclaimed water over an extended screen length and reduces the potential for local groundwater mounding(Lubrecht, 2012).

Sanni *et al.* explained that the impact of produced water (PW) and drilling waste in oil and gas industry of Norwegian offshore. Produced water (PW) is formed from the formation with oil and gas (Bakke *et al.,* 2013). The nature of PW is complex because in many cases, it involves injection water and condensation water. PW usually contains dispersed oil, heavy metals, aromatic hydrocarbons, alkylphenols, and considerable amounts of organic and inorganic materials. All these components are always constant sources of contaminants into seawater during normal drilling activities. The highest average discharged PW from a single field, based on NCS data, is about 76,700 m^3. Polycyclic aromatic hydrocarbons (PAHs), major toxic compounds in produced water, are hydrophobic substances widely present in environmental pollution. The discharge of such compounds has significantly caused environmental contamination. There have also been associations with biological effects due to phenols and alkylphenols (APs) in PW. According to NCS data in 2012, the released phenol and AP were 206 tons and 316 tons, respectively. The high concentration of discharged PW contained metals like arsenic, cadmium, copper, and lead. Produced water contamination does not only affect the seawater but also the biological activities of the underwater organisms. Drilling cuttings and fluids are another source of water contamination. Traditionally, OBFs containing diesel were discharged heavily during drilling operations until 1984. Currently, only WBFs are allowed to be discharged because they are less harmful than OBFs. However, WBF cuttings still induce biological effects when suspended in water and after sedimentation.

John Pichtel *etal* discussed that an useful review on produce water and hydraulic fracturing (HF) fluids are being produced during oil and gas industry which can cause pollution. It has been found that almost 21 billion barrels of produced water is being generates by the United State. With the use of HF, it has able to extract hydrocarbon in low permeability formation which were thought as unattainable and futile. The hydraulic fracturing fluids can be classified as (1) viscosified water-based fluids; (2) nonviscosified water-based fluids; (3) gelled oil-based fluids; (4) acid-based fluids; and (5) foam fluids. It normally contains a variety of chemicals, namely proppants, gelling and foaming components, cross-linkers, corrosion inhibitors, breakers, pH adjuster, friction reducers, biocides, scale inhibitors, surfactants, clay stabilizers, iron controlling compounds (Pichtel, 2020).

Remedial measures:

A. Ahmed *et al.* studied that 1.7-8.8 million metric tonnes of petroleum hydrocarbon is released into the marine environment globally with 90% attributed to accidents due to human failures and release from oil tanker incidents at sea (Ossai *et al.,* 2020). Surface and groundwater remediation involves converting polluted environments into less harmful forms through biological, physical, and chemical methods. Biological treatments include biosparging, phytoremediation, phytostabilization, and rhizofiltration, which utilize plants or microorganisms to remove contaminants. Biosparging injects air and nutrients into the saturated zone to stimulate microbial activity, reducing groundwater contaminants. Phytoremediation employs algae, such as Chlamydomonas and Chlorella, to remove pollutants, degrade hydrocarbons, and increase oxygen levels. Phytostabilization uses plants to immobilize contaminants, preventing leaching and runoff, while rhizofiltration leverages plant roots to absorb contaminants, with plants like Pistia stratiotes and Thlaspi caerulescens acclimatized to pollutants for effective use. Phytohydraulics, using deep-rooted plants like poplar and willow, regulates the movement of contaminants like BTEX and MTBE, while bioelectrochemical systems enable anaerobic oxidation of organic waste, converting contaminants into electrical energy or by-products, with efficiency improved by bioaugmentation. Physical methods include containment booms and skimmers to collect oil spills and hydraulic control, which pumps contaminated groundwater for treatment and reinjection. Chemical methods such as air and steam stripping remove volatile organic compounds by heating and phase separation, while emulsification with surfactants stabilizes oil-water emulsions, enabling hydrocarbon recovery. Ultraviolet oxidation, using UV light and oxidants like ozone or hydrogen peroxide, and photocatalytic oxidation, generating hydroxyl radicals, degrade organic contaminants effectively. Activated carbon filtration adsorbs contaminants onto carbon surfaces for wastewater treatment, and electrokinetic remediation uses low-intensity electric currents to remove organic and inorganic contaminants, with surfactants enhancing efficiency. These combined methods are effective in addressing pollution from industrial and hydrocarbon activities, restoring environmental health and mitigating the impact on water resources.

J. Santos *et al.* studied that a conical screen centrifuge, named cutting dryer is used to decontaminate drilled cuttings and recovers maximum drilling fluid but Operational risks regarding this equipment and the residual drilling fluid content achieved is very close to the legal threshold (Santos *et al.,* 2014). So, an alternative technique named Microwave heating is used to make the drilling fluid solid free. For oil-based fluids, power, heating time and initial moisture content in the cuttings affect the microwave drying of cutting contaminants. The free water promotes the heating of materials but the interstitial water drags the hydrocarbons. The decontamination of cuttings contaminated with synthetic based drilling fluid by microwave batch drying is significantly higher than the commercial cuttings dryer and the heating rate is inversely proportional to the removal of organic phase. Furthermore, the initial fluid concentration, the mass of cuttings, and the specific energy influence the process. The initial fluid concentration pays a negative impact on drying and the mass and specific energy pays positive impact on the drying treatment. Mixtures of cuttings more circular and large particle lead to the greater removal of less-circular and finer particles also the higher water content of the cuttings lead to the greater removal of organic phase.

S. Jafarinejad *et al.* discussed thatthe activities and process such as exploration and production of petroleum (crude oil and natural gas), processing of hydrocarbons, storage, transportation, distribution, and marketing of petroleum products generates large amounts of aqueous waste containing different contaminants that must be treated before discharging (Jafarinejad and Vahdat, 2021). The three major steps in the treatment of wastewater produced by the petroleum industry are primary treatment, secondary treatment, and tertiary treatment. In primary treatment, methods used include API separators, an American Petroleum Institute separator which helps remove large solid contaminants. Secondary treatment is composed of biological processes such as suspended and/or attached growth biological systems, which help break down organic contaminants. Tertiary treatment includes advanced techniques such as sand and membrane filtration, ion exchange, chemical oxidation, and advanced oxidation processes (AOPs) and must be included to ensure discharge limits compliance and to achieve water reuse. Pressure-driven membrane technologies that are extensively used in oily wastewater treatment include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). These are based on the application of high pressure to separate the contaminants from each other depending on size and charge. Forward osmosis (FO) technology, another membrane process, is applied for wastewater treatment and seawater desalination. In FO, water (solvent) is allowed to pass through a membrane, while solute molecules or ions are rejected, which results in a concentrated feed solution and a diluted draw solution. For reuse and cleaning of the wastewater, a subsequent separation unit is needed to re-concentrate the draw solution. Some major elements which determine the performance of FO include pH, temperature, and the flow rate of FS concentration, along with its flow rate, and, membrane and DS properties contribute much to the process performance. Surface modification techniques like chemical treatments, UV irradiation, plasma treatment, surface coating, and grafting are employed to improve membrane performance, particularly to increase solvent flux, solute rejection, and fouling resistance. Among these, chemical modification is the most effective. To generate the ideal osmotic pressure, low viscosity and low reverse solute flux draw solution along with high diffusion coefficient are required that improve the FO process performance and overall efficiency in the treatment of oily wastewater.

P. Industries stated that disposal of produced water can be achieved by reinject into formations after treatment, discharge to the environment, reuse in oil and gas industry (e.g. drilling, workover operation) and after significant treatment produced water may be consumed for irrigation, wildlife consumption and habitat and even drinking water (Industries, 2014). For warm and dry climates because of the potential for high evaporation rates, an artificial pond named evaporation pond is used for treatment which is a large area of land and designed to efficiently evaporate water by solar energy. Ion exchange is a technique for decontamination of formation water or any ion containing solution with use of solid ion exchangers. The finished water can be used for irrigation, livestock or watering in some jurisdictions and a brine water is produced which is disposed at an approved facility. Membrane filtration treatment is also used to decontaminate the waste water. Absorption is used to remove manganese, iron, total organic carbon (TOC), BTEX, oil, and more than 80% of heavy metals present in produced water with the use of variety of adsorbents such as activated carbon, organoclays, activated alumina, zeolites etc. chemical oxidation is a technology used to remove colour, odour, COD, BOD, organics, and some inorganic compounds from produced water by using chemical oxidants such as ozone, peroxide, permanganate, oxygen, and chlorine. The oxidants are introduced to wastewater which reacts (oxidation/reduction) with the organic compounds such as amines, phenols, chlorophenols, cyanides, halogenerated aliphatic compounds, and mercaptans and results high quality water and a brine water depends on chemistry which is disposed at an approved facility. The efficiency of this technique is improved by combined with other treatment technologies. For the waste disposal deep well so that the material is deposited in impermeable strata which are hydraulically isolated from potable aquifers and surface waters. Dumping of not treated wash waters into deep well results an area that is permanently impacted and withdrawn from potential beneficial use also leakage may occure in the underlying geology and the monitoring of leakage is difficult and expensive enough to install. So it is not reasonable to apply this technique.

G. Ferguson *et al.* studied that deep aquifers that have not been subject to depressurization through hydrocarbon production is likely the targets for injection wells. 72% of injection wells have been completed in Mesozoic formations, 28% are completed in Palaeozoic formations and a few are in Cainozoic sediments (Ferguson, 2015).

Jalal Seyedmohammadi discussed that the effect of different types of drilling fluids and some model to protect the environment from such type of pollutants (Seyedmohammadi, 2017). Oil and Gas industry played a vital and fragile role in causing environmental pollution. Amongst different sources drilling well is one of them. The drilling process involves drilling fluid in various purposes which are like water-based fluid (WBF), oil-based fluid (OBF), synthetic based fluid (SBF) that produces some large amount of waste fluids and cuttings. Uses of WBF would not be as harmful as other type of drilling fluid. Each developing Exploratory well discharged WBF and cuttings around 200 metric tons into the seas. Discharge OBF cuttings into the sea would be hazardous as it contains diesel, mineral oil, barite and other additives and SBF are developed fluids which could be as an alternative of OBF.

Harpreet *et al.* discussed that the impacts of oil spill on environment and also a remedy for minimizing the water pollution from oil spills by using magnetic Nano materials (Singh *et al.,* 2020). Oil spills are most important water pollution source that cause environmental destruction and economic loss. From total water content on the Earth 96.5% water is found in oceans and only 3.5% is present as fresh water. With increasing energy demand, oil exploration and production operation has also increased. So, the threat of oil spill had increased during exploration and production and transportation, storage etc. A number of accidental leakages of crude oil from pipelines, drilling platforms and rigs are some reasons that oil got spilled onto the oceanic waters which caused a huge destruction on environment, eco system and natural resources. Sometimes naturally oil dumped into the coastal waters because of some natural disaster. Biodiversity and environment are greatly affected by oil contaminants such as poly-aromatic hydrocarbons (PAH). Some remedies were already encountered but they were not enough to restore the polluted environment to normal position. Oil spills could be controlled by some physical processes like booms, skimmers, adsorption by some sorbents, etc. chemical methods such as dispersants, solidifier etc. Thermal remediation method i.e. in situ burning oil and also some biological methods are used. Nano technology is field of science that synthesis and development of Nano materials. Most utilized Nano material is super hydrophobic iron oxide also called as SPIONS. Novel material with super hydrophobicity and oleophilicity as well as magnetic nanoparticles was used to treat oil spill sorbents. Magnetic oil is formed when ferromagnetic particles mixed and got spread into the oil and this oil could be easily determined by magnetic field. The nano materials could be easily collected again after the oil adsorption with the external magnetic field and can be regenerated by washing them with ethanol or hexane for further oil-water separation.

Muhammad Afzal *et al.* discussed that the remediation methods of oil contaminated water by using floating method treatment. Contaminated waste water filled with hydrocarbons has become a one of the ingenious remediation of waste water by using floating treatment wetlands (FTWs) (Afzal *et al.,* 2019). FTWs involve free-floating plants (macrophytes) cultivated on hydroponic mats with roots submerged in water. The roots in turn harbor rhizospheric microbes, which break down organic pollutants such as hydrocarbons through plant root exudates utilization. An oil and gas company at Chakwal, Pakistan applied FTWs to crude oil contaminated water in a stabilized pit for 18 months with plants like Typha domingensis, Phragmites australis, Leptochloa fusca, and Brachiaria mutica. Significant reduction in COD (97.43%) and BOD (98.93%) was found within six months. The pH declined from 7.55 to 6.99, and TDS reduction was 82.42%.

The plants and microbes absorbed and sequestered inorganic elements like Na^+, K^+, SO_4^{2-}, and Cl^-, while reducing heavy metals in the order of Fe (99.9%) > Cu (95.2%) > Cr (95%) > Pb (93.54%) > Cd (88.8%) > Ni (84.9%). At first, the water was only partially detoxified as shown by fish mortality after six and twelve months, but no fish deaths were observed after 18 months, indicating complete detoxification. This study highlights the potential of FTWs as an effective biological treatment for oil-contaminated water in stabilization pits within the oil and gas industry.

Alalayah *et al.* discussed that as oil pollution in water have negative effects on all lifestyles, oil waste water removal of oil and gas industry is an rising problem (Demirbas *et al.,* 2017). The oily wastewater is formed in these oil and gas producing industry which also includes heavy oil-water emulsions, mainly asphaltenes, resin, sludge, flocs of microorganisms and it makes the separation even hard. Wastewater treatment (WWT) is very important for using in rivers and streams for aquatic ecosystem and human too. WWT is the process in which polluted contaminants from wastewater has been removed using physical, chemical and biological processes. There are various oil-water separators which can treat different contaminants in waste water. The processes for the treatment of waste water are normally, gravity sedimentation, coagulation, floatation, de emulsification, membrane separation, flocculation treatment, chemical precipitation and biological treatment. API oil-water separator can eliminate the oily contaminants and suspended solids from wastewater, refineries, petrochemical and chemical plants etc. Centrifugal oily water separator can remove the oil and water by centrifugation and this device consists of a cylindrical container, which rotates in a larger fixed container. Gravity plate separator contains a series of plates of contaminated waste water while the aim of this device is to make sure that the oil droplets in the water are accumulated at the bottom of the plate, due to which the larger oil droplets float in plates and get contained in the top of the chamber. In Bioremediation treatment microbes are being used to treat waste water. It needs careful management of environment in which these microorganisms get nutrients and hydrocarbon, such as oil or other pollutants and oxygen. Underground oil-water separator separates oil and gas that is produced at the bottom of the well. Electrochemical emulsion purification apparatus produces electrolytic bubbles which can attract contaminants, which when reaches the top of the treatment chamber; the pollutants are being transferred to a waste oil deposit. In Gravity sedimentation method, waste water which uses gravity to eliminate the suspended solid particles. To remove the precipitated solids, settlement ponds are built and tanks that are built for continuous removal of solids with mechanical methods are being called clarifiers. The sedimentation process is followed by a chemical coagulation and flocculation phase it allows the particles to be divided together into large flocculates. Flocculation treatment is a conventional method which includes gravity settling, dewatering and incineration that is performed poorly for emulsified oil and suspended solids. It is used for minimization of oil content and COD. In present scenario the bio-flocculants is of more interest in research as they are economically feasible, biodegradable, and simple and of low toxicity. In Floatation treatment hydrophobic solid additives and liquid suspended in water can be easily removed. It is the process that eliminates pulverized ore particles based on their relative capacity of floating on a given liquid fraction. This WWT is a fully developed technology which has a good and stable effect on oil water separation. Flotation DAF (Dissolved air flotation), flotation and jet propeller flotation are the widely used methods. Membrane separation technology used to remove gas streams or liquid streams using membrane technology. It is normally of three types i.e., microfiltration, ultrafiltration and reverse osmosis. Hydrostatic pressure or electric potential is the main driving force in this process. The most effective in removing dissolved inorganics and high-molecular weight organics from waste water. Chemical treatment is the most commonly used methods for eliminating contaminants is chemical method. The most favoured agents for de emulsification are ferric and aluminium salts as other coagulants are still in researching stage. This treatment process normal contains expeditious mixing of coagulants with oil mixed waste water which is followed by flocculation and floatation or sedimentation.

Erik *et al.* studied that the deep-water oil and gas industry and its impacts on marine environment (Cordes *et al.,* 2016). The main phases such as exploration, production and decommissioning have adverse effect on environment. Seismic surveys that are used in offshore oil and gas activities can have impacts such as underwater sound and light emission. Direct physical effects from production phase can also occur when pipelines are laid and the increased volume of discharged produced phase. To mitigate these indirect or direct impacts three strategies have been considered: activity management, temporal management and spatial management. Activity management tends to reduce the environmental effects by restriction of certain discharges or by banning employment of certain technologies. However temporal management is not very widely used in deep water oil and gas activities. While the spatial management is the strategy to banning some particular activities from certain areas where sensitive habitats are existing.

Yusran Hedar *et al.* described that the environmental damage caused by produced water or oilfield waste water (Hedar and Budiyono, 2018). It can be from formation water and saline water. Produced water that is also called formation water, brine or saltwater, contains mainly dissolved and dispersed oil compounds, dissolved formation minerals, production chemical compounds, production solids, dissolved gases. The produced water from oilfield normally consists of corrosion inhibitor, crust inhibitor, biocide compounds, emulsion destroyer and purifiers, coagulants, flocculants, solvent to reduce paraffin deposits. As produce water is toxic to environment, it is important to treat produced water.

Gravity separation is the most used method that uses gravity to separate oil droplets from waste water. Corrugated Plate Interceptors (CPI) is a technology that depends on gravity separation method. It can be used to eliminate the oil droplets that are of size 40 microns or above. Flotation is also the method that depend on gravity force. It is used to separate small suspended particles in gas bubbles that are difficult to separate while using settling or sedimentation. Adsorption can be used to remove soluble hydrocarbons from produced water. It can be used to eliminate iron, manganese, organic carbon, heavy metals and oil from produced waste water. Biological treatment of waste water is done by the use of aerobic and anaerobic microbes. The technologies that are used is activated sludge, tricking filter, sequencing batch reactors (SBRs), chemostate reactors, biological aerated filters (BAF), and lagoons.

Conclusion:

To meet the global demand for energy, oil and gas sectors exploration and production operations are increasing. Due to increase in the amount of waste water or discharging sources in petroleum industry the discharge effect of such components have become important environmental problems. Meanwhile a single treatment method is normally not enough to remove these all pollutants because of their highly complex composition. As Oil and Gas exploration involves numerous operation activities that contribute a large number of hazardous pollutants to the marine environments. Different combustion process and also some physical and chemical activities released huge number of complex chemical substances react with rain and form acid rain. Oil spills and leakages have become one of the most serious sources of marine pollution causes severe impact on water pollution. Produced water is the formation water that is brought to the surface during oil and gas production and it the largest liquid waste generated in petroleum industry. The composition of produced water is highly complex discharging such components in the marine water severely make impact on aquatics lives such as aquatic plants, animals etc. Almost 1.7-8.8 million metric tons of petroleum hydrocarbon is released into the marine environment globally with 90% attributed to accidents due to human failures and release from oil tanker incidents at sea. Discharging different types of drilling fluids and cuttings in large volume during drilling operations reduces the quality of water and causes temporary and permanents hearing loss of aquatic animals as most of the marine animals finds their food by hearing. There are some handling technologies which were already discovered to reduce and eliminate the pollutants from different sources of petroleum industry. Because before discharging such components in to water, treatment of such components is indeed. This review paper has described their respective remedial measures. Contaminants can be treated by physically, chemically, electrically and also biologically. Biological treatment involves plants and living microorganisms which are injected into the formation under high pressure. For example, in biosparging that involves oxygen and nutrients, Phytoremediation which involves different types algae, Phytostabilisation, Rhizofiltration etc. Some physical remedial techniques such as Containment Booms, skimmers, Hydraulic control, Pump and treat, Air stripping and steam stripping etc. are used. Also, there are some chemical treatment is done by Emulsification, Ultraviolet oxidation, Photo catalytic oxidation, Activated carbon treatment etc. Hydrophobic solid additives and liquid suspended in water are more easily separated from water by flotation method and different types of Oil–water separators can be considered to treat a variety of contaminants in water, including free floating oil, emulsified oil, dissolved oil, and suspended solids. Cellulose-based materials can also be responsible for an efficient, low-cost and pollution-free option for the wastewater treatment in petroleum industry.

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PUBLIC PARTICIPATION IN THE MANAGEMENT OF CONTAMINATED AQUIFERS

Nishtha Naudiyal* and Hema Kandpal

Department of Environmental Science,

G.B Pant University of Agriculture and Technology, Pantnagar (263145), Uttarakhand

*Corresponding author E-mail: nishthanaudiyal@gmail.com

Abstract:

Aquifers are the fundamental water resources that have been an indispensible cog in the wheel of hydrological cycle that replenish water demands of human race for various purposes to thrive. But with the course of time anthropogenic activities have led to deterioration of water quality of these aquifers beyond sub-standard. Therefore this chapter aims to throw some emphasis on management of aquifer contamination through role of active public participation keeping weary of the sustainable challenges in their management. Public participation is pivotal in sustainable management of aquifers as it ameliorates data quality, increases awareness, backs the legislation and adds an edge towards proactive community based solutions. Moreover, a penetrative study is invariably desired to delve deep into various aspects of public issues and their perspective. Apart from this stakeholders play a keen role in aquifer management by laying out unique dimensions of expertise, and duties to the table making it less challenging. All in all a balanced approach between scientific and social strata is required to forge sustainable policies for management of aquifers.

Keywords: Aquifer, Community, Contamination, Management, Public, Participation, Stakeholders, Sustainable.

Introduction:

Aquifers are essential freshwater reserves hidden beneath the surface of the Earth that is crucial to the functioning of the global hydrological cycle. They are essential in maintaining ecosystems and providing valuable elements for a variety of human activities. The need for drinking water for residential and commercial use, industrial processes like mining and thermoelectric production, tourism, agricultural practices, landscape modification and urbanisation are some of the specific human activities that cause groundwater reserves to be depleted. Impermeable surfaces brought on by urbanisation and industrialization increase runoff that contains contaminants like, heavy metals, oil etc., and results in aquifer contamination. Moreover, the worldwide influence of climate change has also affected the aquifer recharge patterns thus highlighting the critical requirement of sustainable aquifer management plans in response to the present changing environmental challenges. Developing sustainable solutions requires integrating studies on socio-economic implications, urbanisation consequences, mining and agricultural activities, industrial discharges, the effects of climate change and public participation [Boldy *et al.* (2021); Hou *et al.* (2023); Ibkar *et al.* (2023); Li *et al.* (2021) and Piao *et al.* (2010)].

Aquifer contamination is a global issue and has severe impact on the human health and ecological services. The ramifications of aquifer contamination are extensive which includes threats to public health, effects economy; deteriorate ecology, and social injustices. From an economic standpoint, contaminated aquifers result in higher operational costs for businesses and substantial losses in agriculture due to lowered crop quality. Global research has demonstrated that significant increases in nitrogen fertilisation occur along with increases in nitrate-nitrogen in groundwater. Although the amounts of insecticides in groundwater are often below acutely harmful levels, many are concerned about potential long-term impacts. The ecological fallout includes destruction of aquatic life, disturbance of ecosystems, and loss of biodiversity. Such widespread contamination of aquifers is of real concern because of the potential for long-term and widespread exposure. Thus, promoting the principles of sustainable aquifer management a necessary element in the resolving these problems. Public participation is necessary as an effective solution in the sustainable aquifer management [Adelodun *et al.* (2021); Burri *et al.* (2019); Chandnani *et al.* (2022); Hallberg (1987) and Li *et al.* (2021)].

Public participation is one of the most important factors in the field of aquifer contamination and dealing with the challenges for sustainable aquifer management. The understanding of public opinions and the role a community is eminent in promoting sustainable aquifer management. Public participation in sustainable aquifer management is vital and diverse, tackling challenges related to maintaining these subterranean water sources. Public participation builds a strong framework for sustainable aquifer management via improving data collection, supporting legislation, encouraging community-based solutions, and increasing awareness [(Al-Masri *et al.* (2023); Miguel *et al.* (2024); Rousseau and Deschacht (2020) and Shao *et al.* (2023)].

In a nutshell, in order to sustainably manage the contaminated aquifers, thorough understanding on public participation, their role, function, perspectives and the issues they face is required which ensures the long-term health and sustainability of these vital natural freshwater resources as we traverse the complex web of problems.

Aquifer management: Challenges and role of public participation

Aquifer management faces numerous issues to confront, each creating a different set of challenges to their long-term care. The economic gains from resource development have been reinvested in aquifer management, raises questions about the contamination and sustainable aquifer management. According to recent studies and efforts, public participation in aquifer management is crucial for obtaining fair and sustainable results. The 'Theory of the Commons' and 'Rule of Capture' when put together, predicts that over-exploitation of aquifers provides immediate benefits but the long-term costs passed on to society as a whole is the severe contamination of aquifers. Therefore, public education and awareness are essential components of public participation and sustainably managing the aquifers [(Foster and Chilton (2003); McCay and Acheson (1987) and Sophocleous (2010)].

1. One of the major challenges in sustainable aquifer management is the scarcity of thorough data and monitoring systems, which are essential for comprehending aquifer and their contamination levels due to which decision-making gets hampered. The issue is made worse by lack of financial and technological resources making it difficult to provide enough money for monitoring, research and clean-up initiatives leading to compromised execution of sustainable alternatives. One way is to improve the collection of data through citizen-science programmes, in which local communities actively participate in aquifer monitoring, providing additional information to official data and fostering a sense of shared responsibility for the management of aquifers. The creation of community-based solutions suited to local requirements is facilitated by public participation which in turn guarantees the socio-economic and environmental conditions into account [(Little *et al.* (2015); Manda *et al.* (2020); Matham *et al.* (2023) and Prajapati *et al.* (2021)].

2. Another problem for managing aquifers is it might take years or even decades for the repercussions on the population via contaminated aquifer system. The challenge is increased manifolds by the wider effects of climate change on land subsidence, anthropogenic and geo-genic contamination, aquifer storage and depletion trajectory management, seawater intrusion, supply vulnerability and long-term sustainability. Management strategies must be modified in response to these changes in order to ensure the resilience of aquifers. Recent studies emphasize the necessity of merging community-based solutions, technological advancements, and public participation in order to tackle these challenges along with the most recent scientific results [(Gorelick and Zheng (2015); Green *et al.* (2011); Kelly *et al.* (2013) and Ward *et al.* (2019)].

3. Regulatory shortcomings are yet another significant problem that causes aquifer contamination. There is need for more stringent rules in order to regulate extraction rates and prevent contamination. Incentives are to be provided for the personal motivation of any customer to cut back on usage to save up more for later. Public participation strengthens the resilience of vital aquifers and guarantees that their management strategies are inclusive and contextually relevant [Foster and Cherlet, 2014].

Communities could support improved funding, legislation and resource allocation, which aids in bridging the divide between the public's concerns and governmental policies. In order to guarantee that multiple perspectives are considered and therefore, it is imperative to include stakeholders.

Stakeholders in contaminated aquifer management

Successful contaminated aquifer management requires the active involvement of stakeholders. These sectors bring unique perspectives, expertise and duties to the table. Since they represent a range of roles, functions and viewpoints, stakeholders are essential in ensuring that decisions are made in a way that takes into account a variety of interests, transparency, collective problem-solving and developing sustainable strategies. Various stakeholders in relation to the sustainable management of contaminated aquifers include:

1. Academic and research institutions:

Sustainable aquifer management requires better monitoring technology, raw data recording and data collection. Research scholars and academicians use rigorous scientific research to understand aquifer dynamics, water quality and the effects of human activity. New methods to modelled experiments and multi-model analysis are made possible because of researchers to conduct effective aquifer management through advancements in computer efficiency and techniques that address parameterization and uncertainty. The expertise and information gained from researching intricate aquifer systems is provided by academic and research institutions, which aids in the creation of appropriate aquifer management rules and regulations. Water-quality preservation and rejuvenation are embraced by aquifer management regulations, which encourage advancements in water-quality detection, monitoring, and mitigation [Banta *et al.* (2006); Doherty and Skahill (2006); Focazio *et al.* (2002); Georgopoulos and Lioy (2006); Hamby (1994); Poeter and Hill (1998) and USGS (2002)].

2. Community and indigenous groups:

This group of stakeholders is directly affected by the aquifer contamination since they depend on using aquifer water for their livelihood. These people recognise the value of the planet's natural resources on a social and cultural level supplying conventional wisdom and management concerns for aquifers, providing valuable information and supporting data gathering. Through citizen science initiatives, these groups can also assist in putting community-based solutions into practice [(Maheshwari *et al.* (2014) and vanSteenbergen (2006)].

3. Environmental organizations:

Many organisations, such as the World Water Assessment Programme (WWAP) of the United Nations, focus on environmental issues which includes addressing early changes in aquifer dynamics and preventing social disruption. These organisations assist in assessing an aquifer's sustainability in the context of resource planning with comprehensive understanding and knowledge and engaged in trade-offs between policy and resource development. They help in preventing societal unrest as well as support and preserve the integrity of diverse cultures and societies [Puri *et al.* (2001)].

4. Government bodies and regulatory authorities:

The role of this group of stakeholders is to ensure that freshwater resources are available for future generations while supplying it to various sectors, which is achieved by establishing laws and implementing them effectively. Higher-level authorities are more likely to facilitate the beneficial management of aquifers in terms of the economy, society and environment [Lopez-Gunn and Cortina (2006)].

5. Industries:

This group release a range of harmful wastes in the environment and use a significant amount of water from aquifers. Industries must emit contaminants in accordance with the guidelines established by the WHO, CPCB, BIS and other organisations. The cost-benefit analysis and financial efficiency for sustainable aquifer management, encompasses reduced capital expenditures, energy pumping savings and reserve values for droughts. A unique viewpoint is provided by the industrial processes viz. technical breakthroughs, compliance difficulties, financial gains, etc. [Banadkooki *et al.* (2022) and MacEwan *et al.* (2017)].

6. Water utilities:

Water distributors and municipalities are among the stakeholders in this group. They are involved in satisfying the needs of every family and carrying out the directives issued by the government, treatment of wastewater, provision of clean drinking water and other activities. These utilities can start a strategy to manage the aquifer resource in tandem with surface water and assess the sustainability and feasibility of using aquifer water to supplement the area's water supply. Water distribution and supply managers offer a pragmatic perspective, focusing on maintaining potable water quality and treating water as necessary. Their involvement is essential for the adoption of treatment technologies, monitoring water quality and mitigating the effects of pollution on water supply infrastructure [Riemann *et al.* (2011) and Timmins (2002)].

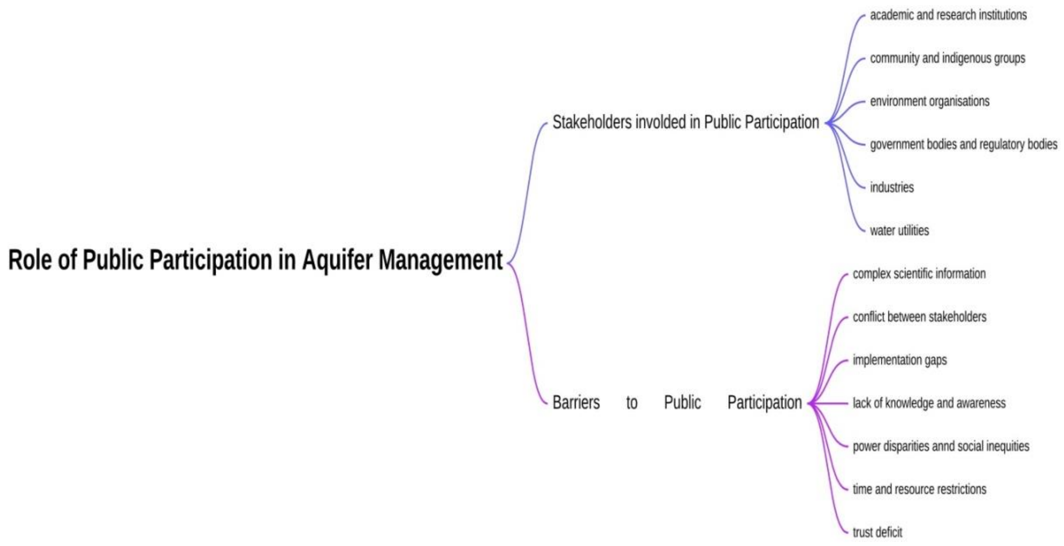

Figure 1: Stakeholders involved and barriers to public participation

Therefore, the collaborative efforts of several stakeholders are essential for the sustainable management of contaminated aquifers. Their efforts are crucial in developing holistic approaches that address environmental, social and economic factors. Maintaining the ecological integrity of aquifers while balancing stakeholder requirements is a difficult task that frequently encounters barriers.

Barriers to public participation in management of contaminated aquifers

There are a number of barriers that stand in the way of meaningful public participation in aquifer management decision-making processes. By understanding and addressing these barriers, we can foster transparency, diversity and long-term solutions. The common challenges that a range of stakeholders in contaminated aquifer management face are:

1. Complex scientific information:

Research on local water quality issues is becoming a typical barrier in aquifer management. This includes advancement in scientific understanding and involvement of locals in the management, which may be technically challenging. Elaborate models, dearth of data and scientific terminology might occasionally deter non-technical persons from actively engaging. People need to get the right scientific training and skill development in order to overcome this [Jackson-Smith (2018)].

2. Conflict between various stakeholder groups:

Different stakeholder groups may hold different views about minimum standards adherence, power asymmetries, procedure narrowing and "color-blind" planning. In Denmark farmers and hydrologists disagreed over the extent to which pesticide use impacted aquifer water quality. To avoid such situations, decisions must take into account the opinions of both sides, rather than favouring one over the other to aid taking into account both sides of the argument, accepting things as they are and creating a foundation for further compromises [Emanuel and Wilkins (2020) and Henriksen *et al.* (2007)].

3. Implementation gaps:

Implementation gaps are caused by deficiencies in the ability of municipal and provincial governments to manage aquifers according to the already existing laws [DeLoë and Kreutzwiser (2005)].

4. Lack of knowledge and awareness:

The absence of easily comprehensible and publicly available information on aquifer contamination is a primary barrier to public participation; hence, the public is largely deprived of meaningful access to the decision-making process. According to Rollason *et al.* (2018), aquifer dynamics solidify traditional management approaches that view public participation as a barrier to the achievement of top-down management objectives. As a result, local communities and participatory movements and participation in public meetings is restricted by limited awareness [Laurian (2004)].

5. Power disparities and social inequities:

Impoverished, women, youth and farmers find challenging to participate meaningfully in society. It has been noted that males managed aquifer resources more than women do, especially when it comes to gathering data and putting policies into action. Diversity and inclusion must be guaranteed in decision-making processes in order to redress these power imbalances and achieve environmental justice [Ashford and Rest (2001) and Piyapong *et al.* (2019)].

6. Time and resource restrictions:

Sustainable aquifer management has been hampered by a number of variables, including financial, technical and temporal ones due to which neither the community are not completely integrated into decision-making processes nor are they formally informed or consulted. Research can help to address the issues surrounding the long-term efficacy and application of emerging technologies [Garande and Dagg (2005) and Richardson and Nicklow (2002)].

7. Trust deficit:

Past incidents where communities felt neglected or when decisions benefited particular interests have eroded trust. As sovereign nations and independent experts, people are rarely allowed to participate in environmental decision-making settings, and their ideas are routinely ignored. Building trust requires open communication, responsibility, and a commitment to involve the public in decision-making. Therefore, increased openness through inclusive and communicative public engagement is necessary for effective local aquifer management [Emanuel and Wilkins (2020) and Garande and Dagg (2005)].

Eliminating these barriers would raise the standard of choices and contribute to the long-term sustainability of aquifer management initiatives. In order to successfully minimise these barriers, there is necessity for democratic governance, rigorous research, risk communication and sustainable development [Majone *et al.* (2015); McCarthy (2002) and Mooney *et al.* (2022)].

Conclusion:

Aquifers cater a primary source of water demands for various human activities but they have become an alarming source of apprehension due to constant insistence subdued by anthropogenic activities. This leads to a detrimental effect on human/ animal health, severe environmental implications and remunerative damages. Therefore, it is coherent that an adequate management of contaminated aquifers in light of sustainable challenges. Amid various setbacks in management of contaminated aquifer, active public participation is paramount when it comes down to keeping judicial management for gaining desired sustainable outcomes. Dissemination of knowledge and creating awareness among communities is explicit component in aquifers management. The role of stakeholders can't be neglected as they bring distinguished edge to the perspectives on issues and expertise into action which tends to incite up a holistic problem resolving attitude among public. In a quick rundown, to achieve sustainable management of contaminated aquifers different components mentioned in this chapter have to be on same scale with local support in a balanced manner to achieve desired target.

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THE CONTAMINATION OF WATER BODIES AND ITS PURIFICATION

Ashok Kr. Singh

SRTC PG College Utraula, Balrampur UP -271604 India

Corresponding author E-mail: ashokarsingh@gmail.com

Introduction:

Water is the elixir of life. It is an essential part of protoplasm and creates a state for metabolic activities to occur smoothly. Therefore, no life can exist without water. In addition, there are thousands of microorganisms which live in water and are transported through it.

Major area about three-fourth of earth surface is covered by water, mainly by oceans and to some extent by lakes, rivers, streams, ponds, etc. However, water is constantly in continuous circulation. This phenomenon of movement of water is called hydrological cycle or water cycle. Also, water is present below the land which is recovered by tube wells. Water is also present in the form of ice in South and North poles of the earth, on the top of high mountains, etc. From the earth surface water is lost through evaporation, transpiration and exhalation. About 93% of evaporated ocean water cools and falls back in the form of rain on the sea, and water moves along with wind current over land surface and joins the cloud stock of over double this quantity of water obtained through evapotranspiration from land.

Water receives microorganisms from air, soil, sewage, organic wastes, dead plants, animals etc. It is obvious that at times almost finding favourable conditions grow and multiply to increase their population. In this chapter we shall briefly describe the sources of water, physicochemical and biological properties, microbiological examination and water treatments.

1. Types of water

Natural water is commonly grouped into four well-marked classes: (a) atmospheric water (b) surface water (c) stored water and (d) ground water.

1.1. Atmospheric water

Rain and snow are included under the atmosphere water. Microorganisms in the form of cells or dormant propagules and dust particles remain suspended in water and snow, Considerable number of bacteria can be isolated from rainwater. After heavy rain or snow fall, the dust particles and bacteria are washed from the atmosphere. Therefore, atmosphere for some times remains free from microorganisms.

1.2. Surface water

The water present on earth surface is known as surface water. It is found in the form of several water bodies such as rivers, streams, ocean, lakes, etc. As soon as raindrops or snow touches the earth, it becomes contaminated by the microorganisms present in soil. Total microbial number in water depends on microbial population of soil, types of soil, types of organic materials present in soil and on types of microorganisms and their activities. Moreover, microorganisms of water are governed by climatic, chemical and biological conditions. The microbial population in ponds, pools and lakes would be several times higher than that of the rivers and streams. Also, microbial population is influenced by anthropogenic activities. Frequent bathing of animals, throwing of excreta and effluents in water bodies certainly affect the total microbial load in water.

1.3. Stored water

The stagnant land water present in ponds, lakes, etc. are called stored water. During storage, in general, the number of microorganisms gets reduced; thus, it establishes to some extent the purity and stability. However, in stored water the microorganisms are affected by several factors such as sedimentation, ultraviolet light, temperature, osmotic effects, food supply, and activities of other microorganisms as well.

1.3.1 Sedimentation

Microorganisms have specific gravity slightly more than the distilled water. therefore, they slowly settle down the bottom of water bodies. Bacterial cells get attached to suspended particles that cause sedimentation. As the suspended particles settle down, the upper layer of water is made free from the microorganisms.

1.3.2 Microorganisms

Predatory protozoa are present in water. They need living or dead bacteria for their food. If enough oxygen is present, many these microorganisms are engulfed by the predatory protozoa. However, when dissolved oxygen and bacteria are absent, the protozoa will not be present in water.

1.3.3 Light rays

Both the vegetative cells and spores of microorganisms are killed in the presence of prolonged exposure of direct sunlight. The diffused light does not cause any effect.

However, in a water supply toxicity of ultraviolet light is governed by the turbidity of water i.e. it is inversely proportional to turbidity. In a clear water ultraviolet light is effective to a depth of about three meters but in turbid water light rays cannot penetrate. In bright light some of the free-floating cyanobacteria sink down for some time, and float again when brightness of light is diminished.

1.3.4 Temperature

Effect of temperature on organisms varies. Increasing temperature is harmful to microorganisms. But some pathogenic microorganisms multiply well with increasing temperature.

1.3.4 Food supply

The number of microorganisms is likely to increase with increased food supply in water. Several waste materials present in water act as food bases. In addition, algae growing in water act as food for microorganisms when algae are dead after completing its life cycles. In addition, toxic substances viz., acids, bases, etc. cause marked reduction in microbial community. There are certain dissolved gases such as CO_2 H_2 etc. which have harmful effect on water microflora. All together these factors bring about changes in water pH which, however, influence microbial community of water.

1.4. Ground water

Soil consists of particles of varying size; therefore, soil pore size varies. The percentage, space and size of pores regulate the quantity of rainwater than can be soaked and held in soil. The large pores allow a free percolation of water due to gravitational force. This is known as gravitational water. The gravitational water moves down and accumulates in the form of ground water. A huge amount of fresh water is present in the form of ground water.

As water moves down through soil pores, bacteria and other microorganisms with suspended particles are filtered. Therefore, the microorganisms are carried only to some distance. Deep wells contain negligible number of microorganisms.

2. Microorganisms

Many microorganisms both saprophytes and pathogens are found in water which fall under the group’s bacteria, fungi, algae, protozoa and nematodes. Several animal viruses are also transmitted through water. Most bacteria found in water belongs to groups: fluorescent bacteria such as *Pseudomonas, Alginomonas*, chromogenic rods

Xanthomonas, etc, coliform group *E. coil, Aerobacter*, etc., Proteus group, non-gas forming, non-chromogenic and non-spore forming rods, spore formers of the genus Bacillus, and pigmented and non-pigmented cocci Micrococcus.

A significant work on aquatic fungi has been done at different centres in India. Many fungi, both saprophytes and pathogens, have been reported from a variety of water sources including potable water.

2.1. Marine microbes

Marine microbiology deals with microorganisms living in sea. About 97% of earth's water is present in sea. Ocean at its greatest depth is slightly more than 11,000 meters deep. Therefore, pressure in the marine environment increases by about 1 atm/10 meters in depth. The bacteria growing in vertically differentiated marine environment can be categorised in three groups:

a) Barotolerant -bacteria growing between 0 and 400 atm but best at normal atmospheric pressure.
b) Moderate Basophiles -bacteria growing optimally at 400 atm, but still grow at 1 atm.
c) Extreme Basophiles -bacteria growing only at higher pressure at 6000-11,000-meter depth.

The hydrostatic pressure can reach 600 to 1,100 atm in the deep sea, whereas the temperature is about 2 to 3°C. Increased pressure does not affect the barotolerants. Some bacteria living in gut of deep-sea invertebrates amphipods and holothurians are truly basophilic. These basophilic bacteria play a significant role in nutrient cycling.

In the marine system, the major source of organic matter is phytoplankton planktons wandering i.e. free-floating plants. A common planktonic alga is *Synecococcus* which can reach to a density of 10 to 105 cells/ml at the ocean surface. Picocyanobacterial very small cyanobacteria may represent 20 to 80% of total phytoplankton biomass. In turn these acts as a source of food for marine fish and other animals Recently, a very interesting group of bacteria as archaeobacteria has been discovered from the marine system. It has been found that about 1/3 of oceanic picoplankton's are archaeobacteria associated with hostile environment i.e. hot springs, deep marine black smoker areas, saline and thermoacidophile region. The isolation and functional role of these bacteria are still to be studied in detail.

1.2. Fresh water microbes

Lakes and rivers provide the major freshwater bodies which are used for potable water. However, due to growth of phytoplankton and decomposition of organic matter nutrient status varies throughout the year. In addition, animal activities including man also influence the nutrient level of lakes and rivers. The nutrient-poor lakes are known as oligotrophic lakes, whereas the nutrient-rich lakes are called eutrophic lakes. The nutrient-rich lakes contain high number of bottom sediments containing organic matter. Eutrophication enrichment of lake due to high concentration of nutrients of lakes occur by multifarious ways where anthropogenic activities are of much importance. The eutrophic lakes support luxuriant growth of bacteria and algae. Some of the fast-growing algae at optimum condition bloom well showing their maximum population. This phenomenon is known as water blooming, and microorganisms associated with it are called water blooms. The two most important lakes of India which are fully eutrophicated are the Dal Lake Srinagar, J and K and Naina Lake Nainital which are the only source of potable water. The microorganisms growing in lakes are the genera: *Anabaena, Microcystis, Nostoc Oscillatoria, Oedogonium, Spirulina, diatoms, protozoa,* etc. The capacity of rivers and streams to process the added organic material is limited. If too much organic material is added, the water becomes anaerobic. This situation arises in those rivers and lakes which are present near the urban areas. In streams and rivers untreated or inadequately treated municipal wastes and other organic materials are discharged. These organic wastes cause changes in microbial community. Release of organic wastes from known sources is called point source of pollution. When the number of organic materials added is not too high, it supports the growth of several algae. Algae produce O_2 during photosynthesis in day light and evolve CO, in day and night. This results in diurnal oxygen shifts. In the meantime, oxygen level completes the self-purification process. This demand of oxygen is expressed in terms of biological oxygen demand (BOD) or the chemical oxygen demand (COD).

3. Purification of water

There are several methods for purification of water the use of which depends on amount and quantity of water. For example, purification of water required for a single household differs from that of a town or city. Secondly, purification of water is essential before its consumption so that disease cycle of pathogenic microorganisms can be broken. Thus, purification of water results in prevention of pathogen to reach the human body.

Therefore, water purification is done with the prospect of making it satisfactory in appearance, taste, odour and free from pathogens. There are three chief methods which are used for the purification of drinking water in municipal supplies as. sedimentation, filtration and disinfection.

3.1. Sedimentation

Sedimentation is done when water consists of large sized organic materials such as leaves. and gravels which have run off from the soil. Suspended particles settle down depending on their size and weight and conditions of the stored water. Sedimentation is done in large reservoirs or in restricted area of settling tank. The rate of sedimentation is enhanced by adding alum, iron, salts, colloid silicates which act as coagulants. The suspended materials and microorganisms are entrapped by coagulants and settle down rapidly. This procedure is called coagulation or flocculation. The microorganisms remain viable for some time. Thus, sedimentation provides partial reduction of microorganisms in water due to their settling down on bottom but does not sterilize the polluted water.

The population of Phys arum a slime Mold is reduced as it settles down on bottom, but full sterilization of polluted water does not occur by sedimentation.

3.2. Filtration

It is the second step of purification. After sedimentation the water is further purified by passing to filtration unit. It is the effective means of removing microorganisms and the other suspended material from the water. There are two types of sand filters which are used in water purification such as slow sand filter and rapid sand filter.

3.2.1 Slow sand filter

In slow sand filtration plants, the rate of filtration of water is slow, hence the plant requires a considerable area. This plant consists of a concrete floor containing drainage tiles for collection of filtered water. The tile is covered with first coarse sand and finally 2 to 3 feet of sand at the top of plant.

Water is passed through this plant. Water passes slowly through the filter and collected by tile drainpipes at the bottom which later is pumped into a reservoir. If water is turbid, slow sand filters are clogged soon. Therefore, turbid water, which is to be filtered, should be clarified first by sedimentation, thereafter, passed through slow sand filters. The capacity of slow sand filter plant is to filter about 5 million of water per acre per day.

Water purification is done not by physical action but by physiological mechanisms supported by microorganisms. In the surface of layers of fine sand a colloidal material, consisting of bacteria, algae and protozoa, is attached. This mucilaginous material makes the pores more effective by closing the pores between the sand grains. Sand grains have positive charges and bacterial cell walls have negative charge. Therefore, bacteria are adsorbed on the surface of sand. Protozoa ingest bacteria. Due to intense microbial interactions, chemical concentration of water is reduced. When filtration efficiency of the plant is reduced, due to deposition of thick mucilaginous material, the plant is taken out for cleaning. Through this plant, the pathogenic microorganisms such as Giardia and its cysts which are not removed by any other methods can be filtered from water.

3.2.2 Rapid sand filter

Like slow sand filter, the rapid sand filter is also constructed. This plant consists of layers of sand, gravel and rock. Before filtration, water is treated with alum or ferrous sulphate in a settling tank where precipitates settle down. Then water is allowed to pass through rapid sand filter plant. This plant depends on physical trapping of fine particles and flocs or coagulants. The pores of the plants are soon clogged. It is cleaned by forcing cleaned water backward ie. back washing through the beds of gravels and sands without disturbing the fine sand.

About 99% bacteria are removed by this plant. But unfortunately, the use coagulants, rapid of filtration and chemical disinfection often does not remove Giardia lamblia cysts, Cryptosporidium calocysts, Cyclospora and viruses. More consistent removal of these pathogens is possible through slow sand filter. Therefore, water collected after filtration needs further treatment.

In addition, rapid sand filter plant operates about 50 time, faster than slow sand filter plant, and can delivers about 150 to 200 million gallons of water per acre per day. It requires less land area, less cost and less maintenance. Therefore, many plants are constructed in a chain. If one plant is being cleaned, the others are under operation.

3.3 Disinfection

Some of the bacteria pass through filter even after filtration which must be killed before consumption of water. Therefore, disinfection of public water supply needs to be done. Disinfection is the final step of water purification. Solutions of sodium hypochlorite are treated in small towns but in recent years, chlorination of public water supply has become popular. Chlorination involves the release of chlorine gas in water which gets readily mixed up with water. The amount of chlorine required depends on organic matter and number of microorganisms present in water, and duration of time to act upon. High concentration of chlorine quickly acts upon microorganisms and vice-versa. Therefore, the amount of chlorine required for disinfection is called chlorine demand. Water is chlorinated to contain about 0.1 to 0.2 ppm of residual chlorine which reaches to this concentration after 20 minutes of its addition. However, if the concentration of chlorine exceeds its demand, peculiar odour and tastes are experienced. If action of chlorine prolongs in water containing high amount of organic matter, chloramines, are formed. Change in odour and taste of water is due to the formation of chlorophenols. In the presence of high organic matter, chlorine reacts with it and produces halomethanes which are a group of carcinogenic compounds.

The mechanism of action of chlorine on microorganisms is obvious. After reacting with water, chlorine is converted into hypochlorous acid which in turn quickly releases nascent oxygen. The nascent oxygen soon oxidises the cellular components of microorganisms as well as organic matter. In addition, chlorine fails to kill the microbial spores. The other gas which behaves like chlorine is the ozone. The simplest method to make water free from microbes and for consumption is boiling for 10-15 minutes.

Conclusion:

Water pollution is a major problem affecting human health and environment worldwide. The main source of pollution is industrial waste sewage disposal and agriculture runoff. It also damages aquatic ecosystem by depleting oxygen level. The water treatment facilities must upgrade for remove contaminations more effective before water is discharged back into environment.

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ADVANCED GRAPHENE NANOMEMBRANES FOR CLEAN WATER SOLUTIONS

Kailash Nemade

Department of Physics,

Indira Mahavidyalaya, Kalamb, Dist. Yavatamal 445401, Maharashtra.

Corresponding author E-mail: krnemade@gmail.com

Abstract:

Graphene nanomembranes offer a revolutionary approach to water purification due to their unique properties, including atomic thickness, high mechanical strength, chemical stability, and exceptional permeability. These membranes are highly efficient in removing contaminants such as salts, heavy metals, organic pollutants, and microorganisms, making them ideal for applications like desalination and wastewater treatment. Graphene oxide (GO) membranes, with their sub-nanometer pores, enable precise filtration with lower energy consumption compared to conventional methods. Their anti-fouling properties further enhance operational efficiency and lifespan. Despite their promise, challenges such as scalability, long-term durability, and high production costs hinder widespread adoption. This work highlights the role of graphene nanomembranes in transforming water purification technologies and addressing global water challenges. Innovations in fabrication and cost reduction are key to unlocking their potential for sustainable and energy-efficient water treatment solutions.

Keywords: Graphene; Nanomembranes; Nanotechnology

1. Introduction:

Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, has captivated the scientific community since its discovery in 2004. Known for its remarkable mechanical, electrical, and thermal properties, graphene has paved the way for advancements in various scientific and industrial fields. Among the many applications of graphene, its use in nanomembranes has gained significant attention. Graphene nanomembranes (GNMs) are ultra-thin sheets of graphene or graphene derivatives that serve as selective barriers, allowing specific molecules to pass while blocking others. This property makes them promising candidates for applications in filtration, sensing, energy storage, and beyond. This document explores the fundamental properties of graphene nanomembranes, their synthesis techniques, current and potential applications, and the challenges faced in their development and commercialization [1].

2. Properties of Graphene nanomembranes

2.1 Mechanical strength

Graphene is renowned for its exceptional mechanical strength, with a tensile strength of approximately 130 GPa and a Young's modulus of around 1 TPa. These properties make GNMs highly durable and resistant to mechanical deformation, even when reduced to atomic thickness.

2.2 Permeability

One of the most intriguing properties of GNMs is their ability to selectively allow certain molecules to pass through. Pristine graphene is impermeable to all gases and liquids; however, by introducing nanoscale pores, its permeability can be engineered for specific applications such as water desalination, gas separation, and molecular sieving.

2.3 Electrical conductivity

Graphene's high electrical conductivity is another key feature, making GNMs suitable for applications in electronics and sensing. The unique electronic properties of graphene are attributed to its zero bandgap and high carrier mobility, which can be tuned by functionalizing or doping the material.

2.4 Chemical stability

Graphene exhibits remarkable chemical stability under various environmental conditions. This stability is crucial for applications in harsh environments, such as industrial filtration or chemical processing.

2.5 Thermal properties

Graphene is an excellent conductor of heat, with thermal conductivity values exceeding 3000 W/mK. This property enhances the durability and performance of GNMs in applications where heat dissipation is critical [2].

3. Synthesis techniques

3.1 Chemical Vapor Deposition (CVD)

CVD is one of the most common methods for synthesizing large-area graphene films. In this process, a carbon-containing gas (e.g., methane) is decomposed at high temperatures on a catalytic substrate, typically copper or nickel. The graphene film can then be transferred onto a desired substrate or used as a freestanding nanomembrane.

3.2 Liquid-phase exfoliation

This technique involves exfoliating graphite in a solvent to produce graphene flakes. While this method is relatively simple and scalable, it often results in smaller graphene sheets with lower uniformity compared to CVD.

3.3 Chemical reduction of graphene oxide

Graphene oxide (GO) is produced by oxidizing graphite, making it hydrophilic and dispersible in water. The GO can be chemically reduced to obtain reduced graphene oxide (rGO), which retains some of the properties of graphene. rGO is often used in nanomembrane applications due to its ease of fabrication and functionalization.

3.4 Mechanical exfoliation

This method, also known as the "Scotch tape" method, involves peeling layers of graphene from graphite. While it produces high-quality graphene, its scalability is limited, making it more suitable for research purposes than industrial applications [3].

4. Applications of graphene nanomembranes

4.1 Water filtration and desalination

GNMs have demonstrated the ability to efficiently filter and desalinate water. By introducing nanoscale pores in the graphene sheet, researchers have developed membranes capable of removing salt ions and contaminants from water while allowing water molecules to pass through. These membranes offer high throughput and energy efficiency compared to conventional reverse osmosis membranes.

4.2 Gas separation

GNMs are also being explored for gas separation applications. Their tunable pore sizes and chemical functionalization enable the selective separation of gases such as hydrogen, carbon dioxide, and methane. This capability is particularly valuable in industries like petrochemicals and carbon capture.

4.3 Energy storage

In energy storage devices such as batteries and supercapacitors, GNMs can serve as ion-selective separators or conductive substrates. Their high surface area and electrical conductivity enhance the performance of these devices by improving ion transport and charge storage capacity.

4.4 Sensing

Graphene’s high sensitivity to changes in its environment makes GNMs ideal for sensing applications. They can detect trace amounts of gases, biomolecules, or chemicals, enabling advancements in environmental monitoring, medical diagnostics, and security.

4.5 Protective coatings

Due to their mechanical strength and chemical stability, GNMs can be used as protective coatings for various surfaces. They resist corrosion, wear, and chemical attack, extending the lifespan of materials in harsh environments.

4.6 Biomedical applications

GNMs are being investigated for use in biomedical applications, including drug delivery, biosensing, and tissue engineering. Their biocompatibility and functionalizability allow them to interact with biological systems in a controlled manner [4].

5. Role of graphene nanomembrane in water purification technology

Graphene nanomembranes are increasingly recognized as transformative materials in water purification technology due to their exceptional properties. Here is an overview of their role:

Key properties of graphene nanomembranes

- **Atomic Thickness:** Graphene is a single layer of carbon atoms arranged in a hexagonal lattice, making it exceptionally thin yet robust.
- **High mechanical strength:** Graphene's tensile strength allows the fabrication of durable membranes.
- **Hydrophobicity with tunable hydrophilicity:** Chemical functionalization makes graphene adaptable for specific water filtration requirements.
- **Superior permeability:** Water can pass through graphene oxide membranes rapidly, while rejecting impurities due to narrow pore sizes.
- **Chemical resistance:** Graphene membranes are stable in various chemical environments, which is advantageous for desalination and industrial wastewater treatment [5].

6. Role in water purification

6.1 Salt rejection in desalination:

Graphene oxide (GO) membranes exhibit excellent salt rejection due to their sub-nanometer-sized pores, which allow water molecules to pass while blocking ions and other contaminants.

They operate with lower energy requirements compared to conventional reverse osmosis technologies [6].

6.2 Removal of contaminants:

Graphene membranes can filter out heavy metals, organic pollutants, and biological contaminants like bacteria and viruses. Functionalized graphene enhances the selectivity for specific pollutants.

6.3 Anti-fouling properties:

The smooth surface of graphene reduces fouling by biofilm formation, increasing the operational lifespan of the membranes.

6.4 Advanced wastewater treatment:

Graphene membranes are used to treat industrial effluents, including dyes, oil spills, and pharmaceutical waste, by leveraging their high adsorption capacity.

6.5 Energy efficiency:

Compared to traditional purification systems, graphene membranes require less pressure to operate, making the process more energy-efficient [7].

7. Challenges and future directions

- **Scalability:** Developing large-scale graphene membranes with uniform properties remains a challenge.
- **Durability:** Long-term performance and resistance to mechanical stress need improvement.
- **Cost:** High production costs of graphene materials hinder widespread adoption [8].

8. Challenges and limitations

8.1 Scalability

Producing high-quality graphene at a large scale remains a significant challenge. Techniques like CVD offer high-quality graphene but are expensive and time-consuming. On the other hand, scalable methods like liquid-phase exfoliation often result in lower-quality material.

8.2 Defect control

Controlling the size, shape, and distribution of pores in GNMs is critical for their performance in applications like filtration and sensing. Achieving precise control over these defects at the nanoscale is challenging and requires advanced fabrication techniques.

8.3 Stability in real-world conditions

While graphene is chemically stable, GNMs can degrade under certain conditions, such as exposure to high humidity, extreme temperatures, or oxidative environments. Enhancing their durability in real-world applications is essential for commercialization.

8.4 Cost

The high cost of graphene production and processing hinders the widespread adoption of GNMs. Developing cost-effective synthesis and fabrication methods is crucial for making GNMs commercially viable.

8.5 Integration with existing systems

Incorporating GNMs into existing industrial systems or devices often requires extensive modifications and testing. Ensuring compatibility and reliability in real-world applications poses additional challenges [9].

9. Future prospects

Despite the challenges, the potential of graphene nanomembranes remains immense. Ongoing research aims to address the limitations and unlock new possibilities for GNMs. Key areas of focus include:

- **Advanced fabrication techniques:** Developing methods for precise pore engineering and large-scale production of high-quality GNMs.
- **Hybrid materials:** Combining graphene with other materials to enhance its properties and expand its application scope.
- **Functionalization:** Exploring new ways to functionalize GNMs for specific applications, such as targeted drug delivery or advanced filtration.
- **Sustainability:** Investigating eco-friendly and cost-effective production methods to reduce the environmental impact of graphene manufacturing.
- **Commercialization:** Collaborating with industries to scale up production and integrate GNMs into commercial products [10-13].

Conclusions:

Graphene nanomembranes represent a groundbreaking advancement in water purification technology, offering superior efficiency and versatility compared to traditional methods. Their atomic thickness, exceptional mechanical strength, and precise filtration capabilities make them highly effective for applications such as desalination, removal of heavy metals, and treatment of industrial wastewater. The ability of graphene oxide membranes to reject salts and contaminants while allowing rapid water permeability presents a sustainable and energy-efficient alternative to conventional technologies like reverse osmosis. Additionally, the anti-fouling properties of graphene membranes significantly reduce maintenance requirements, enhancing their longevity and operational efficiency. Despite these advantages, challenges such as high production costs, scalability for large-scale applications, and long-term durability remain critical barriers to their widespread adoption.

Advancements in fabrication techniques, along with efforts to reduce production costs, will be essential for realizing the full potential of graphene nanomembranes. Continued research and development can address these challenges and pave the way for the large-scale implementation of graphene-based solutions in addressing global water scarcity and pollution issues. By leveraging these innovative materials, the future of water purification can move toward more sustainable, cost-effective, and energy-efficient solutions, contributing significantly to the resolution of pressing environmental challenges.

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SUSTAINABLE WATER MANAGEMENT: STRATEGIES FOR RESILIENCE AND EQUITY

Jaymala Kumawat
Vishwakarma University, School of Pharmacy, Pune, Maharashtra, India.
Corresponding author E-mail: jaymalakumawat@gmail.com

Abstarct:

Water is an indispensable resource essential for sustaining life, ecosystems, and economic development. As global populations expand and urbanization accelerates, the growing demand for water has resulted in challenges such as overuse, pollution, depletion of groundwater resources, and climate-induced water scarcity. The critical nature of water as a finite resource necessitates a paradigm shift toward sustainable water management practices to ensure its availability and quality for current and future needs.

Sustainable water management emphasizes balancing environmental conservation, social equity, and economic viability. It incorporates a holistic approach that integrates watershed management, technological innovation, governance, and community participation. Strategies include the efficient allocation and use of water resources, protection and restoration of natural ecosystems, and the implementation of water-saving technologies and practices across sectors such as agriculture, industry, and households.

Addressing the impacts of climate change is a cornerstone of sustainable water management. With increasing variability in precipitation patterns, rising temperatures, and extreme weather events, adaptive strategies are essential. These include the development of resilient water infrastructure, enhancement of water storage and recharge capacities, and promotion of climate-smart agricultural practices.

Principles of sustainable water management

Holistic water resource management

Holistic water resource management involves considering the interconnected social, economic, and environmental dimensions of water use. By integrating these perspectives, it is possible to create strategies that optimize water usage without compromising ecological balance or economic development. Key approaches include: Integrated Resource Management: Ensuring water planning and distribution align with land use, agriculture, and urban development to meet diverse needs effectively.

Stakeholder participation:

Actively involving local communities, industries, governments, and non-governmental organizations in decision-making to ensure equitable and inclusive water governance.

Water efficiency and conservation

Efficient water usage is essential to meet growing demands while conserving this finite resource. Core principles include:

- Minimizing Waste: Promoting technologies like efficient irrigation systems, low-flow fixtures, and water-smart industrial processes to reduce unnecessary water consumption.
- Awareness Campaigns: Educating the public and industries on sustainable practices and encouraging behavioral changes to foster water conservation at all levels

Protection of ecosystems

Healthy ecosystems are critical for natural water regulation, purification, and biodiversity. Sustainable management prioritizes:

- **Preservation:** Safeguarding wetlands, forests, rivers, and aquifers to maintain their ecological functions and prevent degradation.
- **Restoration:** Rehabilitating damaged ecosystems through reforestation, wetland reconstruction, and pollution clean-ups to restore natural water cycles and biodiversity.

Climate resilience

Adapting to climate variability is essential for maintaining water security. Key measures include:

- **Risk management:** Developing plans to mitigate the impacts of extreme weather events, such as floods, droughts, and rising sea levels.
- **Resilient infrastructure:** Investing in infrastructure, such as flood barriers and drought-resistant water storage systems, to safeguard communities from climate-related disruptions.

Strategies for implementation

1. Assessment and monitoring

Effective water management begins with understanding the current state of resources. Strategies include:

- **Comprehensive monitoring:** Regularly measuring groundwater levels, surface water quality, and usage patterns to inform decisions.
- **Technological tools:** Employing remote sensing, geographic information systems (GIS), and AI for precise data analysis and forecasting.

2. Effective governance

Strong governance structures are vital for equitable and sustainable water use. Steps include:

- **Legal frameworks:** Establishing clear laws and policies to regulate water use, pollution, and distribution.
- **International cooperation:** Strengthening agreements on transboundary water resources to promote peaceful and efficient sharing.

3. Demand management

Reducing water demand through innovative practices ensures sustainability. Examples include:

- **Agricultural efficiency:** Utilizing advanced irrigation methods like drip and sprinkler systems to reduce water wastage.
- **Urban recycling:** Encouraging greywater recycling and rainwater harvesting in urban settings to reduce dependency on freshwater sources.
- **Economic incentives:** Implementing water pricing mechanisms that reflect its true value, discouraging overuse.

4. Pollution prevention

Maintaining water quality is crucial for the sustainable management of water resources. It ensures the availability of clean water for various purposes, including drinking, agriculture, industry, and maintaining ecological balance. The following initiatives are integral to preventing pollution and safeguarding water quality:

Regulatory enforcement

Stringent enforcement of environmental regulations is vital to curb the release of harmful substances into water bodies. Key measures include:

- **Control of industrial discharges**: Ensuring industries comply with environmental standards by monitoring effluents, setting discharge limits, and penalizing violations. This minimizes the release of heavy metals, toxins, and hazardous chemicals into water systems.

- **Management of agricultural runoff**: Implementing regulations to reduce the use of fertilizers, pesticides, and herbicides that contribute to nutrient pollution and eutrophication. Encouraging sustainable farming practices like buffer zones, crop rotation, and precision agriculture further reduces runoff.
- **Public awareness and compliance**: Educating stakeholders, including industries and farmers, about the environmental and economic benefits of adhering to regulations, thereby fostering voluntary compliance.

Wastewater treatment

Constructing and upgrading wastewater treatment facilities is fundamental to water pollution prevention. These facilities play a critical role in recycling water and removing pollutants before discharge or reuse. Key components include:

- **Primary treatment**: Involves the removal of large solids and sedimentation of suspended particles to reduce the pollutant load.
- **Secondary treatment**: Uses biological processes to degrade organic matter and reduce biochemical oxygen demand (BOD), ensuring the water is safe for ecological discharge.
- **Tertiary treatment**: Advanced treatment processes, such as filtration, disinfection, and nutrient removal, are employed to eliminate pathogens, phosphorus, nitrogen, and trace contaminants.
- **Reuse of treated water**: Treated water can be used for irrigation, industrial processes, and even as a supplement for drinking water after advanced treatment.

Supporting initiatives

1. **Integrated Water Resource Management (IWRM)**: Promoting a coordinated approach to managing water, land, and related resources ensures sustainable development while addressing pollution sources.
2. **Community involvement**: Engaging communities in monitoring water quality, reporting pollution incidents, and participating in clean-up drives fosters collective responsibility.
3. **Technological innovations**: Encouraging the adoption of eco-friendly technologies, such as biofilters, constructed wetlands, and membrane bioreactors, enhances wastewater treatment efficiency and sustainability.

5. Innovative infrastructure

Modern infrastructure can address challenges related to water availability and distribution. Key actions include:

- Efficient systems: Developing advanced water storage and distribution networks to minimize losses during transportation.
- Rainwater harvesting: Implementing large-scale and community-based rainwater collection systems to enhance water supplies in arid regions.

Challenges

- **Water Scarcity:** Rapid population growth and overextraction have strained water availability. Efficient allocation among competing sectors remains a critical challenge.
- **Pollution:** Contamination from industrial, agricultural, and domestic activities threatens water safety and ecosystem health.
- **Climate Change:** Shifting weather patterns disrupt water cycles, leading to unpredictable availability.
- **Financial and Institutional Barriers:** Insufficient funding for sustainable water projects and a lack of coordination among governing bodies impede progress.
- FUTURE DIRECTIONS
- **Technological Advancements:** Adopting smart water management systems and AI-driven analytics for real-time monitoring and decision-making. Exploring innovative purification methods to expand potable water access.
- **Community Involvement:** Empowering local populations to take active roles in water conservation efforts. Providing education on the importance of sustainable water practices.
- **Global Cooperation:** Encouraging international partnerships to share knowledge, technology, and funding for sustainable water projects.

Conclusion:

Sustainable water management is a cornerstone of addressing the pressing challenges of water security in the face of growing global populations, urbanization, industrialization, and climate change. Water scarcity, pollution, and ecosystem degradation pose significant threats to human health, food security, and economic development. Therefore, a comprehensive, forward-looking approach to managing water resources is indispensable for ensuring long-term availability and equitable access to this vital resource. By integrating technology, innovative solutions can be developed to optimize water use and enhance resource efficiency. Advanced techniques such as precision agriculture, smart irrigation systems, wastewater recycling, desalination, and water quality monitoring enable societies to use water more effectively while minimizing waste. Furthermore, data-driven tools like remote sensing and geographic information systems (GIS) provide insights into water resource management, aiding in informed decision-making and real-time monitoring of water systems.

Policy frameworks play a pivotal role in sustainable water management. Governments must implement and enforce robust regulations to prevent over-extraction of groundwater, control industrial and agricultural pollution, and safeguard water bodies. International cooperation is essential for transboundary water management, ensuring that shared resources are allocated equitably and used sustainably. Economic instruments such as water pricing, subsidies for efficient technologies, and incentives for conservation practices encourage responsible water use across all sectors.

Community engagement is equally critical in fostering a culture of conservation and stewardship. Public participation in water management decision-making promotes transparency and ensures that the voices of marginalized groups are heard. Community-driven initiatives, such as rainwater harvesting, afforestation, and local watershed restoration projects, empower individuals to contribute to sustainable water practices. Public awareness campaigns and educational programs also play a key role in changing behaviors and cultivating a sense of responsibility toward water conservation.

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WATER MANAGEMENT AND BIODIVERSITY CONSERVATION: SUSTAINING THE KASAL GANGA RIVER AMIDST AGRICULTURAL EXPANSION AND CLIMATE CHANGE

Amol B. Mamlayya[1] and Sagar A. Vhanalakar[2]

[1]Department of Zoology,

Rayat Shikashan Sanstha's, Karmaveer Bhaurao Patil Mahavidyalaya, Pandharpur (Autonomous), Maharashtra

[2]Department of Zoology,

Shri Mouni Vidyapeeth's, Karmaveer Hire Arts, Science, Commerce and Education College, Gargoti, Dist. Kolhapur, Maharashtra

Corresponding author E-mail: abmamale@gmail.com, sagarayan36@gmail.com

Abstract:

The Kasalganga River, a vital tributary in Solapur district, Maharashtra, exemplifies the ecological and socio-economic significance of smaller rivers. Originating from Katpahl village and traversing 23 villages across Sangola, Pandharpur, and Malshiras tehsils before merging with the Bhima River at Shelve village, the river supports agriculture, fisheries, and rural livelihoods, functioning as a crucial economic corridor. Despite its importance, the river's biodiversity remains understudied. This study aims to bridge this gap by exploring the flora, fauna, and microhabitats associated with the Kasalganga River. Conducted over two years (December 2022 to November 2024), the research highlights the ecological value of the river and its role within the socio-economic framework of the region. The findings provide critical insights for biodiversity conservation and promote sustainable management practices to preserve this vital ecosystem.

Keywords: Kasalganga River, Diversity, Micro Habitat, Ecology

Introduction:

Freshwater ecosystems, including rivers, lakes, wetlands, and aquifers, are vital for Earth's biodiversity and human livelihoods, offering essential ecosystem services (Harrison *et al.,* 2018). Despite their significance, these ecosystems are under severe threat due to habitat destruction, pollution, overextraction, invasive species, and climate change (Dudgeon, 2019; Cowie, Bouchet, and Fontaine, 2022). Addressing this crisis requires integrated, science-driven approaches and robust policy frameworks (De and Dwivedi,

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2024). India, with its diverse network of freshwater ecosystems, faces growing challenges to biodiversity from rapid urbanization, industrialization, and agricultural expansion (Government of India, 2012). Biodiversity hotspots like the Western Ghats harbor unique freshwater species, including endemic and threatened taxa, yet face persistent anthropogenic pressures (Ali *et al.,* 2013; Naniwadekar and Vasudevan, 2014). Smaller rivers, often overlooked in biodiversity research, play critical ecological and socio-economic roles in sustaining local communities.

The Kasalganga River in Solapur district, Maharashtra, exemplifies the importance of such smaller rivers. Originating in Katpahl village and flowing through 23 villages across Sangola, Pandharpur, and Malshiras tehsils, the river merges with the Bhima River at Shelve village. Functioning as an economic corridor, it supports agriculture, fisheries, and rural livelihoods. Despite its significance, the biodiversity of the Kasalganga River remains understudied, necessitating focused research for sustainable management. This study aims to explore the biodiversity associated with the Kasalganga River, highlighting its ecological importance and role in the socio-economic framework of the region. By documenting the flora, fauna, and microhabitats, the research provides valuable insights into conservation needs and sustainable practices for this vital ecosystem.

Globally, freshwater conservation strategies integrate ecological, hydrological, and socio-economic factors to sustain ecosystem health (Arthington and Pusey, 2003; Arthington *et al.,* 2004). India employs methodologies like the Tennant Concept and adaptive management systems to balance ecological and human water demands (Amrit, Mishra, and Pandey, 2017; Biggs and Rogers, 2003). Programs like the Namami Gange showcase the potential for large-scale restoration efforts (Press Information Bureau, 2022). However, climate change compounds threats to freshwater ecosystems by altering hydrological cycles and ecosystem functionality (Mujumdar, 2008). Research reveals heightened vulnerability to extreme climatic events, emphasizing the need for resilience in water resource management (Bond, Lake, and Arthington, 2008). Studies like Allan and Flecker (1993) argue for landscape-level perspectives that address both local and regional influences on freshwater ecosystems.

The Kasalganga River study aligns with these global and national efforts, underscoring the ecological and socio-economic value of smaller rivers. By integrating ecological research, policy recommendations, and community engagement, this study seeks to bridge science and practice, offering a model for conserving overlooked freshwater systems. The findings contribute to broader conservation narratives, ensuring sustainable management for future generations (Arora *et al.,* 2024; Lynch *et al.,* 2023).

Materials and Methods

Duration of study

The study was conducted over a period of nearly two years, from December 2022 to November 2024**.**

Study area

The research focused on the Kasalganga River, which originates in Katphal village and flows through 23 villages in Sangola, Pandharpur, and Malshiras tehsils of Solapur district, Maharashtra. The river serves as an economic corridor, supporting agriculture, fisheries, and rural livelihoods, before merging with the Bhima River at Shelve village. Sampling sites included Katphal**,** Mahud**,** Supali**,** Upari, and Shelve**.**

Biodiversity studies

Biodiversity assessments included the study of:

1. **Phytoplankton and zooplankton**: Collected and analyzed from the river water at various sampling points.
2. **Entomofauna**: Surveys were conducted for insects associated with the Kasalganga River and nearby agricultural fields.
3. **Ichthyofauna (Fish)**: Fish data was gathered through interviews with local fishermen who harvest fish from the river and Katphal dam.
4. **Other fauna**: Amphibians, reptiles, birds, and mammals associated with the Kasalganga River and its surrounding habitats were observed and documented.

Field visits

Regular field visits were conducted to the selected sampling sites to collect data and samples.

Sample and data analysis

The research was conducted in two phases:

1. **Field phase**:
    - Direct observations and sample collections were carried out at the selected sites along the Kasalganga River.

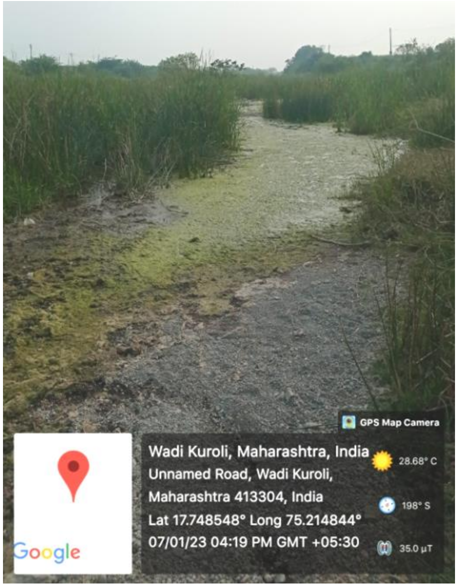
- Collected specimens included aquatic organisms (phytoplankton, zooplankton, and fish), terrestrial insects, and other fauna.

2. **Laboratory phase**:
    - Specimens were identified using field guides and taxonomic keys.
    - Water samples were analyzed at ANALAB, Solapur, to evaluate physicochemical parameters, providing insights into the river's water quality and its influence on biodiversity.

Biodiversity survey of Kasalganga river

Main stem of Kasalganga river Behind Katpahal Lake

View of Katphal Lake



Algae in the Kasalganga river

Algae in the Kasalganga river

Results and Discussion:

I. Physicochemical parameters of water, zooplanktons, and phytoplanktons

Water samples were collected from five sites (Katphal Lake, Mahud, Supali, Upari, and Shelave) between 6:00 AM and 7:00 AM. The key water quality indicators—Hardness, Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD)—were assessed, and the results are summarized in Table 1**.**

- **Hardness**: The permissible limit for hardness is set at 600 mg/L by the Bureau of Indian Standards (BIS). All sites, except Shelave, were within this limit. Shelave exhibited a hardness value of 793 mg/L**,** indicating an elevated concentration of salts and suggesting potential ecological impacts for aquatic life.
- **Chemical Oxygen Demand (COD)**: The permissible COD limit is less than 250 mg/L. All sites were within the allowable limit, with values ranging from 16.3 mg/L to 49.0 mg/L**.**
- **Biochemical Oxygen Demand (BOD)**: According to BIS, the BOD limit is 30 mg/L. All sites were well below this threshold, with values ranging from 5.45 mg/L to 16.8 mg/L**.**

Overall, while the water quality for COD and BOD is within the permissible limits at all sites, the Shelave site shows an alarming increase in hardness, which may have significant implications for the local aquatic ecosystem.

Table 1: **Hardness, COD, and BOD of Five Different Sites from Kasalganga River**

Sample ID	Hardness as $CaCO_3$, mg/I	C.O.D. mg/I	B.O.D. /I
Katphal	231	49.0	16.8
Mahud	425	32.7	11.5
Supali	244	24.5	8.00
Upari	219	16.3	5.45
Shelave	793	38.4	12.7

The study conducted by Chinamalli and Vijaykumar (2022) provides valuable insights into the water quality of the Bhima River, crucial for assessing its suitability for drinking purposes. The use of a water quality index (WQI) revealed that the water quality of the river fluctuated between "good" and "very poor," with some locations exceeding the Bureau of Indian Standards (BIS) limits for key physicochemical parameters such as electrical conductivity (EC), total hardness (TH), and total alkalinity (TA), all of which were influenced by anthropogenic activities. This study highlights the necessity of continuous water quality monitoring to ensure safe drinking water and to address the impact of human activities on freshwater systems. The significant correlation between EC and TDS, and between TH and TA, points to the need for careful consideration of anthropogenic impacts when evaluating water for consumption.

Various studies have highlighted the significance of monitoring water quality in river systems. Kleiner (1999) discusses the critical role of water as an essential nutrient, underlining the importance of ensuring safe and clean water sources for human consumption. Hashem and Qi (2021) review the impact of treated wastewater irrigation, pointing to how human interventions, like industrial wastewater, affect water quality, which is also seen in the Bhima and Kasalganga rivers. Falah and Haghizadeh (2017) conduct hydrochemical evaluations of river water quality, demonstrating how key physicochemical parameters like hardness and alkalinity are influenced by anthropogenic activities, as observed in both rivers. Kumar and Dua (2009) emphasize the use of the Water Quality Index (WQI) to assess river health, a method also employed to measure water quality in the Bhima and Kasalganga rivers. Lastly, Teng *et al.* (2011) explore how urbanization and industrialization contribute to surface water quality degradation, a trend evident in the Bhima and Kasalganga rivers, where human activities significantly alter the water's physicochemical characteristics. These studies collectively reinforce the importance of ongoing water quality assessments to safeguard public health and the environment.

II. Zooplankton composition

Table 2 presents the composition of common zooplankton species in the Kasalganga River, illustrating a diverse and ecologically significant community:

- **Daphnia species**, known for their sensitivity to environmental changes, are key indicators of water quality.
- **Brachionus species** contribute significantly to nutrient cycling within the aquatic ecosystem.
- The presence of **Calanoida** and **Cyclopoid copepods** suggests a productive environment capable of supporting multiple trophic levels.

This diverse zooplankton community plays an essential role in the river's food web, supporting higher trophic levels and helping to maintain ecological balance.

Table 2: **Composition of Common Zooplanktons in the Kasalganga River**

Sr. No.	Scientific Name
1.	*Brachionus calyciflorus*
2.	*Brachionus angularis*
3.	*Keratella species*
4.	*Calanoida species*
5.	*Lecane species*
6.	*Daphnia species*
7.	*Cyclopoid copepod*
8.	*Calanoid copepod*
9.	*Cyclops*
10.	*Daiptomus*
11.	*Coscinodiscus*

III. Phytoplankton Composition:

The phytoplankton community in the Kasalganga River, detailed in Table 3, is diverse and plays a crucial role in the river's primary production. Key observations include:

- Chlorella and Microcystis species are vital contributors to oxygen generation through photosynthesis, sustaining the river's ecosystem.
- Anabaena species are important for nitrogen fixation, which enriches the water column with essential nutrients that support aquatic life.
- The presence of a variety of green and blue-green algae underscores the river's high ecological complexity and productivity, forming the foundation for a healthy aquatic food web.

This rich diversity of phytoplankton enhances the river's ability to support various trophic levels and maintain ecological balance.

Table 3: **Composition of Common Phytoplanktons in the Kasalganga River**

Sr. No.	Scientific Name
1.	Chlorella species
2.	Microcystis species
3.	Green algae species
4.	Tetraedron species
5.	Acutodesmus species
6.	Anabaena species
7.	spirogyra species
8.	chroococcus species
9.	Nostoc species
10.	Brown algae
11.	Red algae

Dede and Deshmukh (2015) recorded a total of 21 species of zooplankton belonging to four classes: Rotifera, Cladocera, Copepoda, and Ostracoda, from the Bhima River near Ramwadi village. The class Rotifera represented 9 species, Cladocera 5 species, Copepoda 5 species, and Ostracoda 2 species. The work of various researchers has contributed significantly to the understanding of freshwater ecosystems and zooplankton diversity. Adoni *et al.* (1985) authored the *Workbook for Limnology*, offering essential theoretical and practical knowledge on freshwater ecology in India. Annalakshmi and Amasth (2011) focused on the hydrobiology of the River Cauvery and its tributaries, specifically studying zooplankton in the Kumbakonam region, Tamil Nadu. The APHA (1998) provided standardized methods for the examination of water and wastewater, which are widely used for water quality analysis. Bhouyain and Asmat (1992) explored the diversity of freshwater zooplankton in Bangladesh, contributing to understanding species distribution in South Asian freshwater habitats. Dhanapathi (2000) provided taxonomic insights into the Rotifera group in India, enhancing the classification of rotifer species in aquatic systems. Dhembare (2011) examined zooplankton diversity in Mula Dam, Maharashtra, and its relationship with water quality parameters, emphasizing ecological indicators. Edmondson (1959)**,** through *Freshwater Biology*, laid the groundwork for studying freshwater ecosystems, particularly species diversity. Gaike *et al.* (2012) studied seasonal variations in zooplankton populations in Nagatas Dam, Jalna, highlighting temporal shifts in aquatic biodiversity. Finally, Gayathri *et al.* (2014) analyzed zooplankton population dynamics and seasonal abundance in Doddavoderahalli Lake, Bangalore, contributing valuable insights into community structure in freshwater lakes. Together, these studies provide a comprehensive understanding of zooplankton diversity, seasonal variation, and the physicochemical factors affecting freshwater ecosystems.

IV. Entomofauna in and around Kasalganga River

The Kasalganga River region, with its rich and diverse ecosystems, harbors a variety of insect species across multiple orders, which play significant ecological roles. The entomofauna recorded in this region reflects the balance between aquatic and terrestrial environments and their health. Below are the major insect groups observed in and around the Kasalganga River:

1. **Grasshoppers and Crickets (Order: Orthoptera):** Table 4 presents a list of grasshopper and cricket species recorded in the Kasalganga River region. The order Orthoptera, including species from the families Acrididae, Pyrgomorphidae, Tettigoniidae, and Gryllidae, contributes to herbivory and serves as prey for various higher trophic levels. Notable species include:
    - ***Dittopternis venusta*** (Acrididae)
    - ***Trilophidia annulata*** (Acrididae)
    - ***Phaeoba infumata*** (Acrididae)

- ***Hieroglyphus banian*** (Acrididae)
- ***Acrida turrita*** (Acrididae)
- ***Mecopoda elongata*** (Tettigoniidae)

Table 4: Orthoptera Species Recorded in Agricultural Fields and Grasslands Around Kasalganga River

Sr. No	Name of the Species	Family
1	*Dittopternis venusta* Walker, 1870	Acrididae
2	*Trilophidia annulata* Thunberg, 1815	Acrididae
3	*Gesonula punctifrons* Stal, 1860	Acrididae
4	*Phaeoba infumata* Brunner Van Wattenwyi 1893	Acrididae
5	*Acrida turrita* Linnaeus,1758	Acrididae
6	*Hieroglyphus banian* Fabricius, 1798	Acrididae
7	*Stenocatantops splendens* Thunberg, 1815	Acrididae
8	*Acrida exaltata* Walker, 1854	Acrididae
9	*Cyrtacanthacris tatarica* Linnaeus, 1758	Acrididae
10	*Gastrimargus marmoratus* Thunberg, 1815	Acrididae
11	*Eyprepocnemis alacris alacris,* Serville, 1839	Acrididae
12	*Atractomorpha crenulata* Fabricius, 1793	Pyrgomorphidae
13	*Chrotogonus trachypterus trachypterus* Bianchard, 1836	Pyrgomorphidae
14	*Conocephalus maculates* Le Guillous 1841	Tettigoniidae
15	*Mecopoda elongate* Linnaeus, 1758	Tettigoniidae
16	*Holochlora* sp.	Tettigoniidae
17	*Trigonocorpha unicolor* Stall, 1787	Tettigoniidae
18	*Euconocephalus incertaus* Walker,1869	Tettigoniidae
19	*Phonarellus minor* Chopard, 1959	Gryllidae
20	*Gryllodes sigillatus* Walker, 1869	Gryllidae
21	*Modicogryllus confirmatus* Walker,1859	Gryllidae
22	*Telegryllus mitratus* Burmeister, 1838	Gryllidae
23	*Trigonidium humbertianum* Saussure, 1878	Trigonidiidae

2. **Scarabaeid Beetles (Order: Coleoptera, Subfamilies: Melolonthinae, Rutelinae, Cetoniinae, Dynastinae)** Table 5 lists Scarabaeid beetles observed in agricultural fields around the Kasalganga River. These beetles, especially from the subfamilies

Melolonthinae, **Rutelinae**, and **Cetoniinae**, play crucial roles in soil aeration and organic matter decomposition. Notable species include:

- **Holotrichia fissa** (Melolonthinae)
- **Anomala bengalensis** (Rutelinae)
- **Oryctes rhinoceros** (Dynastinae)
- **Adoretus versutus** (Cetoniinae)

Table 5: Scarabaeid Beetles Recorded in Different Agricultural Fields

Sr. No.	Name of the Species	Name of Subfamily
1	*Holotrichia fissa* Brenske	Melolonthinae
2	*Maladera castanea* Arrow	
3	*Maladera holosericea* Scopoli	
4	*Maladera sp.*	
5	*Apogonia sp.*	
6	*Anomala bengalensis* Blanchard	Rutelinae
7	*Anomala dorsalis* Fab.	
8	*Anomala sp*	
9	*Adoretus versutus* Harold	
10	*Adoretus sp.*	
11	*Adoretus sp.*	
12	*Chiloloba acuta* Wied.	Cetoniinae
13	*Anatona stillata* Newman	
14	*Oryctes rhinoceros* Linn.	Dynastinae
15	*Phyllognatus dionycious* Fab	

3. **Coprophagous Beetles (Family: Scarabaeidae, Order: Coleoptera)** Table 6 outlines the coprophagous beetles in the region, vital for dung decomposition and nutrient cycling. Recorded species include:
   - ***Aphodius sp.*** *(Scarabaeidae)*
   - ***Onthophagus sp.*** *(Scarabaeidae)*
   - ***Heliocopris bucephalus*** *(Scarabaeidae)*
   - ***Catharsius molossus*** *(Scarabaeidae)*

Table 6: List of coprophagous beetles recorded during the study period

Sr. No.	Name of the Species	Name of Family	Order
1	*Aphodius* sp.	Scarabaeidae	Coleoptera
2	*Aphodius* sp.		
3	*Onthophagus* sp.		
4	*Onthophagus* sp.		
5	*Onthophagus catta*		
6	*Onitis philemon*		
7	*Oniticellus cinctus*		
8	*Heliocopris bucepalus*		
9	*Scarabaeus* sp.		
10	*Catharsius molossus*		

The study by K Srinivasa Murthy (2020) on the diversity and abundance of scarabaeid beetles in South India highlights significant findings regarding the species distribution in various agroecological regions across Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu. A total of 18 species of scarabaeid beetles were identified in different cropping patterns, including arecanut, coconut, groundnut, millets, mulberry, pepper, sugarcane, tapioca, and vegetables. The study revealed that Melolonthid beetles, known for their leaf-feeding behavior, were the most abundant (38.23%), followed by Rutelinids (20.53%). The occurrence of different species was influenced by various factors, including the specific cropping patterns, geographical locations, and soil types of the regions. These findings emphasize the complex relationship between agricultural practices and beetle diversity, as well as the role of environmental factors in shaping species distribution and abundance. The study contributes to understanding the ecological dynamics of scarabaeid beetles, which are important pests in agricultural systems, and underscores the need for integrated pest management strategies considering the influence of agroecosystem variables.

4. **Odonata (Order: Odonata)**

   The Odonata order, consisting of damselflies and dragonflies, was the dominant group in terms of species richness in the Kasalganga River region. The presence of 9 species from 3 families indicates a healthy aquatic habitat. Notable species include:

   - ***Ischnura aurora*** (Coenogrionidae)

- ***Anax sp.*** (Aeshnidae)
- ***Pantella flavescens*** (Libellulidae)
- ***Orthetrum sabina*** (Libellulidae)

Odonates are bioindicators of water quality due to their larvae's sensitivity to pollution and habitat disturbances.

The work done by Ashish D. Tiple and colleagues (2015) provides a comprehensive study on the Odonata diversity of Maharashtra, revealing a substantial richness of species in this region. Their surveys, conducted between 2006 and 2014, compiled a checklist of 134 species, representing 70 genera and 11 families. The families Libellulidae and Gomphidae were found to be the most diverse. This study not only adds 33 new species to the previously known list but also emphasizes Maharashtra's significant role as a hub of Odonata diversity. The importance of such studies lies in their ability to fill gaps in species distribution data, particularly through the integration of crowd-sourced data. This work highlights the ongoing need for long-term monitoring of Odonata populations in Maharashtra, as such research is crucial for biodiversity conservation and understanding the health of freshwater ecosystems. By identifying and documenting species diversity, it allows for better-informed conservation strategies and ecological management, ensuring that these valuable habitats are protected for future generations.

5. **Hemiptera (Order: Hemiptera)**

   The Hemiptera order includes predatory species that regulate the populations of other aquatic invertebrates. Species observed in the Kasalganga River region include:

   - **Nepa sp.** (Nepidae)
   - **Belostoma indica** (Belostomatidae)
   - **Notonecta sp.** (Notonectidae)

These species play a crucial role in controlling the population of other invertebrates in the aquatic ecosystems.

6. **Coleoptera (Order: Coleoptera)**

   The Coleoptera order, especially aquatic beetles from the families Gyrinidae, Dytiscidae, and Hydrophilidae, is indicative of healthy aquatic environments. Key species observed include:

   - **Dineutus indicus** (Gyrinidae)

- **Cybister sp.** (Dytiscidae)

7. **Diptera (Order: Diptera)**

   The Diptera order, represented by mosquitoes and midges, plays a role both as prey in the food web and as potential disease vectors. Species observed in the Kasalganga River include:

   - **Anopheles sp.** (Culicidae)
   - **Culex sp.** (Culicidae)
   - **Aedes sp.** (Culicidae)

The entomofauna in and around the Kasalganga River demonstrates a diverse and healthy ecosystem, with species from various insect orders indicating a balanced environment. The presence of key groups like Odonata, Hemiptera, and Scarabaeidae reflects the ecological richness of the river basin, supporting a complex food web and robust trophic interactions. Monitoring these insect populations is crucial for assessing both ecological health and managing agricultural and environmental concerns in the region.

The study by Kshirsagar (2010) highlights the diversity of aquatic bugs in lentic water bodies of Pune district, Maharashtra, revealing the presence of 10 species across 7 genera, 4 families, and 2 suborders. Aquatic bugs, particularly from the Belostomatidae family, such as *Diplonychus rusticus*, were found to dominate the diversity. These bugs play a critical role as predators in freshwater ecosystems and are considered valuable bioindicators due to their sensitivity to water pollution. The dominance of *Diplonychus rusticus* suggests that these species may be more resilient to certain environmental conditions, which could inform assessments of ecosystem health and pollution levels. Moreover, the presence of a variety of species in this study reinforces the complexity of lentic ecosystems and the need for continued monitoring to understand the health and sustainability of freshwater habitats. The study by Sivaramkrishnan *et al.* (2000) examined the distribution of 4533 aquatic insect individuals from 72 genera, 45 families, and 10 orders, collected from 17 headwater stream riffles in southwestern India. This research highlights the importance of ecological attributes in understanding the distribution patterns of aquatic insects. The study found that southern, wetter sites with lower human impacts favored specialized, sensitive taxa. These findings suggest that ecological factors are significantly correlated across taxonomic levels, from family to species. Furthermore, the study emphasizes the potential for using family-level data to conduct efficient and participatory inventories and monitoring of aquatic insect populations, contributing to the management and conservation of aquatic ecosystems in the region.

The studies mentioned highlight the significant relationship between aquatic insect diversity and water quality parameters across various regions. Adu and Oyeniyi (2019) explored the water quality parameters and aquatic insect diversity in Aahoo stream, Nigeria, illustrating how aquatic insect populations can serve as bioindicators of stream health. Anish *et al.* (2021) provided valuable insights into the geomorphic evolution of the Chalakudy River Basin, emphasizing how drainage patterns influence aquatic ecosystems, including the distribution of insect communities. Anusa *et al.* (2012) investigated the influence of pool size on species diversity in rock pools, suggesting that physical attributes of aquatic habitats affect biodiversity and water chemistry. APHA (2017) standard methods for water and wastewater examination serve as a vital tool for assessing water quality in various studies, establishing reliable baseline criteria. Arimoro *et al.* (2015) examined anthropogenic impacts on water chemistry and benthic macroinvertebrates in Nigeria, revealing how human activities alter both the chemical makeup of water and the structure of aquatic communities. Finally, Azmi *et al.* (2018) demonstrated the use of aquatic insects as biological indicators for monitoring water quality, particularly in streams in Terengganu, showcasing how these organisms can be used for efficient environmental monitoring.

In summary, these studies collectively underscore the critical role that aquatic insects play in assessing environmental health, reflecting how water quality, physical habitat characteristics, and human activities directly influence aquatic biodiversity. The integration of insect diversity in water quality monitoring offers a holistic approach to understanding and conserving aquatic ecosystems.

Conclusion:

The study of the Kasal Ganga River, encompassing physicochemical parameters, plankton diversity, entomofauna, and scarabaeid beetles, underscores the intricate relationship between water quality, habitat loss, and biodiversity. While the river supports a rich diversity of aquatic organisms, including significant plankton populations and a varied entomofauna, the increasing expansion of agricultural land is altering the natural dynamics of the river. This agricultural encroachment reduces the width of the river, leading to habitat fragmentation and negatively impacting water quality. Moreover, the irregular rainfall patterns, a potential consequence of climate change, are further influencing water levels and the health of the ecosystem. These changes in the river's physical environment directly affect the distribution and abundance of its faunal components, including the entomofauna.

Despite these challenges, the Kasal Ganga River remains a key freshwater ecosystem, supporting diverse life forms. The findings highlight the importance of maintaining water quality and ecological balance to safeguard the river's rich biodiversity. However, ongoing threats from agricultural expansion and fluctuating rainfall underscore the need for proactive conservation strategies to preserve this vital river system. These efforts align with the goals of SDG 6: Clean Water and Sanitation**,** SDG 13: Climate Action**,** SDG 14: Life Below Water**,** SDG 15: Life on Land**, and** SDG 12: Responsible Consumption and Production**.** The collaborative approach suggested in the recommendations is also in line with SDG 17: Partnerships for the Goals, emphasizing the importance of collective efforts for sustainable outcomes.

Recommendations:

1. **Sustainable AGRICULTURAL PRACtices:** To mitigate the negative impacts of expanding agricultural areas, sustainable land-use practices such as agroforestry, buffer zones, and organic farming should be encouraged. This will help preserve the river's width, reduce sedimentation, and maintain water quality by minimizing nutrient and pesticide runoff into the river. This contributes to **SDG 12: Responsible Consumption and Production** and **SDG 15: Life on Land**.
2. **Water management strategies:** Given the irregular rainfall patterns, it is crucial to develop and implement water management strategies that include rainwater harvesting, watershed management, and sustainable irrigation practices. These strategies can help stabilize water levels and maintain consistent quality in the face of erratic weather conditions, supporting **SDG 6: Clean Water and Sanitation** and **SDG 13: Climate Action**.
3. **Ecosystem restoration:** Restoring riverbanks and riparian zones by planting native vegetation will help reduce soil erosion, protect aquatic habitats, and restore biodiversity. Active restoration efforts should focus on maintaining habitat continuity and supporting the entomofauna and other species that depend on these ecosystems. This aligns with **SDG 14: Life Below Water** and **SDG 15: Life on Land**.

4. **Monitoring and research on climate impacts:** Given the influence of irregular rainfall, further research on the impacts of climate change on the river's water quality, biodiversity, and hydrology is essential. Regular monitoring of rainfall patterns, water levels, and their effects on the entomofauna will help in predicting potential impacts and formulating adaptive management strategies. This supports **SDG 13: Climate Action**.
5. **Collaboration for conservation:** Government agencies, local communities, and environmental NGOs should collaborate in the development of conservation programs for the river. This includes educating the public about the importance of preserving water quality, promoting responsible agricultural practices, and encouraging community involvement in monitoring the health of the river and its entomofauna. This is in line with **SDG 17: Partnerships for the Goals**.
6. **Policy implementation:** Enforcing environmental policies that limit the encroachment of agricultural land into riparian areas and that regulate pollution from agriculture will be critical in maintaining the ecological integrity of the Kasal Ganga River. Additionally, policies addressing climate change adaptation and water management at the local level are essential for the river's long-term sustainability. This contributes to **SDG 6: Clean Water and Sanitation**, **SDG 12: Responsible Consumption and Production**, and **SDG 13: Climate Action**.

By addressing the dual challenges of agricultural expansion and erratic rainfall through these strategies, it will be possible to mitigate the negative impacts on the Kasal Ganga River, ensuring the health and biodiversity of the entomofauna and other life forms for future generations. These efforts will contribute to the global sustainable development agenda by promoting clean water, climate resilience, biodiversity conservation, and responsible land-use practices.

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SEASONAL VARIATIONS IN PHYSICO-CHEMICAL PARAMETERS OF MADILAGE VILLAGE POND FROM KOLHAPUR DISTRICT, M.S., INDIA

Rutuja J. Lad, Pratiksha R. Pardeshi and Jyoti R. Gurav

Department of Zoology,

Shri Mouni Vidyapeeth's, Karmaveer Hire Arts, Science, Commerce and Education College,

Gargoti, Dist. Kolhapur, Maharashtra

Abstract:

The water of Madilage village pond, located in Maharashtra, serves multiple purposes, including pisciculture, irrigation, and domestic use. To evaluate the quality of this vital water source, a study of various physico-chemical parameters was conducted from January to December 2008. The results revealed significant seasonal fluctuations in several parameters, indicating the influence of environmental factors on water quality. The water temperature ranged from 22.16 to 28.64°C, turbidity varied between 0.68 to 2.95 NTU, and transparency levels fluctuated from 32.45 to 44.56 cm. The pH ranged from 7.10 to 8.85, dissolved oxygen (DO) from 6.48 to 8.52 mg/l, and free carbon dioxide ($CO2$) from 1.89 to 5.98 mg/l. Alkalinity values ranged from 126.42 to 162.42 mg/l, while total hardness was between 82.46 and 156.26 mg/l. Phosphate concentrations varied from 0.19 to 1.94 mg/l, nitrates ranged from 2.17 to 12.45 mg/l, and chlorides were recorded between 37.26 and 43.48 mg/l. All values were found to be within the acceptable limits defined by the Bureau of Indian Standards (BIS) for drinking water, indicating that the water of Madilage village pond is potable and suitable for pisciculture. This assessment highlights the importance of monitoring water quality to support its sustainable use for various purposes.

Keywords: Water quality; Madilage Reservoir, Kolhapur district

Introduction:

Water is an essential life-sustaining resource, crucial for the survival and development of all living organisms. The absence of clean water makes life and growth impossible, and thus it is vital for healthy development. However, water can become harmful to life when polluted with toxic substances or when sanitation is inadequate (Gupta and Gupta, 1997). The quality of water plays a key role in determining its suitability for various uses, and monitoring water quality is critical for improving its existing conditions. Water quality parameters help assess the suitability of water for its intended uses, which is essential for the management and development of water resources (Lloyd, 1992). Water is needed for domestic purposes, irrigation, sanitation, and waste disposal, and the quality and quantity of surface water bodies like lakes and reservoirs are influenced by climate, catchment areas, geography, and both natural and anthropogenic inputs (Gray, 1994).

Lakes, dams, and rivers are critical sources of fresh water, and their quality can degrade due to microbiological and chemical contaminants. Naturally, water is rarely pure in the chemical sense, as it contains trace amounts of natural impurities. To monitor and assess water quality, physical, chemical, and microbial characteristics are essential. Identifying correlations among these parameters can offer valuable insights into the overall water quality (Dhembhare, 1997). The study of these physico-chemical properties is particularly important, as fluctuations in water quality can significantly impact aquatic ecosystems (Aher and Mane, 2007). This knowledge should be disseminated to both the public and governmental bodies to aid in the development of policies aimed at conserving vital freshwater resources (Ali *et al.,* 2000).

Recent studies (Adewumi *et al.,* 2019; Ndebele-Murisa *et al.,* 2021) emphasize the need for regular monitoring of water quality to ensure safe drinking water and support sustainable aquaculture. This research aims to examine seasonal variations in the water quality parameters of Madilage village pond, assess its suitability for both domestic use and aquaculture, and compare the observed levels with the World Health Organization (WHO) and Bureau of Indian Standards (BIS) guidelines for drinking water and pisciculture quality. Understanding these parameters is essential for promoting water conservation and improving management practices for freshwater ecosystems (Bisht *et al.,* 2022).

Village ponds play an essential role in rural India by providing water for various purposes, such as irrigation, livestock, domestic use, and fishing. They also contribute significantly to groundwater recharge and support local biodiversity. These water bodies are vital for maintaining ecological balance, as they create microhabitats for a wide range of aquatic species. The traditional knowledge passed down through generations has ensured that village ponds are managed in a way that benefits local communities, especially during dry spells when water resources are scarce. Furthermore, ponds serve as cultural hubs, being central to social gatherings and festivals, which foster a sense of community (Saha *et al.,* 2020).

Despite their importance, village ponds are facing increasing challenges, such as encroachment, pollution, and inadequate maintenance. These issues have led to degradation, resulting in poor water quality and the loss of biodiversity. Recent studies have highlighted the importance of rejuvenating and properly managing these ponds to mitigate water stress and enhance agricultural productivity (Singh *et al.,* 2021). Research also emphasizes the need to integrate village ponds into broader water management strategies, considering their role in groundwater recharge and climate resilience (Chopra *et al.,* 2016). Ghosh *et al.* (2022) found that rural ponds are critical for preserving ecosystem health through biodiversity support, while Sharma and Yadav (2019) emphasized their socio-economic contributions through pisciculture and agro-based practices. With proper care, village ponds can continue to provide both ecological and socio-economic benefits to rural communities, contributing to sustainable development.

Materials and Methods:

Study area:

Madilage village pond is located in Bhudargad Tehsil of Kolhapur District, in the state of Maharashtra, India. The pond is situated in a rural setting, serving as an important water resource for the surrounding agricultural and livestock-based activities. This pond is central to the community, used for various purposes, including irrigation, domestic water supply, and pisciculture. It is a key component of the local water management system, particularly in a region where water scarcity can be a concern during the dry months.

The pond is located in a moderately hilly terrain, which is characteristic of the Western Ghats, with a varied topography of the region. The catchment area of the pond consists of agricultural lands, and the local water flow is influenced by seasonal monsoons, which play a critical role in refilling the pond. During the monsoon season, runoff from the surrounding fields and hills enhances the water levels, although the volume of water can vary significantly based on rainfall patterns. The pond also serves as a groundwater recharge zone, contributing to the replenishment of underground water resources for the region.

Physico-chemical parameters:

The study on physico-chemical parameters of water was conducted from January 2013 to December 2013. Sampling sites were strategically selected along the tank, considering the morphometry and anthropogenic activities in the area. Water samples were collected from four stations situated at various points around the tank, specifically from the periphery at depths ranging from 1 to 1.5 meters. The samples were collected fortnightly in plastic cans with a capacity of 2-3 liters and transported to the laboratory for analysis.

During sample collection, temperature and pH were recorded using a portable kit. The analysis of dissolved oxygen, free carbon dioxide, hardness, chlorides, total alkalinity, inorganic phosphate, and nitrate levels were carried out in the laboratory following standard procedures and methodologies outlined by Golterman *et al.* (1978), Trivedi and Goel (1984), and the American Public Health Association (APHA), American Water Works Association (AWWA), and Water Pollution Control Federation (WPCF) (1998).

Results and Discussion:

The study on the physico-chemical parameters of the Madilage village pond provides valuable insights into the seasonal fluctuations of water quality and its ecological implications for freshwater ecosystems. The findings reveal distinct seasonal variations in water temperature, turbidity, transparency, pH, dissolved oxygen, and other key parameters, influencing the biological activities in the water body.

Temperature

The surface water temperature in Madilage village pond fluctuated between 22.28 ± 0.32°C and 28.96 ± 0.65°C, with the lowest temperature recorded in January (22.16°C) and the highest in May (28.64°C). The seasonal pattern shows low temperatures during winter and high temperatures during summer. These results align with previous studies, such as those by Swaranlatha and Rao (1998), who reported similar trends in temperature fluctuation in Banjara Lake, where winter temperatures were lower, and summer temperatures were higher. Temperature influences various ecological processes, including the metabolic rates of aquatic organisms and the solubility of gases in water, which can directly affect biodiversity and water quality (Cui *et al.,* 2015).

Table 1: Annual physico-chemical status of Madilage village pond (Jan 2013 to Dec 2013)

Sr. No	Physicochemical parameters	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1	Temperature (^oc)	22.16	22.48	24.56	26.48	28.64	27.45	26.47	25.12	25.47	24.18	23.56	22.58
2	Turbidity (NTU)	2.25	2.90	2.95	1.20	1.45	1.65	1.74	1.56	1.90	0.85	0.68	1.56
3	Transparency(cm)	40.10	32.45	35.46	32.48	30.40	42.56	39.42	38.85	35.42	44.56	45.26	46.18
4	pH	7.10	7.65	7.45	7.80	8.10	8.28	8.13	8.12	7.90	8.08	8.10	8.26
5	D.O (mg/l)	7.35	6.48	6.88	8.14	8.52	8.46	8.42	8.26	8.10	8.49	8.10	8.13
6	Free CO_2 (mg/l)	2.52	2.98	2.13	2.78	1.89	1.56	2.47	4.23	4.59	5.58	5.98	6.12
7	Alkalinity (mg/l)	132.45	126.42	132.46	128.46	142.45	131.47	152.47	158.45	148.46	162.42	158.46	152.47
8	Hardness (mg/l)	83.42	82.46	96.43	107.12	156.26	145.72	110.49	102.45	98.24	95.47	91.46	87.48
9	Phosphate mg/l)	0.35	0.31	1.2	1.06	0.82	0.19	0.89	0.67	1.46	1.85	1.92	1.94
10	Nitrate (mg/l)	2.17	2.45	2.22	2.43	2.46	2.17	2.45	6.48	12.45	11.56	6.42	4.23
11	Choloride (mg/l)	38.12	39.23	37.26	38.10	42.26	41.15	43.48	42.45	41.27	40.48	42.26	39.45

Turbidity

Turbidity, a limiting factor for productivity in freshwater ecosystems, was recorded between 0.68 and 2.95 NTU, with the minimum turbidity observed in November and the maximum in March. These results corroborate those of Arvindkumar (1995), who observed maximum transparency in December and minimum in August at a tropical wetland in Bihar. Higher turbidity reduces light penetration, thereby affecting primary production and the growth of hydrophytes, which are essential for oxygen production and providing habitats for aquatic fauna (Patel *et al.,* 2022).

Water transparency

Water transparency in Madilage village pond ranged from 32.45 cm to 44.56 cm, with lower values observed in February and higher in October. This seasonal pattern is consistent with findings by Agarwal and Thapliyal (2005) in the Bhilangana River. Transparency is crucial for the survival of aquatic plants and influences oxygen production through photosynthesis. The decrease in transparency during certain months may lead to reduced light availability, affecting the aquatic plant community and subsequently the entire aquatic food chain (Rath *et al.,* 2020).

pH

The pH of the water samples remained alkaline throughout the study period, ranging from 7.10 to 8.28, with minimum pH recorded in March and maximum in June. Similar pH fluctuations were reported by Altindag *et al.* (2009) in the Karaman stream of Turkey. The pH of water is influenced by temperature, organic matter decomposition, and the presence of dissolved gases. A higher pH in the warmer months can be attributed to reduced carbon dioxide solubility and increased photosynthetic activity (Ranjan *et al.,* 2017). The pH values recorded in this study fall within the acceptable range for tropical fish culture and drinking water, as recommended by the WHO (1984) and the Federal Environmental Protection Agency (FEPA), suggesting that the water quality is suitable for aquatic life and human use.

Dissolved Oxygen

Dissolved oxygen (DO) was recorded between 6.48 and 8.52 mg/l, with the minimum concentration observed in February and the maximum in May. The fluctuation in DO levels is influenced by temperature, biological activity, and water turbulence (Ibe, 1993). Naz and Turkmen (2005) also noted a decrease in DO concentration during summer months due to higher temperatures, which reduce oxygen solubility. The higher oxygen levels during the dry season in the current study may be attributed to reduced organic matter decomposition, which typically occurs more rapidly in the wet season.

Free Carbon Dioxide

The free carbon dioxide content ranged from 1.89 to 5.98 mg/l, with higher concentrations in November and lower in May. Sikabira (2010) also reported similar trends in free CO_2 content in freshwater bodies. The seasonal variation in CO_2 concentrations is influenced by factors such as temperature, organic matter decomposition, and photosynthetic activity. Lower CO_2 levels during warmer months suggest an increase in photosynthetic activity, which helps in the assimilation of CO2, thereby reducing its concentration in the water.

Alkalinity and Hardness

Alkalinity varied from 126.42 to 162.42 mg/l, with the minimum in February and maximum in October, while hardness fluctuated between 82.46 and 156.26 mg/l, with minimum hardness in February and maximum in May. These observations are consistent with earlier studies, such as those by Holden and Green (1960) on the Sokoto River and Tailing and Rzoska (1967) on the Nile River. Alkalinity and hardness are key indicators of the buffering capacity of water, influencing the stability of pH and the availability of essential nutrients for aquatic organisms (Kumar *et al.,* 2019).

Phosphate and Nitrate

Phosphate content ranged from 0.19 to 1.94 mg/l, with maximum concentrations in December and minimum in June. Phosphate levels are crucial for primary production, and their concentration is often inversely related to dissolved oxygen and phytoplankton population (Ghavzan *et al.,* 2006). Nitrate levels varied from 2.17 to 12.45 mg/l, with the lowest concentrations in January and the highest in September. Nitrates are essential for plant growth, but excessive concentrations can lead to eutrophication, which depletes oxygen levels and affects aquatic biodiversity (Seshadri *et al.,* 2015).

Chloride

Chloride content ranged from 37.26 to 43.48 mg/l, with minimum chloride observed in March and maximum in July. Similar seasonal fluctuations in chloride levels were observed by Chourasia and Adoni (1985) in Sagar Lake. Chlorides are generally considered an indicator of pollution from anthropogenic sources such as agricultural runoff and wastewater discharge. Higher chloride levels in summer months could be attributed to increased evaporation and concentration of dissolved salts.

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RAINWATER HARVESTING IN INDIA: A JOURNEY FROM TRADITION TO MODERNITY

C. P. Bhagat*, V. A. Jagtap* and M. S. Desai

Shri Mouni Vidyapeeth's,

Karmaveer Hire Arts, Science, Commerce and Education College,

Gargoti, Dist. Kolhapur, Maharashtra

*Corresponding author E-mail: chetan.bhagat7@gmail.com, jagtapvilas46@gmail.com

Abstract:

Rainwater harvesting (RWH) in India embodies a harmonious blend of ancient traditions and modern innovations, offering sustainable solutions to water scarcity and climate challenges. This paper traces the historical evolution of RWH practices, from the Indus Valley civilization's advanced water management systems to region-specific methods like stepwells, johads, and bamboo drip irrigation. It highlights the cultural and social significance of these systems, emphasizing community involvement and religious integration. Modern RWH approaches, such as rooftop harvesting and recharge pits, adapt traditional wisdom to urban and rural needs, bolstered by governmental policies like mandatory installations and subsidies. Despite challenges like awareness gaps, maintenance issues, and urban constraints, advancements in technology, community engagement, and policy support present immense opportunities. RWH enhances water conservation, reduces dependency on groundwater, and provides economic and environmental benefits, while preserving India's cultural heritage. This paper underscores the need for strategic policymaking, education, and research to revitalize RWH as a key component of India's sustainable water management strategy, ensuring resilience and security for future generations.

Keywords; Rainwater Harvesting (RWH), Sustainable Water Management, Traditional Practices, Water Conservation, Climate Resilience

Introduction:

India, with its diverse climatic conditions ranging from arid deserts to monsoon-drenched coasts, has a profound history of managing water through traditional and innovative methods. Rainwater harvesting (RWH) stands as a testament to this heritage, embodying both cultural wisdom and modern necessity in the face of water scarcity

(García-Ávila *et al.,* 2023). The practice of rainwater harvesting in India can be traced back thousands of years. Ancient civilizations in the Indus Valley employed sophisticated water management systems. Over time, various regions developed unique methods tailored to their environmental conditions.

1. Traditional rainwater harvesting in India:

India's diverse climatic and geographical landscapes have given rise to a rich history of rainwater harvesting (RWH) practices, each uniquely tailored to regional needs. In the arid regions of Gujarat, Rajasthan, and parts of Madhya Pradesh and Haryana, stepwells (baoris or vavs) served as both water reservoirs and community gathering spaces, ingeniously designed to capture and store rainwater. Similarly, large tanks and reservoirs, such as Tamil Nadu's Eri System, were constructed across drainage lines to collect runoff, supporting irrigation and groundwater recharge (Yadav *et al.,* 2022) (Ramya *et al.,* 2019).

In Rajasthan's Thar Desert, underground kunds provided year-long water storage, crucial in arid conditions, while johads—earthen check dams—recharged aquifers and improved water availability, as exemplified in Alwar. South Bihar's Ahar-Pyne system efficiently managed rainwater through embankments and irrigation channels, addressing both droughts and floods. In Kerala, surangams, horizontal tunnels in laterite hills, tapped the monsoon-recharged water table for consistent supply (Yadav *et al.,* 2022).

Ladakh's zing systems directed snowmelt and rainwater into fields for irrigation, adapting to cold desert conditions, and in Meghalaya, bamboo drip irrigation employed gravity-fed bamboo pipes to transport spring water sustainably. These traditional RWH methods showcase India's ingenious approaches to water management, blending functionality with sustainability and cultural relevance (Lalmalsawmzauva *et al.,* 2021).

2. Cultural and social aspects:

The cultural and social dimensions of traditional rainwater harvesting systems in India reflect a deep-rooted connection between communities and sustainable water management. Many of these systems were community-managed, embodying early examples of collective resource stewardship and fostering a shared responsibility for water conservation. Additionally, these structures often carried religious significance, being associated with temples or adorned with sacred motifs, seamlessly integrating water management practices into cultural and spiritual traditions. This fusion of functionality and reverence underscored the sustainability of these systems, as they were meticulously designed and maintained based on a profound understanding of local hydrology. Together, these elements highlight the enduring legacy of harmonizing societal, environmental, and spiritual needs in India's water conservation practices (Raimondi *et al.,* 2023).

3. The need for revival

Despite their historical significance, many of these systems fell into disuse with the advent of modern water supply systems. However, the resurgence of RWH has been driven by several factors. Rapid urbanization, population growth, and climate change have exacerbated water shortages, making traditional methods relevant again. The depletion of groundwater and pollution of water bodies have underscored the need for sustainable water management practices. Additionally, the Indian government has promoted RWH through policies like the Model Building Bye-Laws 2016, which mandates RWH systems for new constructions in many urban areas.

4. Modern approaches to rainwater harvesting

Today's RWH systems in India blend traditional wisdom with contemporary technology: Rooftop Harvesting is probably the most widely adopted method, where rainwater from rooftops is directed into storage tanks or recharges groundwater through recharge wells. Recharge Pits and Trenches are used to enhance the natural recharge of groundwater, particularly in urban settings where space is limited. Check Dams are small barriers built across seasonal streams to capture runoff, reducing soil erosion and increasing groundwater levels. Community-Based Systems in rural areas see a revival of village ponds and collective water management, often supported by NGOs and government initiatives under programs like the Jal Jeevan Mission (Kumar *et al.,* 2006).

5. Challenges of rainwater harvesting (RWH) in India:

Challenges of Rainwater Harvesting (RWH) in India are multifaceted, stemming from various social, technical, and regulatory barriers. Awareness and Education play a crucial role, but a lack of knowledge about the benefits and methods of RWH hinders its adoption. Additionally, cultural resistance in certain areas, where traditional water usage practices are deeply rooted, further complicates acceptance. Maintenance and Quality Control is another critical issue, as RWH systems require regular upkeep, including cleaning gutters, checking for leaks, and ensuring water quality, particularly in urban areas prone to high pollution levels.

In urban contexts, Urban Planning and Space Constraints pose significant challenges, with limited space for large systems and the complexity of retrofitting RWH into existing infrastructure. Furthermore, Funding and Investment remain hurdles, as the high initial costs and unclear economic returns discourage adoption, especially in economically disadvantaged areas.

Policy and regulation issues, such as Inconsistent Implementation across states and bureaucratic hurdles in obtaining permissions, create additional obstacles. The growing unpredictability of rainfall due to Climate Variability further impacts the reliability of RWH. Lastly, a shortage of skilled professionals to design, install, and maintain these systems underscores the importance of addressing the Technical Expertise gap. Together, these challenges highlight the need for comprehensive strategies to promote and sustain RWH in India (Richards *et al.,* 2021).

6. Opportunities for rainwater harvesting in India

Rainwater harvesting (RWH) presents immense opportunities to address water scarcity and enhance sustainable development in India. By leveraging technological advancements, policy support, community engagement, and environmental benefits, India can unlock the full potential of RWH systems. Here is a detailed exploration of the opportunities associated with RWH in the country.

i. Technological advancements

The rapid progress in technology has opened new avenues for enhancing the efficiency and efficacy of RWH systems. Innovative Solutions, such as smart sensors for monitoring water levels and advanced filtration systems, have the potential to improve the overall performance of these systems. These innovations ensure better water quality, minimize wastage, and simplify maintenance processes.

Mobile Apps and IoT further contribute to effective system management. These technologies can provide real-time data on water levels, usage, and system health, enabling users to make informed decisions. Additionally, apps can educate users about proper system upkeep, send reminders for maintenance, and even connect them with experts for technical assistance. The integration of these technologies not only enhances user experience but also drives higher adoption rates by demonstrating the tangible benefits of RWH.

ii. Government and policy support

The role of government and policy in promoting RWH cannot be overstated. Incentives such as tax rebates, subsidies, or grants for the installation of RWH systems can significantly encourage individuals and communities to adopt the practice. These financial incentives help offset the initial costs, making the systems more accessible, particularly in economically disadvantaged areas.

Moreover, Mandatory Installations in new constructions can normalize RWH practices. Enforcing regulations that require RWH systems in residential, commercial, and industrial buildings ensures that water conservation becomes an integral part of urban planning. The government's proactive stance in creating a supportive regulatory environment can drive large-scale adoption of RWH across the country (Glendenning *et al.,* 2012).

iii. Community and social engagement

Community involvement plays a pivotal role in the success of RWH initiatives. Community Programs that foster a sense of ownership and responsibility can lead to better maintenance and sustainable usage of RWH systems. Local initiatives, such as forming water user groups or conducting workshops, empower communities to take charge of their water resources.

Education Campaigns are equally important. Raising public awareness about the benefits of RWH through schools, community groups, and public campaigns can inspire more people to adopt the practice. These campaigns can emphasize the environmental and economic advantages of RWH, dispelling myths and resistance associated with the technology.

iv. Environmental and economic benefits

RWH offers significant environmental and economic advantages. Water Conservation is one of the primary benefits, as it reduces dependency on groundwater and municipal water supplies. By capturing and utilizing rainwater, communities can alleviate pressure on existing water resources, ensuring their long-term sustainability.

Cost Savings is another major incentive. Over time, RWH systems can lead to substantial reductions in water bills, particularly for industries, large institutions, and households. This economic benefit makes RWH an attractive investment, offering long-term financial returns alongside environmental gains (Puppala *et al.,* 2023).

v. Cultural and heritage revival

India's rich tradition of water conservation can be revived through RWH. Integration with Traditional Practices, such as step wells and tankas, not only preserves cultural heritage but also provides practical solutions to contemporary water challenges. These traditional methods, when combined with modern technology, can offer efficient and sustainable water management solutions.

Additionally, showcasing traditional RWH structures can promote Tourism and Education. Educational tourism centered around these structures can create awareness about India's water heritage while providing economic benefits to local communities. This approach bridges the gap between historical wisdom and modern needs, fostering a deeper appreciation for sustainable practices (Jain *et al.,* 2024).

vi. Research and development

Continuous Research and Development (R&D) is essential for optimizing RWH systems. Academic institutions and research organizations can focus on developing tailored solutions for different regions of India, considering the diverse climatic and geographical conditions. Innovations in materials, design, and implementation strategies can enhance the efficiency and cost-effectiveness of RWH systems, making them more adaptable to local needs.

vii. Climate change adaptation

RWH can play a critical role in Climate Change Adaptation. By capturing and storing rainwater, communities can build resilience to both droughts and floods. This adaptability ensures a steady water supply during periods of scarcity and helps mitigate the impacts of excessive rainfall. Incorporating RWH into broader climate resilience strategies can strengthen India's efforts to combat the challenges posed by changing weather patterns (Pandey *et al.,* 2003).

viii. Business opportunities

The increasing demand for RWH systems has created a thriving market for Entrepreneurship. Businesses specializing in the manufacturing, installation, and maintenance of RWH systems have significant growth potential. Entrepreneurs can innovate and offer customized solutions, catering to the unique needs of residential, commercial, and industrial clients. This growing sector not only contributes to water conservation but also generates employment and stimulates economic growth.

Conclusion:

Rainwater harvesting (RWH) in India presents vast and multifaceted opportunities, offering a sustainable solution to the pressing challenges of water scarcity and climate change. By embracing technological advancements, fostering community engagement, leveraging government support, and promoting research and development, India can unlock the full potential of RWH systems. These systems provide significant environmental, economic, and social benefits, making them an indispensable part of sustainable water management.

RWH is not merely a response to water scarcity but a revival of indigenous knowledge systems, adapted to address modern challenges. This approach respects both the environment and India's cultural heritage, blending ancient wisdom with contemporary innovations. By integrating RWH into national water policy, urban planning, and public consciousness, India can significantly enhance its water security and ensure sustainability for future generations.

Strategic policymaking, public education, technological innovation, and active community involvement will play pivotal roles in realizing this vision. The journey from traditional to modern rainwater harvesting exemplifies resilience and ingenuity, demonstrating how age-old practices can effectively tackle today's water challenges with a blend of tradition and modernity.

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Sustainable Water Management

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About Editors

Dr. Muraree Lal Meena is Professor in the Department of Geography, School of Basic Sciences, Central University of Haryana, Mahendragarh (HR), specializing in water resources and geopolitics. He has been awarded Ph.D. from Jawaharlal Nehru University (JNU), New Delhi and trained in Remote Sensing & GIS from the Indian Institute of Remote Sensing (IIRS), Dehradun (UK). He had published six books on water resource management, environment, and has contributed more than 45 research papers in national and international journals and more than 30 chapters in edited books. He has been awarded with research fellowship by UGC, New Delhi, also awarded ESDA Green Leadership national award and has presented more than 120 research papers in National and International Conference/Seminars in India and abroad. He visited more than ten countries including, China, Kenya, Sri Lanka and United Kingdom etc. for academic purpose.

Prof. Dr. Yashodhara Shrikant Varale is presently working as I/C Principal, Dr. Ambedkar College of Commerce and Economics, Wadala 400031, Mumbai. She has been awarded with Ph. D. in 2003 from Dr. Babasaheb Ambedkar Marathwada University, Aurangabad, Maharashtra. Sha has 17 years of teaching and 19 years of research experience. She has published more than 50 research articles in various national and international reputed journals. She has received many National Level Award for her outstanding performance and contribution in the field of teaching, research and social activity. She is working as member of advisory board, reviewer board, editorial boards of many journals. Dr. Varale is Lifetime member of Indian Social Science and many other associations in the field of social science.

Dr. Krishan Kant Upadhyay, is a distinguished academician with an impressive educational background, including MSc, NET, GATE, JRF, and a Ph.D. Currently serving as the Head of the Chemistry Department . He brings over 20 years of undergraduate and 15 years of postgraduate teaching experience. Dr. Upadhyay has a robust research portfolio, including one completed research project and authorship of 12 published research papers. He has participated in 44 conferences and three faculty development programs (FDPs). His contributions extend beyond academia, having executed 30 projects and delivered four invited talks. With a commitment to advancing education and research, Dr. Upadhyay's extensive experience and expertise make him a valuable asset to his institution and a source of inspiration for his peers and students alike.

Dr. Prasenjit Talukdar is working as Associate Professor and Head of the Department of Petroleum Engineering, Dibrugarh University Institute of Engineering and Technology (DUIET), Dibrugarh University, Assam, India. He did his Ph.D from the Department of Petroleum Technology, Dibrugarh University in the area of Non Damaging Drilling Fluid. His current research focuses on advanced EOR techniques, rheology of complex fluids, flow assurance of waxy crude oil, CCUS, and nano-based drilling fluids for challenging environments. He has finished three significant research projects. In his role, he has authored seven book chapters, fifty-one international journal articles, and sixty-seven conference papers.

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