CHAPTER 1
INTRODUCTION

1.1. General

"Water is the driving force of all nature" – Leonardo Da Vinci

It is hard to imagine life without water, yet its availability and quality is one of the most pressing challenges of current and future generations (Seidl et al. 2024). The demand for freshwater has increased over 600 times during the last 100 years (UNSECO, 2021). Global water security has become a serious concern as about 6 billion people would experience a shortage of clean water by 2050, according to the 2018 edition of the United Nations World Water Development Report. Groundwater accounts for 99% of all liquid freshwater on Earth (UNESCO, 2022). Globally, 69% of agricultural, 22% domestic and 9% industrial needs are being met by groundwater extraction (UNESCO, 2022). In context of Sustainable Development Goals (SDG), groundwater resources play a paramount role in ensuring adequate water for all (Conti et al. 2016). It is directly linked to ensuring safe access and sanitation for all (Goal 6) and indirectly linked to other goals such as poverty eradication (Goal 1), food security (Goal 2), gender equality (Goal 5), sustainability of cities and human settlement (Goal 11), combating climate change (Goal 13), and protecting terrestrial ecosystems (Goal 15) (Gleeson et al. 2020).

The widespread availability, low capital cost, and dependability makes groundwater an ideal source of water supply for all sectors (de Graaf et al. 2017; Gebere et al. 2020; CGWB 2022). This increased demand for freshwater driven by population and economic growth under the changing climate patterns have led to the overexploitation and depletion of groundwater resources (Boretti and Rosa, 2019). Climate change has put more pressure on water resources through disruption in weather patterns, increased intensity, and occurrence of extreme weather events such as floods and droughts leading to uncertainty in water availability, increased water scarcity and contamination (Water, U.N. 2020). Groundwater depletion has become one of leading causes of water scarcity in the world (Alam et al. 2021). According to the data from Water Resources Institutes (WRIs) Aqueduct Water Risk Atlas for 2019, 25 countries faced extremely high water stress each year and at least 50% of world population was living under highly water-stressed conditions for at least a month every year (Kuzma et al. 2023). The report measured stress index as the ratio of total water withdrawal to the available renewable surface and groundwater supplies (**Fig. 1.1**).

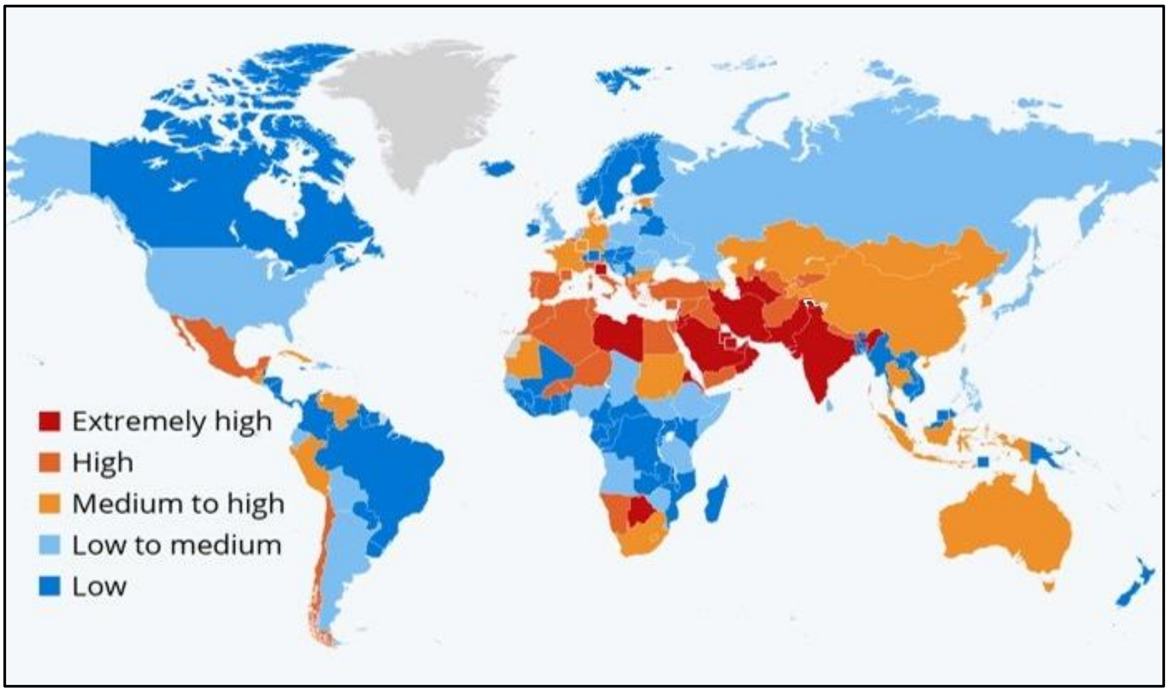

Figure 1.1 Distribution of Global Groundwater Stress (after WRI, Kuzma et al. 2023)

Groundwater is not entirely renewable resource like solar energy, nor it is a non-renewable resource like minerals or petroleum deposit (Alley et al. 1999). Recharge from precipitation, canal seepage and irrigation return flow continually replenish groundwater resources, but it is at much slower rates than the groundwater withdrawal rates (Alley et al. 1999; CGWB, 2022). Sustainable development of groundwater resources has become a compounding challenge under the current groundwater use (Russo and Lall 2017). Groundwater sustainability is influenced by a multitude of factors such as groundwater storage depletion, reduction in streamflow, loss of wetland and riparian ecosystems, land subsidence, saltwater intrusion, and alterations in groundwater quality (Alley et al. 1999). Alley et al. (1999) reported that resources sustainability was an elusive concept to be defined in precise manner with universal applicability and suggested defining groundwater sustainability within the context of complete hydrologic system of which it is a part. Zhou (2009) reported that over-exploitation of groundwater resources may have occurred due to the lack of understanding of safe yields, neglect of groundwater ecosystem functions and the methodology to evaluate them and states that currently it's a widely recognised fact that the effect of pumping is not limited to groundwater depletion but also affects other parts of the system such as maintenance of stream flow requirements for aquatic species, riparian and wetland ecosystems health and other environmental requirements. Among the various groundwater management strategies, underground storage of water via Managed Aquifer Recharge (MAR) has emerged to be the most popular and sustainable solution to various groundwater problems (Hartog & Stuyfzand 2017; Dillon et al. 2019; Zhang et al. 2020; Alam et al. 2021; Maheshwari 2023).

1.2. Managed Aquifer Recharge

Water availability and quality management is the most significant current and future challenge being faced by societies worldwide (Wheeler 2021). Water conservation has been practised through constructions of surface reservoirs since ages, but had common disadvantages like high evaporative losses, high land area requirements, sediment accumulation and vulnerability to contamination and structure failure (Bouwer 2002; Ringleb et al. 2016). Alternatively, excess water could be stored underground during periods of high availability (Pyne 2005; Maliva et al. 2006; Händel et al. 2014). Unlike the natural or incidental recharge, the intentional recharge of water into aquifers for future recovery or environmental benefits can be defined as Managed Aquifer Recharge (MAR)

(Bouwer 2002; Dillon 2005). A term conceived by British hydrogeologist Ian Gale, MAR is a suit of methods progressively used to maintain, enhance, and secure groundwater systems under stress (Dillon et al. 2019; Dillon et al. 2020). It is one of several options for addressing issues such as water scarcity, water security, deteriorating water quality, dropping water tables, and threatened ecosystems that depends on groundwater. (Dillon et al. 2020). It is a promising groundwater engineering approach towards water security (Zhang et al. 2020).

MAR has emerged to be one of the most suitable and sustainable solution to myriad groundwater problems due to its due to its low implementation cost, ability to infiltrate large volumes of water from different sources, overcome temporal mismatch of supply and demand, improve groundwater quality and provide protection against evaporative loss, algae bloom and contamination (Hartog and Stuyfzand, 2017; UN-Water 2018; Dillon et al. 2019; Zhang et al. 2020; Alam et al. 2021; Seidl et al. 2024). MAR implementation is rapidly expanding as a sustainable water resources management strategy to address complex groundwater issues. (Ringleb et al., 2016; Dillon et al., 2019; Zheng et al., 2021). The global MAR capacity had increased from 1 to 10 km^3/year between 1965 to 2015 @ 4.5% per year yet comprised of only 1% of global water extraction (Dillon et al. 2019; Seidl et al. 2024). India leads the world in MAR implementation, accounting for 31% of the worldwide MAR capacity, followed by the United States (26%), Germany (9%), and other countries (Dillon et al. 2019). According to global MAR database for 2016, there have been over 1104 MAR sites registered globally. (IGRAC 2016).

Historically, the initial practices of MAR can be traced to 221 B.C. in China, where infiltration channels were dug to raise groundwater level (Zhang et al. 2020). In Europe and South America, "*careos*" and *"amunas"* or sowing and harvesting methods were being adopted from 500 to 1000 A.D. (Martos-Rosillo et al. 2019). In India, as early as 600 A.D., the construction of *ooranies* or ponds along with recharge wells was practised in coastal towns and villages of Tamil Nadu (Sakthivadivel 2007). During the modern age, river-bank filtration for drinking water was well established in Europe by 1870s (Dillon et al. 2019). In USA, infiltration ponds for storm runoff were widely used in 1930s (Weeks 2002). Since the 1970s, treated wastewater effluent was being stored and further treated in aquifers for subsequent use in California, USA (Mills 2002). Later in 1990s, urban stormwater was widely harvested, recharged, and recovered via wells for public open-space irrigation in Southern Australia (Dillon et al. 2019). Thermal desalination of seawater commenced in Kuwait in the mid-1950s and was used to prevent saltwater intrusion into aquifers. In the 1960s, Shanghai, China, used artificial recharge using wells to stop land subsidence issues (Wang 2011). In India, artificial recharge was undertaken by the government agencies since 1970s, but the focus was on quantity and not water quality (Dillon et al. 2019).

1.3. Managed Aquifer Recharge: Process and Types

According to ASCE (2001), planning, investigation, design and construction, and operation are the four engineering-related stages that make up the MAR process. In each stage multiple key elements were identified that collectively determined the success of MAR application (Yuan et al. 2016; Zhang et al. 2020; Tiwari et al. 2024). All the key elements reported in literature have been summarised in **Figure 1.2.**

In planning stage, it was important to identify the source of recharge water, its ultimate use, and regulations or guidelines (Zhang et al. 2020). Various sources of water have been identified for groundwater recharge such as stormwater, surface water from rivers and lakes, reclaimed water, desalinated water, and groundwater from other aquifers (Yuan et al. 2016; Zhang et al. 2020; Khalil et al. 2022). Based on global IGRAC (2016) data 62% of source water was from rivers, followed by stormwater (20%), reclaimed water

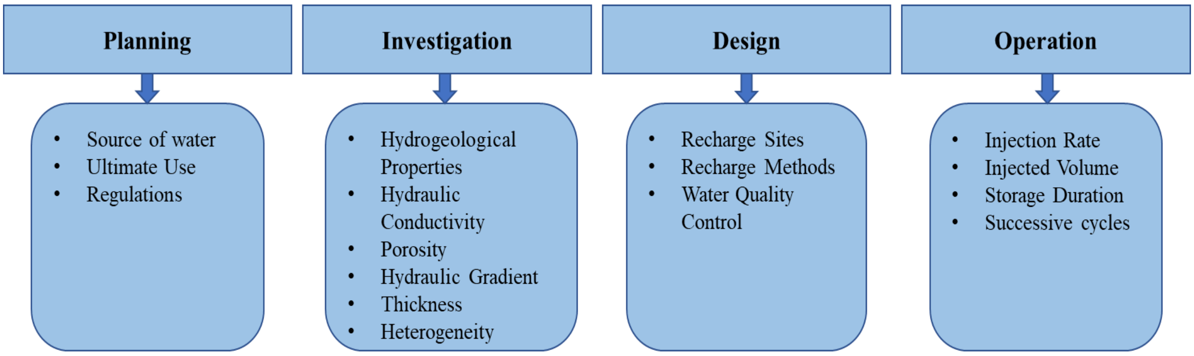

Figure 1.2 Stepwise implementation of MAR project with identified key elements at each stage (after Yuan et al. 2016; Zhang et al. 2020, Tiwari et al. 2024)

(8%), groundwater (8%) and rest were distributed among others. Water quality is an important factor guided not only by its end use but also by the environmental water quality standards (Yuan et al. 2016). Domestic use was the most popular recovery application (60%) followed by agricultural (25%), ecological and environmental protection (9%) and industrial use (4%) (IGRAC 2016). Other uses include barriers against aquifer salinization, flood mitigation, and coastal water quality improvement (Dillon et al. 2009).

Understanding of the local hydrogeology is fundamental to any MAR project. In the investigation phase of MAR process, establishment of the hydrogeological factors at site determines the feasibility of the MAR project and plays a decisive factor in optimal site and structure selection (Zhang et al. 2020; Tewari et al. 2024). In addition to the mentioned parameters in **Figure 1.2**, the determination of water availability, groundwater balance, storage capacity, and boundary inflow and outflow of waters is crucial of MAR project success (Zhang et al. 2020). In the design and construction phase, recharge method, recharge site, water quality control is considered. The choice of optimal recharge sites is crucial since it affects the choice of an appropriate recharge technique, operating plan, and maintenance of MAR schemes (Dillon 2005; Sallwey et al. 2019). Site suitability is often based on intrinsic factors like surface and subsurface hydraulic characteristics, groundwater quality, recharge and recovery methods and political, social, and economic factors (Sallwey et al. 2019; Zhang et al. 2020).

A wide variety of recharge techniques are used for managing aquifer recharge, they can be broadly divided into five major categories: 1) Spreading methods 2) In-channel modifications 3) Well, shaft and borehole recharge 4) Induced bank filtration and 5) Runoff harvesting (IGRAC 2016; Zhang et al. 2020) (**Figure 1.3**). Selection of a particular method is dependent on factors like geological and hydrogeological setting, aquifer type and

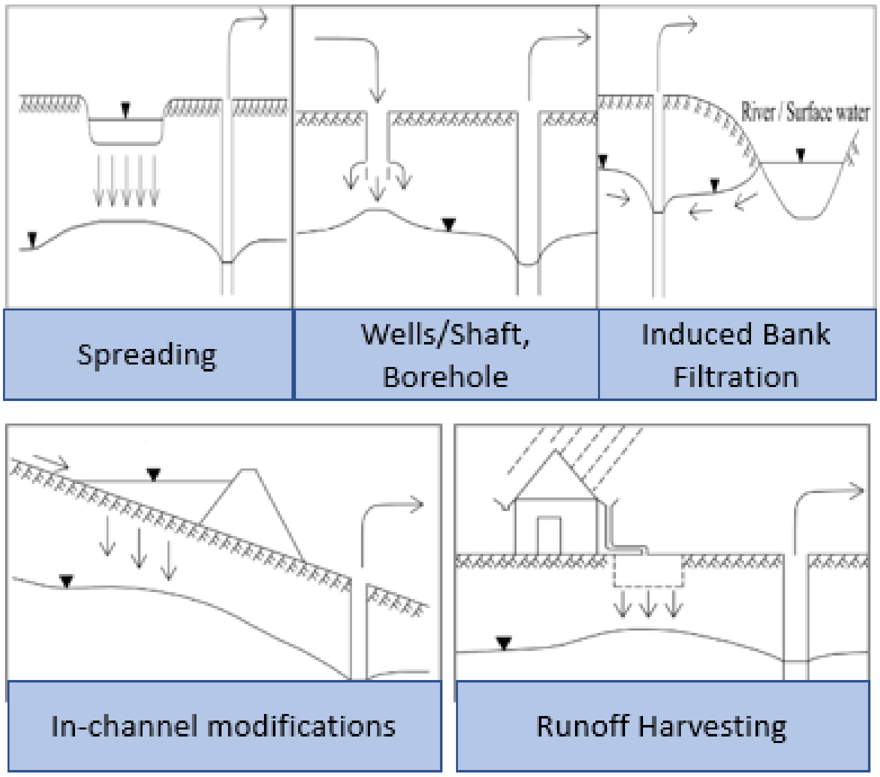

Figure 1.3 Schematic diagram of major types of MAR techniques (after Dillon 2005; Zhang et al. 2020)

thickness, land availability, groundwater quality and cost (Yuan et al. 2016; Zhang et al. 2020). The sub-classifications of the broad techniques and their application conditions is given in **Table 1.1** Water recovery, pumping and recharge rates, operation schedule, and maintenance of applied interventions are considered during the operation stage of MAR process (Yuan et al. 2016; Zhang et al. 2020; Tiwari et al. 2024). In this study, MAR refers to the direct aquifer recharge through injection wells which comes under well, shaft and borehole recharge method. Injection wells were a good way to recharge aquifers because they required less space for installation, didn't clog, and allowed water to be secured at specific sites (Shandilya et al. 2022a).

Table 1.1 MAR technique classification with their application conditions (after Ringleb et al. 2016; Zhang et al. 2020).

No.	MAR Types	MAR Sub-Types	Application
1.	Spreading Methods	Infiltration ponds and basins; Soil aquifer treatment (SAT); Ditch, furrow, drains Irrigation; gabions.	In unconfined aquifers near to ground surface Aquifer Type: alluvium, sandstone and at times carbonate
2.	Well, shaft and borehole recharge	Aquifer Storage and Recovery (ASR); Aquifer Storage, Transfer and Recovery (ASTR); Shallow well/shaft/pit infiltration	In aquifers with impermeable layer above the aquifer. Aquifer Type: deep and clay covered aquifers.
3.	Induced bank filtration	River/lake bank filtration; Dune filtration	In aquifers close to surface water body. Aquifer Type: Dry rivers with (subsurface) dams/sand dams; near perennial rivers or streams with adjacent permeable sand layers.
4.	In-channel modifications	Recharge dams; Subsurface dams; Sand dams; Channel spreading.	Across rivers/streams with good aquifer connectivity
5.	Runoff/ Rainwater harvesting	Rooftop rainwater harvesting; Barriers and bunds; Trenches	Where runoff can be collected for productive use

1.4. Groundwater scenario in India

With an estimated consumption of 251 km^3/year, India is the world's largest user of groundwater (UNESCO 2022). Groundwater is the backbone of socio-economic development in India addressing more than 85% of rural domestic water requirement, 50% of urban requirement and over 50% of irrigation requirements (CGWB 2022). Groundwater exploitation exploded in India during the last 60 years with the increase in private wells, decline in surface water resources and changes in government policies to support groundwater use (Sakthivadivel 2007). The consequences of which extended beyond groundwater depletion to include water scarcity, groundwater quality degradation, and land subsidence. The groundwater availability in India is estimated based on the annual groundwater replenishment and assessed in every three years (CGWB 2021). Then depending upon the ratio of annual recharge to annual extraction, the Stage of groundwater extraction for particular area is determined (CGWB 2021). According to CGWB 2022 report, the annual recharge of groundwater was 437.6 Billon Cubic Meter (BCM) of which 398 BCM was extractable recharge. The annual extraction rate was estimated at 239.16 BCM taking the Stage of groundwater development to 60%, which comes under safe category. However, the stage of groundwater development is spatially variable, and the western, central, and southern regions under semi-critical to overexploited category (**Figure 1.4**) (CGWB 2022).

In response to the mounting water crisis, the Indian government launched prudent measures to ensure groundwater sustainability, among which artificial recharge of aquifers was accepted as a cost-effective method to augment ground water resources (CGWB 2007). Periodic assessment of dynamic groundwater resources was the initial step taken towards this (CGWB 2021), followed by the nationwide aquifer mapping project in 2012 named 'National Project on Aquifer Mapping' (NAQUIM), under which rigorous subsurface study incorporating the hydrogeological, geological, geophysical, hydro-chemical aspects have been conducted (Sinha 2021). The government launched a "Master Plan for artificial Recharge to Groundwater in India" in 2002, later revised in 2013 and 2020 (CGWB, 2021). The revised master plan was made for the whole country at the level of district/Block and

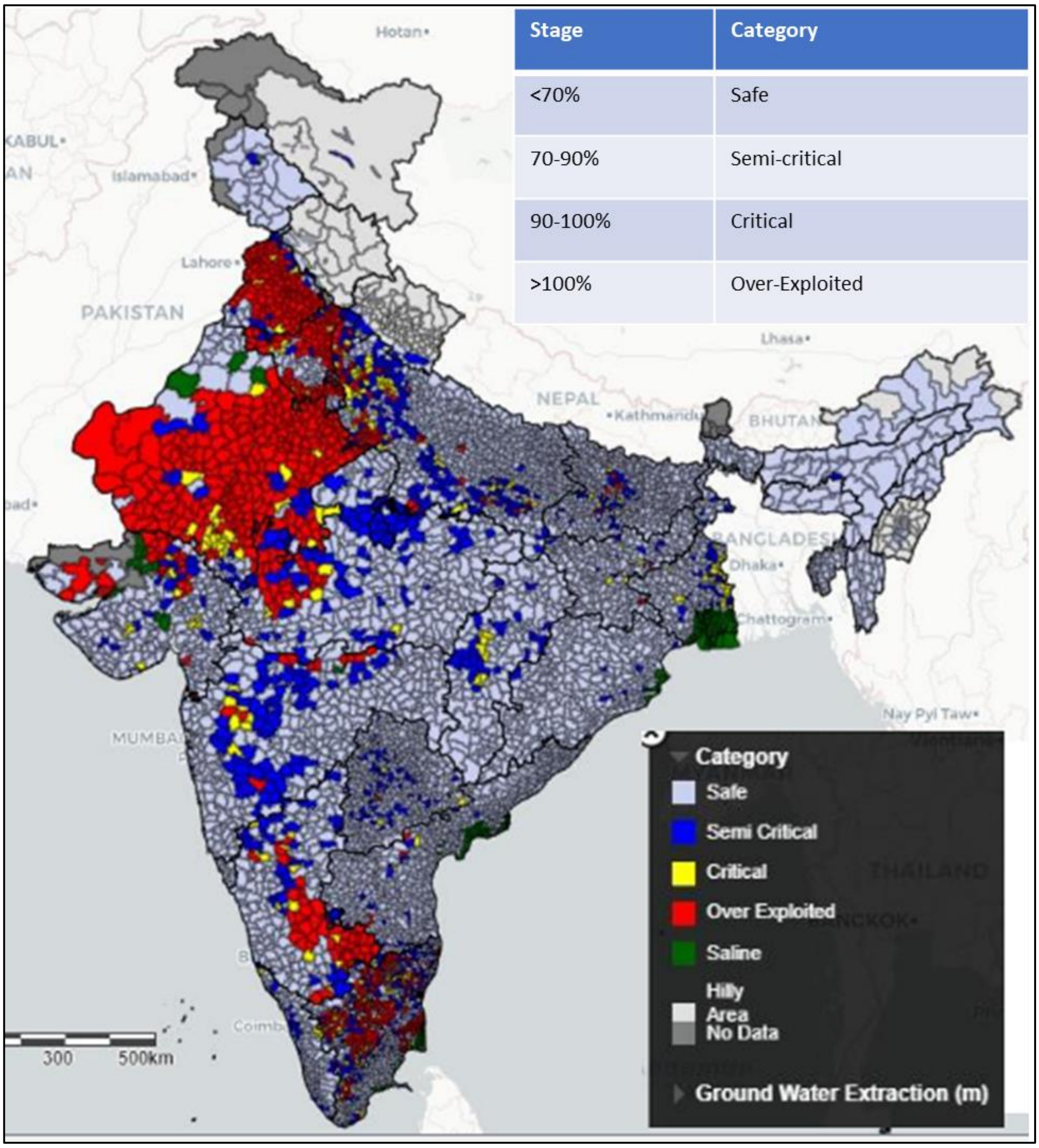

Figure 1.4 Stage of Groundwater Extraction in India, 2022 (after CGWB, 2022)

provided guidelines towards AR process. Over 25 different types of recharge structures were identified across the country, which was standardised into 10 categories, with the group "others" consisting of all uncommon structures. According to the revised Master plan for Artificial Recharge to Groundwater in India, 2020, over 141 crore artificial structures were proposed nationwide to mitigate the twin risks of aquifer zone desaturation and the ensuing decline in groundwater quality. The estimated cost of these structures is 133.5 thousand crores. (CGWB 2021).

1.5. Modelling applications in MAR studies

Although MAR approaches appeared straightforward and globally implemented, the intricacy of site-specific hydrogeological conditions and processes occurring at multiple scales combined with various recharge objectives necessitated a thorough understanding of the system's response to proposed measures (Ringleb et al. 2016). Characterization of hydrogeological systems is best done using field experiments (Maliva et al. 2015), while lab experiments were preferable to understand intricate process. However, lab methods were inadequate in representing field boundary conditions (Ringleb et al. 2016).

With rapid development in computational prowess and widely availability of modelling software, groundwater modelling became standard tools for hydrogeologist and water resource managers (Zhou and Li 2011). Groundwater models have been extensively used as interpretative tool, simulation tool, assessment tool, predictive tool, supporting and screening tool, management tool and visualization tool in groundwater management studies (Zhou and Li 2011). Application of various models had definitive advantages over field or lab MAR studies (Ringleb et al. 2016). They have been widely applied to analyse management scenarios, evaluate site feasibility, compare techniques/operational schemes, optimize operation schedules and quantity, analyse geochemical processes and clogging, predict future scenarios, and assess risk (Kloppmann et al. 2012; Gaur et al. 2012; Ringleb et al. 2016). Modelling studies can be conducted to evaluate field-scale schemes or sites, laboratory experiments or theoretical problems. According to the literature survey from 1985 to 2015, Ringleb et al. (2016) found that modelling tools were being adopted to conducted feasibility studies, assess optimal design, optimize operation schedule, model geochemical process and clogging, quantify recovery efficiency, assess impact of applied MAR on groundwater levels and seawater intrusion. It was used mostly on well, shaft and borehole technique of recharge (57%) followed by the surface spreading technique (27%).

Among the reviewed literature, various software tools or algorithms were applied to model flow and transport processes, most were commonly used groundwater flow model like MODFLOW, but few were specifically developed for MAR applications like NASRI-BF Simulator for design and operation of bank filtration, EL-ASR for water quality issue in ASR wells, CLOG for major clogging problems (Ringleb et al. 2016). Use of modelling tools has become indispensable in groundwater management studies and the Australian guidelines and the ASCE guidelines have recommended the use of numerical modelling during preliminary or feasibility studies of new MAR facility (ASCE 2001; NRMMC, EPHC, NHMRC 2009).

1.6. Motivation of study

Firstly, according to Dillon et al. (2012) the stabilization of storage decline and sustainable groundwater resource utilization could only be achieved through either reduction in demand or by increase in groundwater replenishment. MAR has emerged as one of the most economic, resilient, and socially acceptable solution for sustainable development of groundwater resources (Dillon et al. 2020). MAR implementation is being adopted worldwide for multi-facet groundwater problems and since 1960s it has accelerated at the rate of 5% per year or 10 km^3/year (Dillon et al. 2019). Yet, it had just reached about 1% of global groundwater extraction and required more experiences in good practices to improve efficiency of investment in MAR. There still required to extend number of case studies to improve the site selection process, design operation and monitoring, and translate scientific evidence into governance. Spatial and numerical modelling tools have significantly aided the decision-making process in MAR planning and have reduced its risk of failure (Ringleb et al. 2016). Soft computing tools have been effectively used for various MAR objectives and have been widely adopted at every step of MAR process. However, there still lacked a comprehensive approach that utilized the advancements in spatial and numerical models at each step of MAR process and presented a holistic plan, from source water quantification, safe storage, and utilization, towards MAR implementation.

Secondly, groundwater development in India has already reached critical stage in high demand areas and the over-development have resulted in water level decline, shortage in water supply, saltwater intrusion in coastal aquifers and increase in pumping cost (CGWB 2007). It is more sever in arid and semi-arid regions where dependency on groundwater is more (Bayat et al. 2023). Bundelkhand region in central India, is one such semi-arid region where, frequent droughts, floods and decline in average annual rainfall have resulted in critical poverty, food insecurity and mass migration (Gupta et al. 2014; Chaurasia and Chandra 2021). The problem is further aggravated by the substratum of impermeable rocks resulting in poor groundwater recharge (Sinha 2021). It is a region where the applied interventions to secure water supply haven't been as successful (Suthar 2018) and is in dire need of sustainable groundwater development plans. This thesis attempts to present a conceptual framework for MAR project planning by taking up the case study of Lower Betwa River Basin (LBRB) in the Bundelkhand region of central India. The findings of this research can lay foundations towards development of effective methodologies through the assurance of incorporating spatial and numerical models in the ongoing groundwater management plans in India and aiding in planning of artificial recharge process in a more efficient and economical way, through minimizing the risk of its failure.

1.7. Aim and Research Objectives

Overall, this thesis is an amalgamation of geospatial, analytical, hydrological, numerical techniques, and methodologies developed and evaluated for the purpose of quantifying, controlling, and mitigating groundwater depletion through sustainable interventions such as MAR. The general aim of this thesis is to advance the knowledge and methods available in modelling approaches towards MAR processes, while providing a comprehensive framework for MAR project planning to offset groundwater depletion in the Lower Betwa River Basin (LBRB). The proposed framework consists of 5 steps, which are presented as 5 objectives of this thesis.

The specific objectives planned to accomplish the aim of this thesis are as follows:

1. Quantification of long-term groundwater budget dynamics
2. Identification and quantification of source water for MAR
3. Determination of permissible recharge capacity of aquifers
4. Identification of suitable MAR sites
5. Determination of suitable recharge rates and recharge schedule

1.8. Thesis Structure

The thesis is organized into following eight chapters:

Chapter 1 introduces the concept of MAR, numerical modelling in groundwater management, the Indian context of AR, motivation of study and the research objectives of this thesis.

Chapter 2 presents the literature review of the application of hydrological and numerical models in MAR studies. The chapter discusses the background of hydrological and groundwater models, groundwater modelling process and its applications in groundwater budget quantification, MAR site selection, determination of recharge rates and operation schedule of MAR process. The chapter ends with identified research gaps.

Chapter 3 gives a detailed description of the data requirements, study area, methodology and the development of models used in this study.

Chapter 4 presents the evaluation of groundwater depletion and impact of natural and induced stresses upon the groundwater flow budget components. The chapter discusses the groundwater level trends, spatiotemporal storage variations, block-wise groundwater budget and their variations under different scenarios.

Chapter 5 discusses about the quantification of source water for MAR and the aquifer recharge capacity in the LBRB aquifers. A novel methodology to quantify safe recharge capacity in case of unconfined aquifers is presented along with its application and evaluation in the LBRB.

Chapter 6 describes the application of clustering techniques in identification of optimal MAR recharge sites based on the surface, subsurface hydrologic properties, and the aquifer response to applied interventions. The chapter also presents the methodology to determine suitable aquifer recharge rates and schedule based on the available surplus water and safe recharge capacity.

Chapter 7 discusses the effectiveness of the proposed MAR planning framework on the LBRB and presents the adoptive actions that can be undertaken to stabilize storage loss and prevent aquifer depletion.

Chapter 8 presents the conclusion, generalised framework for MAR planning and the limitations and future scope of this study.