CHAPTER 2
LITERATURE REVIEW

2.1. Background

The need to understand complex hydrological and hydrogeological processes under the ever-growing demand for water has become vital for its management and sustainable development. The application of models has revolutionized water resource management studies (Jayakrishnan et al. 2005) and has become standard tool for water resource managers (Zhou and Li 2011). A model is a simplified representation of real-world systems and have been increasingly used to comprehend the hydrological systems, forecasting and management studies (Moradkhani and Sorooshian 2008; Anderson et al. 2015; Sahu et al. 2023). While hydrological models simplify the hydrological processes occurring at basin or catchment scale (Devi et al. 2015), groundwater flow models use mathematical equations that are resolved by a computer program to simulate how an actual groundwater system operates. (Kumar 2013).

To form a strong foundation for this study, an elaborate literature review was conducted. Firstly, the theory of hydrological and groundwater flow modelling was established. Then the widely available literature on hydrological and groundwater modelling have been narrowed down to its applications in regions similar to the conditions of the LBRB (semi-arid and weathered region), with the objectives of modelling focused on quantification of water balance. Lastly, the literature on model applications at different stages of MAR process is reviewed. The chapter ends with the identification of the research gaps.

2.2. Hydrological Models

Hydrological models were developed to simulate the catchment response to changes in climate, land use or soil (Devi et al. 2015; Thavhana et al. 2018; Sahu et al. 2023). They use mathematical equations to represent the processes governing the hydrological cycle (Woessner, 2012). Either statistical, conceptual, or physical-based approaches is undertaken in hydrological studies (Devi et al. 2015). Statistical or empirical approach take information only from existing data and the mathematical equations are derived from simultaneous input and output time series, without the consideration of hydrological processes.

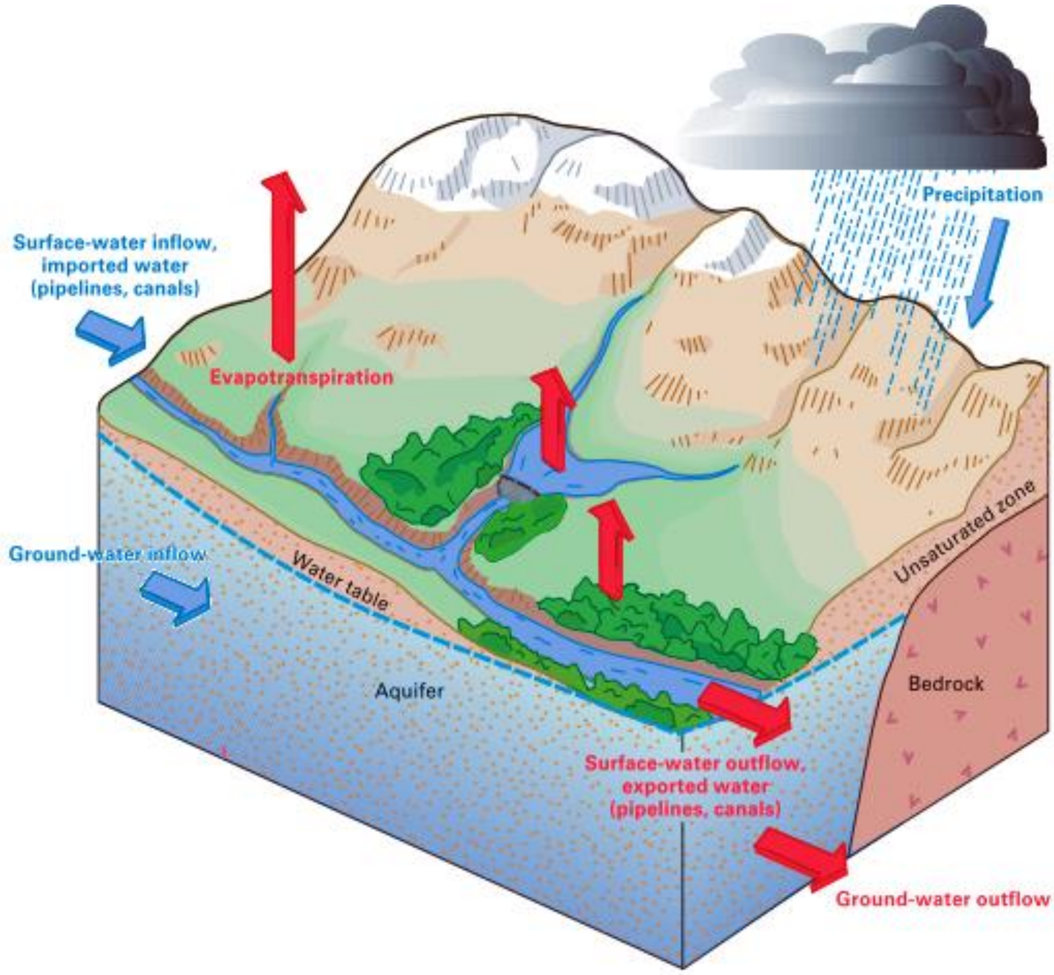

Figure 2.1 Hydrological Cycle for part of a watershed (after Healy et al. 2007)

Also known as data driven or black box models, unit hydrograph, artificial neural networks (ANN) and fuzzy regression models are few examples of empirical approach.

Conceptual or parametric models are based on semi-empirical equations derived from physical elements in a catchment. The model parameters are assessed based on field data and calibration, for which large number of meteorological and hydrological data is required. HBV, TOPMODLE and Stanford Watershed Model IV (SWM) are few examples of conceptual model (Devi et al. 2015; Sahu et al. 2023). Physically based or mechanistic models include the principles of physical processes. They are idealised depiction of real-world phenomenon, and the process of water movement are derived using finite difference equations. Mechanistic models require a large number of input data describing the physical characteristics of catchment but can overcome limitations of other two models and is the most widely adopted model for hydrological studies. MIKE SHE, SWAT, and HEC-HMS are few famous examples of physically based models (Devi et al. 2015).

Hydrological models can further be either lumped, distributed or semi-distributed models based on the degree to which the physical characteristics of the watershed and the processes' spatial variation are captured in the model (Jajarmizadeh et al. 2012; Maskey, 2022). Lumped models represent model domain as one single unit i.e. the model takes only one spatially averaged value for each input variable and model parameter for the entire catchment (Lanen et al. 2023). Distributed models are just opposite of lumped models and can take spatial variations in model input. They are generally constructed with grid or mesh structure. In semi-distributed model structure, instead of employing square or rectangular grids as its spatial unit, the drainage area border is typically used to split the catchment into a number of sub-catchments. The semi-distributed structure made sense hydrologically and were the most efficient models for hydrological simulation of catchment level analyses (Khayyun et al. 2019; Maskey, 2022). Hydrological models can also be deterministic or stochastic based on output results, static or dynamic based on time factor which results in either event based or continuous model output (Devi et al. 2015).

The most prominently used hydrological modelling tools were HBV, HEC-HMS, HYPE, LISFLOOD, MIKE SHE, WaterGap, SPHY, SWIM, Topkai, and SWAT models (Sahu et al. 2023). Selection of a particular model depended upon its specific application and on primary processes that generated runoff, their temporal and spatial extent, data resolution and catchment features (Sahu et al. 2023). The essential characteristics of selecting a model was open-source code, applicable to nexus, available of useful tutorial and having graphical user interface (GUI) (Brannstrom 2019). Only HEC-HMS and SWAT met all the four criterions. However, HEC-HMS is lumped model and didn't allow for spatial variations in input, SWAT model being a semi-distributed model could discretise the basin into homogeneous units of landform, slope, and soil of the watershed (Chathuranika et al. 2022). Moreover, HEC-HMS was developed for temperate climatic conditions of USA and was outperformed by SWAT model in Indian subcontinent (Shekar and Vinay 2021). SWAT models have been applied globally to assist in decision making and management planning and have gained popularity in India as well (Dubey et al. 2023). Hence, in this thesis, SWAT model was employed to characterise the hydrological behaviour, and the review is focused on its applications to quantify surface water balance.

2.2.1. SWAT Model

The Soil and Water Assessment Tool (SWAT) is an open sourced, continuous, daily step, long period, physically based parameter, and distributed hydrologic model (Neitsch et al. 2002). It was developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS), to forecast over an extended period of time, the effects of land management on the yields of water, sediment, and water quality of agricultural watersheds. The key advantages of SWAT that it can be applied to large complex watersheds with ungauged or semi-gauged basins. It has weather simulation model to generate meteorological data like rainfall, relative humidity, solar radiation, temperature, and wind speed from the monthly average values variables of these data and can be also used to model plant growth and the movement of sediments, nutrients, pesticides and pathogens in a catchment (Neitsch et al. 2011; Arnold et al. 2012; Khayyun et al. 2019).

The successful application of hydrological models depends upon its ability to capture environmental conditions with minimum uncertainty (Desai et al. 2021). Quantification of uncertainty in hydrological models is a complex task and several techniques have been created to increase the prediction accuracy and improve model uncertainty (Xie and Lian, 2013). SWAT- Calibration and Uncertainty Programs (SWAT-CUP) platform was developed by Abbaspour et al. (2007) to calibrate and validate the SWAT model. Automatic calibration algorithms such as Generalized Likelihood Uncertainty Estimation (GLUE), Particle Swarm Optimization (PSO), Markov Chain Monte Carlo (MCMC), Sequential Uncertainty Fitting (SUFI-2), and Parameter solutions (Parasol) were made available in the SWAT-CUP tool (Desai et al. 2021). These algorithms vary according to how they conduct assessments and determine parameter ranges for a given objective function. Among the algorithms, SUFI-2 algorithm was computationally efficient in calibrating distributed models in large watershed (Yang et al. 2008; Wu and Chen 2015) and it was the most widely used calibration tool in many Indian river basins (Desai et al. 2021). A wide variety of literature was available on applications of SWAT model in Indian subcontinent, few of the latest and relevant literature on assessment of surface water balance is presented in the following paragraphs. Dubey et al. (2023) reviewed over 110 SWAT model application studies in India between 2012-2022 and observed that in over 90% of the reviewed studies, SWAT model performed well with acceptable accuracy statistics. The base curve number (CN2) was the most sensitive parameter in estimation of water balance and accuracy of the obtained results was closely related to the accuracy of the input weather data.

George and James (2024) applied SWAT to estimate streamflow in ungauged mountainous watersheds of the Western Ghats in India. The authors used eight representative watersheds with stream gauging stations, global average, regression method and common parameter transfer approaches were adopted to regionalise the parameters. The authors observed that the selected approach was effective in simulating hydrological process in the wet humid tropical zone of Kerala. Kausher et al. (2024) employed SWAT model to simulate water balance components of coal mining watershed of Mahan River in central India. The authors observed that mining areas had comparatively lesser sediment yield than non-mining areas and reported that 39% of annual precipitation was lost as evapotranspiration. Out of total discharge, 45.4% flowed as surface runoff, 51.8% as return flow, 2.7% as lateral flow and 7.6% as groundwater percolation into aquifers. SUFI-2 automatic calibration algorithm was used to calibrate and validate the model.

Sabale et al. (2023) applied ArcSWAT model to quantify the water budget of Yeralwadi catchment of Khatav, Maharashtra India and observed that out of the 55.6% total discharge from the Yeralwadi catchment, surface runoff accounted for 41.2% and baseflow for 14.4%. About 17.8% of the discharge percolated into confined and unconfined aquifers, which served as soil and groundwater storage. Model calibration was done using SUFI-2 algorithm in SWAT-CUP to get a better result. Trivedi et al. (2023) evaluated the groundwater recharge requirement and restoration Kanari River, Jabalpur Madhya Pradesh and observed that out of total precipitation in the basin, surface runoff removed 46.2%, groundwater percolation was 26.9%, evapotranspiration was 26.9%, and deep aquifer recharge was estimated at 1.33%.

Kumar et al. (2023) assessed the combined effect of land use and climate change on Betwa River Basin (BRB). A 30-year differences land use image was processed (1990-2020) and an ANN model was used to predict future land use pattern. Between 1990 and 2020, the open and forest land had decreased by 2% and 4%, while the total area under water bodies, built-up areas, and agricultural land had expanded by 3%, 2%, and 1% respectively. Under the predicted climate scenarios, the mean monsoon streamflow was expected to decrease by 30-47% during the 2023-2060 period and the mean monsoon stream flow decreased by 16% as a result of the combined effects of climate change and land use change. Kumar et al. (2022) also reported similar results of streamflow reduction, relative decrease in rainfall, surface runoff and percolation in the upper Betwa River catchment during the 1980-2100 study.

Desai et al. (2021) used multi-site streamflow data for calibration and validation of SWAT model for Betwa River Basin, central India. SUFI-2 algorithm was used for sensitivity analysis, calibration, validation, and uncertainty analysis. Analysis of the annual average water balance for the period 2000–2011 showed that 61% of the total annual rainfall was lost as evapotranspiration from the basin, rest of 31% flowed as surface runoff and 8% as baseflow. No groundwater contribution was mentioned but the authors observed that most of the runoff occurred during the monsoon season (95%) and suggested water conservation to utilize rainwater. Suryavanshi et al. (2017) conducted seasonal water budget analysis using SWAT on Betwa river basin for a long period of 28 years (1973-2001). The authors observed that 90% of annual rainfall and 97% of annual runoff occurred in the monsoon season. The evapotranspiration rates stood at 50% and about 36% of the discharge was surface runoff while the average groundwater contribution was 14%.

Palmate and Pandey (2020), evaluated the effectiveness of best management practices (BMP) using varied annual dependable flows in Betwa river basin to conserve water. SWAT model was used to simulate outputs of different pre and post conditions and observed that strip cropping was the most successful agricultural land treatment, reducing flows by 10-12%. The best channel treatment, however, was grade stabilization structures, which decreased flows by 6–8%. Bo et al. (2020) applied SWAT model to quantify water balance components in Huangbaihe River Catchment, China and observed high evapotranspiration rates (57%) as the main form of water loss due to high forest cover (81.41%) in the study area.

Khayyun et al. (2019) modelled the semi-arid region of Hemren dam reservoir within middle River Diyala reach, Iraq using SWAT and observed that most of the runoff occurred during the wet seasons with no continuous contribution to baseflow. The authors also identified subbasins responsible for most of the baseflow in the basin and that most of the precipitation in the study area was lost as evapotranspiration (84%). Das et al. (2019) evaluated the multisite performance of SWAT model in Gomti River basin, India and observed that moisture condition II (CN2) was the most sensitive parameter for calibration and that the model performance had good agreement between simulated and observed streamflow values.

Ayivi and Jha (2019) predicted the water yield and balance under land use change in Reedy Fork-Buffalo Creek watershed in North Carolina, USA using SWAT model. The authors observed that the impervious land would increase to 36.5% of study area by the year 2030, due to which the surface runoff and water yield would increase by 14% and 8.32% respectively. Nilawar and Waikar (2018) developed SWAT model to determine the potential impacts of future climate and land use change on streamflow and sediment concentration of Purna river, a major tributary of the Godavari River in Maharashtra, India. The authors observed that 50% of the precipitation was lost as evapotranspiration and the surface runoff and baseflow contribution was 68% and 32% respectively. Under the extreme climate scenario, the average temperatures was expected to increase by 0.05 – 1.26 ^{o}c along with the precipitation (10 – 55 mm) and availability of water.

The reviewed literature not only highlighted the effectiveness of SWAT model in comprehension of surface water balance components but also its application in hydrological studies in Indian and global context, under the current and possible future scenarios in the Betwa river basin.

2.3. Groundwater Models

A groundwater model offers a quantitative framework to synthesize field information and to conceptualize the hydrogeological processes (Anderson et al. 2015). Under the scarcity of adequate field data for analysis of a system which is hidden underground, the use of groundwater models is the most dependable option to perform any kind quantitative analysis or future predictions. While groundwater models may not be necessary for all hydrogeological problems, yet they are beneficial for nearly every groundwater issue (Anderson et al. 2015). Toth (1963) was the first one to investigate groundwater flow in hypothetical small drainage basins using analytical solutions. Freeze and Witherspoon (1966, 1967) were the first to simulate steady state regional flow patterns in hypothetical layered aquifer systems using numerical models. Since its inception, groundwater models have been widely used as *interpretative tools* to decipherer groundwater system dynamics, as *simulation tool* to analyse system response to stresses, as *assessment tool* to quantify flow budget components, as *predictive tools* to assess scenarios, as *planning tool* for field data collection, as *screening tool* to evaluate groundwater development scenarios, as *management tool* to assess alternative policies and as *visualization tool* to communicate key information to public and policy makers (Zhou and Li 2011).

Groundwater models can either be classified as physical or a mathematical model. Physical models are scaled down simplified version of real field conditions, for example, the pioneering work of Darcy (1856), used a physical lab scale model to derive relationships between flow and head gradient, which became the basis of all groundwater flow models. Mathematical model describes the physical processes and boundaries of a ground water system using one or more governing equations (Kumar 2013). The equations can be solved either analytically or numerically. Analytical models require extensive simplification of natural process to define a problem which then can be solved manually or computationally. It is usually used for simple problems. Numerical models on the other hand, are used to solve more complex problems as it allows for discretization of space and/or time i.e. it is possible to provide governing equations and boundary conditions that change across time and space. This enabled more realistic representation of groundwater systems that can be solved using a computer (Kumar 2013).

2.3.1. Groundwater Modelling Process

A model should simulate all processes important to addressing the modelling objective (Anderson et al. 2015). So, the first step towards setting up a groundwater flow model is to define the model objectives. It is crucial because the objectives serve as a guide for designing the numerical model and are used to assess whether the model successfully achieved its goal.

Based on the defined objectives, the conceptual model is prepared and is the next step in modelling process. The defined problem will be addressed with a mathematical model which will be based on the conceptual model. A conceptual model is a qualitative representation of the groundwater flow problem which conforms to the hydrogeological principles. Conceptual model generally consists of information on model boundary conditions, hydrostratigraphic and hydrogeologic properties, flow direction, sources and sinks, and field-based estimates of groundwater budget components (Anderson et al. 2015). GIS tools were usually used to synthesize, analyse, and organize the hydrogeological data.

The conceptual model is then transferred to mathematical model through formulation of complex equations. A mathematical model entails a governing equation which represents the processes within the problem domain. The mathematical model then can be solved using analytical or numerical methods. Analytical solutions are quick, numerically accurate and continuous in time and space but, require extensive simplification of natural process (Anderson et al. 2015). It is used for simple problems and can be solved manually; Analytical Element Method (AEM) and GFLOW are few of the widely used analytical model for groundwater problems (Yager and Neville, 2002; Omar et al. 2019). Numerical models on the other hand use approximate form of governing equation to compute head at discrete points (nodes) in space, unlike AEMs. They can solve transient problems in 3D space of heterogeneous and anisotropic aquifers under complex boundary and initial conditions (Anderson et al. 2015). The most commonly used numerical methods are Finite difference (FD) and finite element (FE) methods (Anderson et al. 2015). The FD approach uses indices to assign the nodes' relative positions within rectangular grids in 3D space, whereas the FE method uses mesh spatial coordinates to arrange the nodes in a specific area. A wide range of modelling software has been developed to solve different groundwater problems (Kumar 2019). Some of the widely used FD based models are MODFLOW, GFLOW, Visual MODFLOW, PMWIN, SEWAT Chemflo etc. and models based on FE methods are FEFLOW, AQUA3D, WinTran, ChemFlux etc. (Kumar 2002).

MODFLOW models have been widely adopted due to its easy accessibility, ease of use and versatility (Singh 2014). Since its release in 1988, MODFLOW has emerged as the global industry standard for groundwater modelling due to its adaptable modular design, thorough coverage of hydrogeological processes, and free public domain accessibility.

(Zhou and Li 2011). With rapid development in software engineering, computing capacity and wide use of GIS, several GUIs were developed for MODLFOW, such as Processing Modflow, Visual Modflow, GMS and Groundwater Vista, which enabled study of large groundwater basins.

In this study, GMS 10.7 has been used with the MODFLOW-NWT code for modelling the groundwater behaviour. The selected model is robust and can handle the cell drying and rewetting problem in groundwater models. The reviewed literature is based on the hydrogeological and climate similarity with the chosen study area with the objectives of study focused on the application of the numerical models in quantification of groundwater flow budget, MAR site selection and MAR rate quantification.

2.4. Groundwater Flow Modelling in Weathered Regions

Gobinath et al. (2022) developed a transient (2015-2018) groundwater flow model of a part of the Bemetara district of Chhattisgarh, India using visual MODLFOW to conduct a detailed analysis of groundwater flow in shallow and deep aquifer. The study area comprised of semi-consolidated formations of Chhattisgarh Supergroup rocks. The results revealed that under the current pumping conditions the water table would fall by 2.5 to 4 meters by 2024 and would require reduction of pumping by 15% to prevent the current rate of depletion.

ArunaJadesan et al. (2021) applied MODLFOW to model the groundwater flow in semi-arid region of Palar River basin, Thirukkazhukundram block, Tamil Nadu, India for three years (2017-2019) and observed that under the current pumping conditions, the aquifer systems were stable. Upon 10% hike in pumping and the groundwater table would decline by 0.3 to 0.6 meters in few locations. Jain et al. (2021) evaluated the groundwater flow across formations, quantified the hydrological budget, examined the effects of changes in hydrological stresses in the hard rock region of Narmada River basin, Gujarat, India. The authors developed transient MODFLOW model to simulate the groundwater flow process for 16 years (1986-2002) and predicted for 13 years (2002-2015). They observed that the model was most sensitive to conductance applied to General Head Boundary (GHB) and the aquifer systems was safe under present hydrological stress and that future scenarios would also not much affect the storage as the recharge would increase from GHB and discharge to river Narmada would decrease to maintain the groundwater levels.

Åberg et al. (2021) employed Leapfrog Geo to construct a 3D hydrostratigraphic model and MODLFOW-NWT to simulate the groundwater flow in the complex sediments underlain by fractured and weathered crystalline bedrock in the municipality of Sodankylä in northern Finland. The authors evaluated the effect of simple and complex hydrostratigraphic models on groundwater recharge/discharge patterns and observed that increasing the complexity of aquifer geometry appeared to improve the fit between observed and simulated groundwater level generating more reasonable flow patterns. However, the authors also stated that the hydrostratigraphic modelling process was very time consuming and would require large amount of data.

Prasad et al. (2021) modelled the khondalitic suite of rocks in the Kandivalasa river sub-basin, Eastern Ghats, India, using Visual MODFLOW for four years (2013-2016). The results indicated that the aquifer systems were under stable conditions but would lead to unsustainable conditions if the extraction rate increased by over 2% per year in the future.

Neupane et al. (2020) developed a steady state Visual MODLFOW model of the weathered zone of Choutuppal Mandal, Nalgonda district, Telangana, India to assess the future pumping schemes in the region. The authors observed that the maximum pumping rates to be limited to 24 m^3/day in order for the aquifers to remain sustainable in future. Ray et al. (2020) employed visual MODLFOW to model Seonath-Kharun interfluve area in the Chhattisgarh State of India to quantify, analyse and predict the groundwater balance components from 2013 to 2021. The authors observed that the annual groundwater outflow from aquifers would exceed inflow by 13% and 31% under business as usual and worst-case scenario and suggested that the groundwater draft could by contained at 90% of annual recharge through suitable recharge augmentation and demand control.

Kirubakaran et al. (2018) applied integrated MODLFOW and GIS tools to characterize groundwater flow systems and quantify the groundwater budget in the weathered region of Tirunelveli taluk, Tamil Nadu, India. The authors reported negative flow budget for the study area with an annual loss of 104 m^3 per year. Patil and Chetan (2017) modelled the Hiranyakeshi watershed of Ghataprabha sub-basin in southern Maharashtra and northern Karnataka, India, using visual MODLFOW to provide insights into groundwater system under current and future stresses. The authors observed that under the current pumping rates, the groundwater table would decline by 50 meters in the next 10 years and required reduction of pumping by 50% to overcome the critical conditions.

Jazi and Eckstein (2015) determined the bulk hydraulic properties of weathered/ fractured zone of Appalachian Plateau in Sand Lick watershed in Boone County, West Virginia, USA using inverse numerical simulation of groundwater flow. The authors employed steady state MODLFOW model to simulate the groundwater flow and observed the model closely represents quantitative parameters of the groundwater flow system. Yidana et al. (2014) employed sable isotope and MODLFOW model to determine the origins and flow direction of the groundwater in the Nabogo sub-catchment of White Volta River Basin, Ghana, West Africa. The authors observed that the groundwater in the region was of meteoric origin, most of the shallow aquifer recharge water (34–70.5%) was lost as evapotranspiration due to high temperatures and low humidity and there was no apparent

2.5. Groundwater Budget Quantification

Groundwater flow budget quantification have been done using water budget methods (Yang 2022; Bayat et al. 2023), remote sensing and GIS based methods (Rashid and Ahmed 2018; Nazari et al. 2023) yet numerical groundwater flow modelling has been one of the most effective methods for groundwater resource quantification and have been widely used in groundwater management and flow budget quantification studies (Zhou and Li 2011; Ma et al. 2023). Numerical models have been applied to study storage variations of entire globe. de Graaf et al. (2017) conceptualised a two-layer model using MODFLOW-2000 and observed a global groundwater depletion of 6292 km^3 over the period of 1960-2010. Alattar et al. (2020) simulated the groundwater flux and hydrological process across the entire US contiguous using an integrated MODFLOW- One-Water Hydrologic Model Version 2 (MF-OWHM2) model. Upon quantification of the water budgets, the authors observed that the groundwater levels and river discharges had a strong corelation, but the fully coupled model was limited by grid size and performed poorly in highly heterogeneous terrains. Models have also been applied at smaller scales to quantify urban flow budget of cities like Bengaluru, India (Tomer et al. 2021), by development of 2D model and observed that the city experienced a negative groundwater balance of 40 MLD in 2016.

Simulation model-based groundwater budgets have also been used to determine optimal dewatering rates in case of mines in Godavari valley, Andhra Pradesh, India (Surinaidu et al. 2014), to assess hydraulic connection between neighbouring aquifers in Riardo Plain aquifer, northern Campania Region, Italy (Viaroli et al. 2018) or to determine interaction of artificial lakes (reservoirs) with groundwater in Turawa Lake, south Poland (El-Zehairy et al. 2018). Jones et al. (2017) observed storage loss in the Apalachicola-Chattahoochee-Flint (AFC) river basin, Florida, USA, during 2008-2012 period and that the largest groundwater outflow was through wetlands. Karki et al. (2021) conducted scenario analysis on the same AFC basin using MODFLOW-NWT and reported that the aquifers might not sustain projected increase in water demands under drought conditions.

Groundwater models have been widely used to evaluate the impact of anthropogenic activities and climate change on groundwater budget components and aquifer sustainability. Pinsri et al. (2022) employed MODFLOW model to assess future impact of climate, land use and abstraction impact on groundwater resources in Tak Special Economic Zone, Thailand. The modelling results predicted an increase in forest cover and decrease in agriculture area while the groundwater table would improve in urban areas and decrease in the agricultural areas. Gebere et al. (2021) employed a steady-state MODFLOW-2005 model to quantify flow budget of Modjo River catchment, Ethopia and observed that decrease in recharge rates had more influence on groundwater contribution to rivers and baseflow than increase in abstraction rates. Eltarabily et al. (2018) assessed impact of different recharge and discharge scenarios on Quaternary aquifer east of Nile Delta, Egypt using a MODLFOW model and observed that current rate of abstraction was sustainable, and an increase of 50% pumping would result in reversal of stable conditions.

Surface and groundwater have been perceived and managed traditionally as separate resources (Sisay et al. 2023). However, they interact with each other continuously and any changes in one part of the system may affect other parts of the hydrological cycle (Healy et al. 2007). SWAT model in conjugation with MODFLOW models have been widely used to quantify, assess, and mitigate water resource problems and promote sustainable use. Mohsenifard et al. (2023) used SWAT results as input to MODFLOW-2000 to assess the impact of land use changes on groundwater sustainability in Shazand watershed, Iran. Optimization of cultivated area based on water consumption and income of each crop resulted in possible reduction of 2 million cubic meters groundwater extraction in 7 years. Sisay et al. (2023) used SWAT and MODFLOW-NWT models to investigate the surface-groundwater interaction in the Modjo River basin in central Ethiopia and observed that increase in abstraction and decrease in recharge would result in decrease of groundwater flow into downstream catchments.

2.6. MAR studies using Numerical Modelling

There has been a constant increase in the number of MAR studies with application of groundwater models (Ringleb et al. 2016). It has been explicitly mentioned in the Australian guidelines to use groundwater flow, transport, and geochemical models during the investigation and trial phase of a new MAR facility (NRMMC, EPHC, NHMRC 2009). The American Society of Civil Engineering's (ASCE) standard guidelines also recommend using modelling for the MAR project's feasibility assessment or early design (EWRI 2001). Although modelling and GIS techniques can be applied at each stage of MAR process, but most of the literature is available on the planning, design and operation phase of MAR project (Ringleb et al. 2016). The application of spatial and numerical tools in MAR is further reviewed under two specific sections of MAR suitable site selection and the quantification of MAR capacity and operation schedule.

2.6.1. Suitable MAR site selection

GIS based multi-criteria decision analysis (MCDA) techniques has been extensively applied in potential MAR site identification (Sallwey et al. 2019). The author reviewed 63 such studies all across the globe, most of which (22) was conducted in India between 1998-2017. About 467 unique criterions were identified with an average of 7.4 criteria used in each study. The most used criterions were slope, land use, geology, soil type, drainage density, geomorphology, aquifer thickness, and hydrological soils. While geomorphology and hydrological soils were less preferred criteria, their weightage and rank were the highest. While highly popular, the method was more suitable for spreading and in-channel modification method of recharge. Moreover, there were no established procedures for choosing significant elements or allocating appropriate weights to them (Alkhatib et al. 2021). Important factors such as water availability, subsurface features, or the aquifer response was given no consideration (Sallwey et al. 2019; Tewari et al. 2024).

Some authors have generated suitability maps based on the surface vis sub-surface parameters and numerical models. The commonly adopted sub-surface parameters were aquifer thickness, aquifer hydraulic conductivity, confining layer thickness, aquifer storativity, vadose zone thickness, and historical changes in water table elevation (Mondal et al. 2008; Rahman et al. 2013; Russo et al. 2015; Jasrotia et al. 2019; Kumar et al. 2021). Gaur et al. (2011) combined spatial modelling using GIS and groundwater modelling to assess different scenarios for identification of rainwater harvesting structures in subbasin of the Banganga River, Jaipur, India. Groundwater model was applied to generate flow vectors and to assess the impact of recharge structures on proposed potential zones.

Rahman et al. (2013) applied spatial MCDA techniques and mathematical modelling to identify and rank suitable MAR sites in the coastal aquifer of North Gaza. The criteria included surface and sub-surface characteristics, groundwater quality and cost of transport. The very good sites were checked against long term groundwater flow and transport simulations under MAR operation conditions. Russo et al. (2015) used GIS and numerical modelling to address MAR site suitability problem in Pajaro Valley Groundwater Basin (PVGB), central coastal California, USA. The most used surface and subsurface parameters was employed to generate MAR suitability map. Groundwater model was used to quantify its relative impact on groundwater levels The analysis revealed that locations farther inland than the coast resulted in long term reduction in sea water intrusion without losing groundwater into sea.

Sashikkumar et al. (2017) identified suitable recharge sites in the Kodaganar river basin, Dindigul district, Tamil Nadu using weighted index overlay method and assessed its performance using a MODFLOW model. Jasrotia et al. (2019) considered surface and sub-surface parameters in weighted index overlay method to identify suitable MAR sites in Jammu Himalaya, India. The authors compared GIS based results to groundwater model-based maps and observed that the excellent recharge zones had gentle piedmont slope with deeper water table. Kumar et al. (2021) applied integrated GIS based weighted overlay technique with fuzzy-analytical hierarchy process (fuzzy-AHP) technique to map groundwater potential zones in data scarce regions. A total of 20 Surface and subsurface parameters were considered for the weighted overlay analysis.

Although numerous studies on MAR site selection were available, very few have considered the aquifer response to MAR in site selection studies. Since it is a crucial indicator of the hydrodynamic influence of artificial recharge on groundwater levels, the generated groundwater mound beneath the recharge structure can be used to gauge the aquifer response to MAR. (Russo et al., 2015; Alam et al., 2020). Water injection works best in areas where large amounts of water can be injected without changing the groundwater flow direction or raising headwater levels too much. (Khalil et al. 2022). Groundwater mound studies have made extensive use of Glover's (1961) and Hantush's (1967) analytical solution to examine the development and deterioration of groundwater mounds beneath infiltration basins (Smith and Pollock, 2012; Dewandel et al. 2021). While analytical solutions were associated with simplifications, the application of numerical models was computationally elaborate (Alkhatib et al. 2021). Numerical models have been widely implemented to derive the influence area and mound heights (Mirlas et al. 2015; Alam et al. 2020). Alkhatib et al. (2021) employed combination of analytical and numerical techniques to identify suitable MAR sites in Azraq Basin, a transboundary aquifer shared between Syria and Jordan. Khalil et al. (2022) employed two group criteria which included hydrological components and complementary components to identify suitable ASR sites in Al Ain region, Emirate of Abu Dhabi in the UAE. Based on the results two most suitable sites were selected and groundwater flow model was employed to simulate five different scenarios of recharge and determine the distribution of injection wells. The authors observed that a minimum spacing of 1200 m was requisite to avoid excessive head build up and Al-Khrair site was better than Al-Shuwaib site for MAR activity.

2.6.2. MAR capacity, technique, and operation

Selection of a particular technique for aquifer recharge depended upon several inter-related factors such as source water availability, aquifer capacity to store and discharge water, lithology, quality of source water and cost of implementation, each discussed at length by Alam et al. (2021). The authors analysed 1127 MAR projects and 33 research studies globally and provided a decision framework to guide MAR implementation with added benefits such as land subsidence minimization, flood risk mitigation, salt-water intrusion prevention, and augmentation of low dry-weather flow for ecosystem services. In this thesis, MAR refers to the direct aquifer recharge through injection wells and the literature review for injection capacity and operational schedule has been focused on well/shaft and borewell recharge technique of MAR. Direct recharge of aquifers was advantageous over other techniques as it required less land area for installation, had no clogging problems as in surface spreading technique and water could be secured at target locations (Shandilya et al. 2022a). Keeping the aquifer conditions at the LBRB study area in mind, injection capacity in unconfined aquifers is only mentioned in this thesis.

In case of injection wells in unconfined aquifers, determining the appropriate recharge rates becomes crucial in order to prevent excessive head buildup or water logging (Dillon et al. 2014; CGWB, 2021). Bower (2002) states that aquifers should be adequately transmissive to avoid excess build-up of groundwater mound. Despite their vital importance, injection capacity in unconfined aquifers have been the subject of very few published research (Shandilya et al. 2022). Choi and Kim (2023) evaluated the interference effect between injection wells using the results of the pilot injection test and the groundwater numerical model in multiple regions in South Korea. The authors also conducted cost analysis and observed that construction cost reduced with increased distance in recharge wells and the optimum interval was about 5 meters. Shandilya et al. (2022) worked out aquifer-scale injection capacity map in confined and unconfined aquifers of Minnesota, USA, by applying Theis (1935) solution for infinite confined homogenous aquifer with constant rate of injection. The authors observed that two to four wells were required to inject water volume equivalent to one-month domestic water requirement. Alam et al. (2020) conducted pilot studies to assess the performance of recharge wells in directing monsoon runoff water in Jiwai Jadid village, Rampur district, Uttar Pradesh, India and observed that inter and intra-annual variability in groundwater levels strongly influenced gravity recharge and lateral groundwater flows. Gibson et al. (2018) applied Theis (1935) and Copper-Jacob (1946) approximation to ASR wells to find regional and local suitability of recharge sites in Washington State, USA and observed that over 50% of the locations had potential of 6400 MLD of injection. Mathias and Moutsopoulos (2016) presented approximated solutions for water injection in unconfined aquifers with unsteady flow using Forchheimer's equation and observed that non-Darcy effects were expected to be significant around both injection and production wells in unconfined aquifers. Field study was conducted by Dwivedi et al. (2015) on a semi - confined aquifer in Patna urban area, middle Ganga Plain in Bihar, eastern India to determine recharging capacity.

2.7. Summary and Identified Research Gaps

Groundwater overexploitation to satisfy ever-growing demand from various sectors have led to the global depletion of major aquifers (Richey et al. 2015). The depletion is disproportionally severe in semi-arid or arid regions (Wada et al. 2010) and increasing crop production under such conditions have led to current practices of groundwater use to be unsustainable (Russo and Lall 2017). Although MAR has emerged as a popular choice in groundwater management strategies, its implementation, suitable site and method selection, and operation is a challenging task, dependent upon multiple factors (Dillon 2005).

Although several authors have reported the importance of water budget estimation in various aspects of water resource management and several modelling-based studies have been conducted in aquifers across the globe, yet only few have discussed about the components of groundwater flow budget and the influence of recharge and abstraction stresses upon it.

Various methods such as MCDA techniques based on surface and subsurface parameters, numerical techniques based on analytical solutions of developed groundwater mound hight, MCDA in tandem with numerical models have been employed to identify suitable MAR sites. However, literature on integrated studies that considered the important surface and subsurface factors while bearing in mind the aquifer response to planned interventions was not available.

In case of unconfined aquifers, only few literatures were available on determination of safe recharge rates of injection wells, and none incorporated a holistic approach of quantification of source water availability, frequency and duration in a catchment, safe storage capacity in aquifers and suitable recharge rates and operation schedule based on available surplus water.