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Review Paper

Interlinking of Lakes with Emphasis on Groundwater Recharge Under the Climate Change Impact

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ABSTRACT

Climate change has intensified water-related challenges, particularly in regions that depend on seasonal rainfall and groundwater for agriculture and daily needs. Among nature-based solutions, the interlinking of lakes has emerged as a promising approach to improve groundwater recharge, manage surface runoff, and enhance long-term water resilience. This review paper explores the concept of lake connectivity as a decentralized and adaptive strategy for sustainable water resource management under changing climatic conditions. It compiles and analyzes existing research on the hydrological, ecological, and climatic impacts of interlinking lake systems, with particular emphasis on their contribution to groundwater replenishment. This paper aims to synthesize the current state of

research on lake interlinking, focusing on its potential to enhance groundwater recharge and contribute to climate change adaptation. It compiles insights from academic literature, technological approaches, case studies, and institutional practices to offer a comprehensive perspective on this nature-based solution. The synthesis of findings reveals that interlinking lakes can serve as a nature-based solution to mitigate the adverse effects of climate change, enhance groundwater sustainability, and support integrated watershed development. The paper does not aim to test a specific hypothesis or introduce a new predictive model. Instead, it serves as a foundation by synthesizing existing knowledge, examining current research directions, and outlining areas that require further exploration.

INTRODUCTION

Water is a requisite resource desirable in all aspects of human activities (Rodriguez & Iturbe 2000). Globally, the complex interactions of geophysical, hydroclimatic, and human variables determine the availability of water in hydrological systems (Tijerina et al. 2021). There is just 3% fresh water on Earth, with little more than two thirds of it locked in polar ice caps and glaciers. The remaining 97% of the water on earth is saline water (Hanafi 2010).

Water supplies are under tremendous strain in the majority of nations today. The world's population is expanding quickly, and projections indicate that by 2030, there will be a 40% gap between the projected demand and the existing supply of water due to present practices (Alkhawlani.et.al. 2025a, Alkhawlani.et.al. 2025b, Saini et.al. 2025). According to estimates, more than 40% of people on Earth reside in regions with limited water supplies, and this issue affects about ¼ of global GDP (World Bank 2023).

One of the major risks to achieving the objectives of sustainable development is the growing demand for freshwater resources, which is fuelled by a number of environmental and socioeconomic factors (such as climate change, agricultural development, urbanization, industrialization, population growth, and food and security policies) (Connor 2015, Sharma & Meshram 2015). Instead of being located in lakes and rivers, the majority of the fresh water on earth is found underground in aquifers. In terms of the social and economic well-being of the urban populace in emerging nations, groundwater is crucial (Wakode et al. 2018).

Although ground water is a resource that may be replenished every year, its accessibility varies throughout time and space (CGWB 2023) (Fig.1). Groundwater supplies 42% of the water for agriculture, 35% in homes, and 3% in industries worldwide (IAH 2016). Most aquifers will be stressed if the increasing trends in groundwater usage continue, which would result in overuse of groundwater resources.

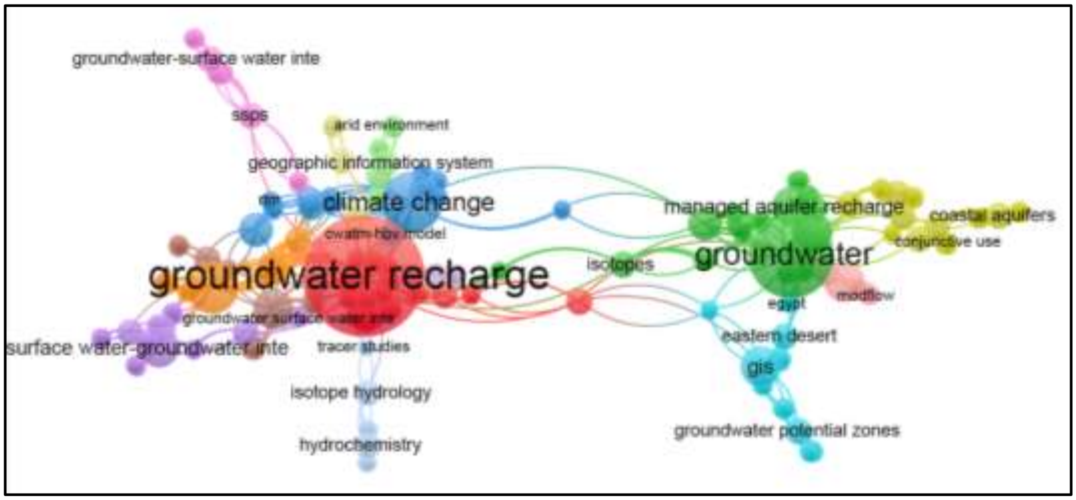


Fig. 1: Network visualization of key concepts in groundwater and climate resilience research.

India makes up roughly 1.6 %t of the world's population, 4% of its water resources, and 2.45% of its surface area (Jain 2019). India receives about 3880 billion cubic meters (BCM) of rainfall on average each year. However, it is anticipated that the net accessible water resources for usage are approximately 1123 BCM because of an inconsistent distribution of rain and elevated rates of evaporation. Surface water makes for about 690 BCM of the total water resources that are available, with groundwater accounting for the remaining 436 BCM. The annual extractable groundwater resource is estimated to be 398.08 BCM after taking natural discharge into consideration (CGWB 2022) and 407.21 BCM is the annual amount of extractable ground water resources (CGWB 2023). India is therefore the world's top groundwater extractor, extracting 239 BCM of groundwater annually. India's water supply is predicted to reach 1140 m3 per person per year by 2025 (Sharma & Sahani 2023). In many regions of India, over consumption for household, commercial, and farming uses was causing groundwater levels to drop quickly (Meshram et al. 2014).

With 164 BCM of surface water and 34 BCM of groundwater, Maharashtra state's water resources are expected to be available on average per year at a rate of 198 BCM. The yearly draft is roughly 17.07 BCM, while the net groundwater availability is 31.48 BCM. A sizable portion of the state has a disparate allocation of water resources. Approximately 42.50% of the state is located in sub-basins that are in deficit or severely deficit. Water scarcity and frequent droughts are plaguing the state. In many areas of the state of Maharashtra, inadequate water supply has emerged as the main problem. A significant portion of the state is already experiencing water stress. The situation is projected to worsen due to the threat posed by climate change (WRD 2019). The irrigation of cash crops is placing an excessive amount of strain on the groundwater supply, and the groundwater aquifer has been continuously exploited over the last few decades. The slow decline in groundwater levels and the decline in well productivity are further ongoing problems (Vijesh 2013).

Groundwater storage, which provides fresh water to irrigated agriculture and a significant portion of the world's population, is fuelled by recharge (Scanlon et al. 2023). When water enters the saturated zone and replenishes the water table's surface, groundwater recharge takes place (Tilahun & Merkel 2009). In order to develop humanity and its water resources sustainably, groundwater must be replenished. Rainfall recharge, which accounts for around 60% of the total yearly ground water recharge, is the primary source of replenishable ground water supplies. The primary way that the future climate will impact recharge is through changes in precipitation, which will increase groundwater recharge more than expected (Berghuijs et al. 2024). Groundwater degradation is now a worldwide issue because of excessive groundwater use in many areas, which has led to a gap among recharge and discharge (Sorensen et al. 2021).

The nation's total yearly groundwater recharge has been calculated to be 449.08 BCM. Groundwater recharging is mostly influenced by monsoon precipitation in India. Furthermore, India has put in place watershed development programs in an attempt to improve the groundwater recharge process organically (CGWB 2023). Additionally, the condition of groundwater recharge in particular regions of the nation can be influenced by regional variables, climatic trends, and agricultural practices (Meshram et al. 2023, Gupta & Lataye 2018).

Groundwater recharge is difficult to accurately quantify and predict. The water table fluctuation, water balance approach, the isotope procedure and conservative geochemical tracers (chloride ion concentration) are some of the procedures available for estimating groundwater recharge (Dereje & Nedaw 2019). The accessibility of the information, the recharge method, and the necessary spatial-temporal levels all influence the appropriate choice of recharge estimating strategies (Yenehun et al. 2022). Prior research employed a variety of methodologies, which can be divided into numerical (Arshad et al. 2022, Cheema et al. 2014, Yifru et al. 2021), physical (Lee et al. 2008, Scanlon & Healy 2002, Healy & Cook 2002) and tracer approaches (Chand et al. 2004, Rangarajan et al. 2005, Shahul et al. 2015) for assessing groundwater recharge. Researchers are increasingly using the numerical method to assess groundwater recharge, which entails examining either the aquifer or the surface, or combination (Semiromi et al. 2019, Dowlatabadi et al. 2015).

Lakes and reservoirs have a direct bearing on climate change prevention and adaptation. Recent research shows that they play important roles in mitigating Global biogeochemical cycles rely on climate change as a significant organic carbon sink (Bastviken et al. 2004, Cole et al. 2001, Raymond et al. 2013, Sobek et al. 2003). Furthermore, because of their enormous water holding capacity, lakes and reservoirs have acted as hydrological shields to stop extravagant weather activities like floods; melting of snow and glaciers, which are anticipated to happen extra often due to climate variation (Schallenberg et al. 2013, Gupta & Lataye 2019). However, a significant challenge to productive improvement of lakes and reservoirs is climate change (Arthington et al. 2016). The tank (surface) water storage determines the well recharge. Lakes play a significant role in supporting groundwater recharge, particularly in regions where surface water and groundwater systems are closely interconnected. Moreover, lakes that are sustained by rainfall, river inflow, or upstream reservoirs serve as temporary storage systems, slowly releasing water into the subsurface over time. In semi-arid and monsoon-dependent regions, such as parts of India, lakes act as critical recharge zones during the wet season. They help buffer groundwater depletion by storing surface runoff and gradually contributing to the aquifer recharge during dry periods.

The idea of connecting basins by canals is not new; it has been used for ages and Rao (1973) was the first to envision interbasin water transmission. Based on the water content status in the interlinking basin, the national water policy also assigns weights for interbasin water transfer from basins of abundance to basins of shortfall. It is feasible to connect minor water storage structures in the same way as rivers are linked (Mosse 1997).

Lake interlinking, sometimes referred to as "interbasin water transference" is a massive water conservation initiative that entails joining lakes to move water from areas with a plenty of water to those with a shortage. These projects' main objectives are to reduce water scarcity, offer irrigation and lessen the impact of flooding. The idea of connecting lakes or rivers is not new; it has been suggested and used in a number of nations worldwide.

Bhandara district in eastern Maharashtra is characterized by a network of natural and man-made lakes, including the historically significant Malguzari lakes, and lies within the Wainganga River basin (Fig. 2 and Table 1). A large portion of agricultural and domestic water needs in this district is met through groundwater. However, overextraction through open wells and borewells, combined with population growth and infrastructural development, has led to a gradual decline in groundwater levels. CGWB (2013) suggested that abandoned malguzari tanks should be resuscitated and existing reservoirs should be given proper care by desilting them regularly and reclamation of reservoirs for other purposes should be avoided. The declining groundwater levels in the shallow alluvial aquifers of part of the district resulted in decreased yield of groundwater, which had adversely affected the irrigation potential and sustainability of groundwater dependent drinking water sources (Gajbhiye et al., 2017). Despite these challenges, district-level research on groundwater dynamics in the context of climate change remains limited.

Fig. 2: Water bodies in Bhandara district

Table 1. List of lakes in Bhandara district

Sr No.	Name of the Lake	Village	Tahsil	Location of the Lake (Latitude & Longitude)
1.	Kurmuda	Kurmuda		21.5570 N, 79.6679 E
2.	Kawlewada	Kawlewada		21.5635 N, 79.7779 E
3.	Pawnarkhari	Pawnarkhari		21.5375 N, 79.7064 E
4.	Ambagad	Ambagad		21.4514 N, 79.6692 E
5.	Paraswada	Paraswada	Tumsar	21.3373 N, 79.7181 E
6.	BetekarBothali	BetekarBothali		21.4277 N, 79.5494 E
7.	Tanga	Tanga		21.3839 N, 79.6604 E
8.	Hivra	Hivra		21.4043 N, 79.5041 E
9.	Dongargaon	Dongargaon	Mohadi	21.3435 N, 79.6563 E
10.	Yelkazari	Yelkazari		21.2397 N ,79.8325 E
11.	Jambhora	Jambhora		21.2575 N, 79.8184E
12.	Kesalwada	Kesalwada		21.3312N, 79.8584E
13.	Amgaon	Amgaon		21.1404N, 79.7482E
14.	Mandangaon	Mandangaon		21.2031N, 79.7239E
15.	Dodamazari	Dodamazari		21.1556N,79.7571E
16.	Malipar	Malipar	Bhandara	21.0815 N, 79.7044E
17.	Bhivkhidki	Bhivkhidki		20.559N, 79.7393E
18.	Katurli	Katurli	Pauni	20.9219N, 79.7623E
19.	Pilandri	Pilandri		20.93N , 79.78E
20.	Gudhari	Gudhari		21.1021N, 79.922E
21.	Ekodi	Ekodi		21.1495N, 79.9395E
22.	Walmazari	Walmazari		21.1435N, 79.9948E
23.	Pindkepar	Pindkepar		21.1304N, 79.9838E
24.	Sawarbandh	Sawarbandh	Sakoli	21.0353N, 79.9813E
25.	Parsodi	Parsodi		21.0563N, 80.0610E
26.	Khandala	Khandala		21.0179N, 79.9710E
27.	Sangadi	Sangadi		20.9677N, 79.9794E
28.	Bhugaon (mendha)	Bhugaon (mendha)		20.9495N, 79.9329E
29.	Rengepar (Kohli)	Rengepar (Kohli)		21.1223N, 79.8236E
30.	Wakal	Wakal		20.8940N, 79.8208E
31.	Khurshipar	Khurshipar	Lakhani	21.1532N, 79.8561E
32.	Kaneri	Kaneri		20.9930N, 79.8527E
33.	Channa	Channa		21.0361N, 79.8092E
34.	Rajoli	Rajoli		20.9008N, 79.8346E
35.	Pimpalgaon	Pimpalgaon		20.7559N, 79.9184E
36.	Chapral	Chapral		20.7148N, 79.9120E
37.	Indora	Indora		20.7002N, 79.9550E
38.	Dighori	Dighori	Lakhandur	20.8803N, 79.9458E
39	Dahegaon	Dahegaon		20.8125N, 79.9133E
40.	Zari	Zari		20.8477N, 79.9358E

Surface and groundwater resources are projected to be influenced by climate change because of anticipated variations in evapotranspiration and rainfall, as well as the spatial and temporal allocation of these crucial components of the water equilibrium (Kirby et al. 2016). In compliance with the Intergovernmental Panel on Climate Change (IPCC AR5 2014), over-all average temperature might escalate by 4 °C by 2100, substantially affecting worldwide access to water and demand. Higher surface runoff rates, greater potential of flooding, and lower rates of groundwater rejuvenating will occur from higher precipitation intensity (Trenberth 2011, Gupta & Lataye 2017). Climate change is likely to add tremendous pressure to groundwater resources by affecting seepage rates and altering groundwater availability. Enumerating consequences of climate change on the aquatic equilibrium at provincial and localized (basin) level is necessary for improving water management to address future issues. The water cycle is altering globally, and IPCC-Fifth Assessment Report (AR5) implicit that this change will likely become more severe in the coming year as consequences (IPCC 2013). This raise concerns that drought and flood disasters will happen frequently and severely in a various areas eventually. Especially in Southeast Asia, where water conservation and adaptation will become a major anxiety in the 21st century to prevent catastrophic natural disasters (Dlamini et al. 2017). Regrettably, India is among the nations dealing with this problem.

The National Action Plan on Climate Change (NAPCC) was announced by Indian government in 2008. Indian States were instructed in 2009 to create State Action Plans on Climate Change that followed the framework and tactics of the NAPCC. When it came to creating Maharashtra State Adaptation Action Plan on Climate Change (MSAAPCC), Maharashtra government led way by ordering a thorough vulnerability assessment study, which included producing model-based climate projections adapted to the geographical features of the State. The study's main prescriptions for the water resources sector are to improve groundwater recharge and storage, conserve and restore rivers and other water bodies, and increase water usage efficiency (TERI 2014). The study's climate model was created to simulate across the state of Maharashtra; it was not created with district-scale climate projections in view.

Usually, the simultaneous replication of groundwater; surface water using a hydrological model is the favoured way for researching the subject of climate impact on the hydrological regime. Many hydrological models are available now that can be applicable to simulate groundwater and surface water.

The two hydrological models that are constantly related to this problem are SWAT and MODFLOW (Bailey et al. 2016). The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) and the Modular Finite Difference Flow Model (MODFLOW) (McDonald & Harbaugh 1983) (SW; GW models, respectively) are two linked hydro(geo)logical models used in SWAT–MODFLOW to produce an integrated output. The constraints of each component model are addressed by coupling them to produce a key that is extra true to factual world hydro(geo)logy.

Notably, MODFLOW is in charge of GW routes comprising saturation flow and GW release into streams, while SWAT handles processes related to SW hydrology like temperature, precipitation, surface runoff, soil water, actual evapotranspiration, and river flow. The SWAT and SWAT-MODFLOW models offer spatially detailed simulations that are essential for evaluating recharge strategies like lake interlinking.

Existing models such as the Maharashtra State Action Plan on Climate Change (MSAAPCC) provide climate projections at the state scale, but lack the granularity needed for planning at the district or watershed level. Moreover, no known studies have applied hydrological modeling tools like SWAT or SWAT-MODFLOW to assess how lake interconnectivity could influence groundwater recharge under changing climatic conditions in Bhandara.

This review seeks to critically examine existing research on lake interlinking with a specific focus on groundwater recharge and to assess the application of hydrological models such as SWAT and SWAT-MODFLOW in evaluating these systems in climate-vulnerable regions like Bhandara district. The study aims to guide future research by highlighting knowledge trends and methodological approaches.

To depict the complete image associated to Interlinking of Lakes with Emphasis of Groundwater Recharge under the Climate Change Impact, large number of publications related to the groundwater recharge, importance of lakes, models used in groundwater recharge assessment, interlinking of lakes and impression of climate change on groundwater recharge from 2000 to 2024 is reviewed.

1. METHODOLOGY

This review adopts a structured methodology to synthesize existing knowledge related to lake interlinking and groundwater recharge, with a regional focus on Bhandara district in Maharashtra, India. A comprehensive literature search was carried out using databases such as Scopus, Web of Science, and Google Scholar. Search terms included "lake interlinking," "groundwater recharge," "Bhandara district," "climate change resilience," "SWAT model," and "GIS-based hydrological analysis." The review considered studies published between 2000 and 2025 that explored the hydrological connectivity of lakes, watershed-based interventions, and groundwater recharge assessment techniques. Inclusion criteria focused on empirical studies, regional assessments, and modeling approaches relevant to semi-humid and hard rock terrain characteristics typical of Bhandara. Articles lacking methodological clarity or regional applicability were excluded. Selected studies were analyzed thematically, with key themes emerging around GIS-based lake mapping, groundwater recharge estimation, SWAT and MODFLOW modeling, and climate adaptation strategies. This structured review provides a foundational understanding for developing a localized framework for lake interlinking to enhance groundwater sustainability and climate resilience in Bhandara.

The current work is focused more specifically on the overview on interlinking of lakes, groundwater recharge and climate change impact on groundwater. In first part SWAT, SWAT-MODFLOW model applications, groundwater recharge by lakes, climate change impression on groundwater resources and interlinking of lakes are thoroughly discussed. In the second part, groundwater recharge assessment models, impact of climate variation on groundwater recharge and linking lakes are depicted with reviews.

The selection process for studies included in this review was conducted in accordance with the PRISMA 2020 guidelines. A total of 1,020 records were initially identified through database searches. After removing 320 duplicates, 700 records were screened based on titles and abstracts. Of these, 600 records were excluded for not meeting the inclusion criteria. The full texts of 100 articles were then assessed for eligibility, of which 10 could not be retrieved. Out of the remaining 90 articles, 20 were excluded due to irrelevance, insufficient data, or methodological limitations. Ultimately, 108 studies were included in the final synthesis. The complete process of identification, screening, eligibility assessment, and inclusion is illustrated in the PRISMA 2020 flow diagram (Fig. 3).

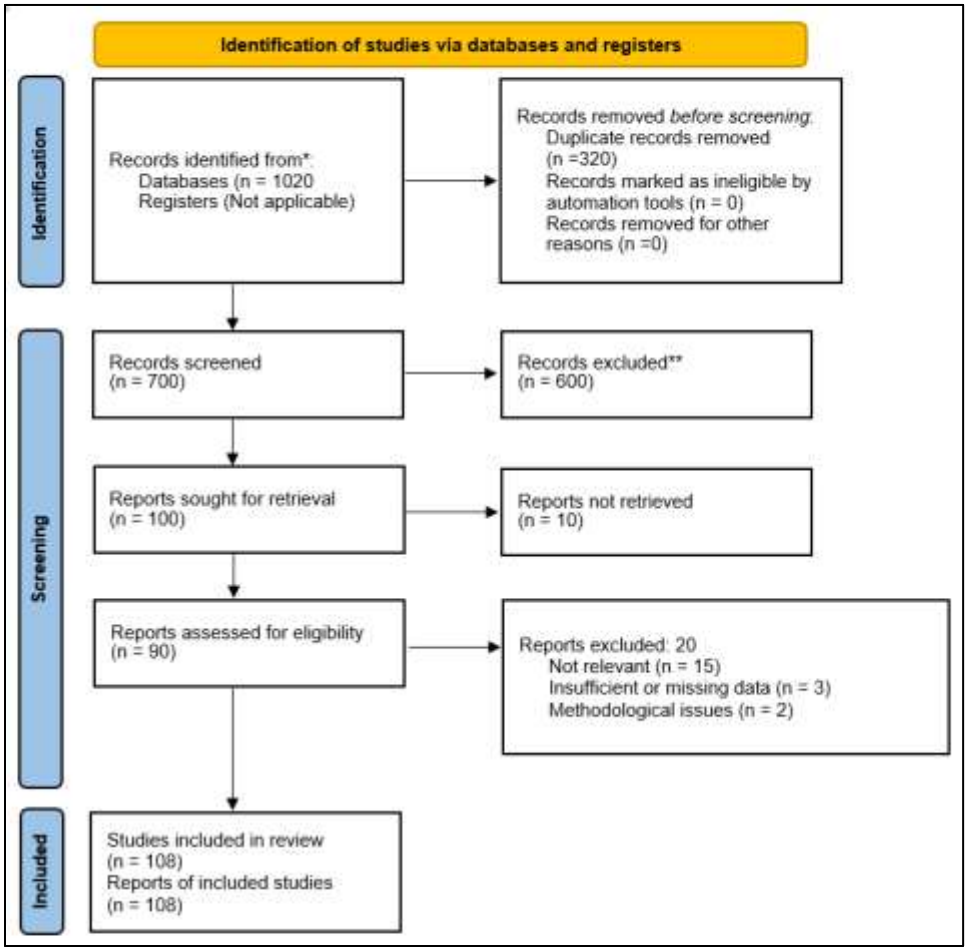


Fig. 3: PRISMA 2020 Flow diagram depicting the selection of studies for inclusion in the review

2.1 Groundwater recharge by lakes

The urban lake is a vital part of the ecology, offering valuable recreational and environmental benefits (Fig. 4). However, because of the quick development and growth, lakes are going through different levels of environmental deterioration correlated to encroachment, eutrophication (caused by industrial and household wastewater) and sedimentation (Reddy & Char 2006). Tank conservation must take into account its numerous uses, which include irrigation, drinking water for humans and animals, and groundwater recharge (Anilgupta 1992, Gupta & Dharaskar 2024). It is evident that the water table rises suitably in tanks that are properly maintained, such as by maintaining the bund and clearing sediment from the canal, wetlands, vegetation, and water fungus. There is conjecture that effective tank governance could elevate the nearby groundwater table (Sowbi et al. 2017, Gupta et al. 2021).

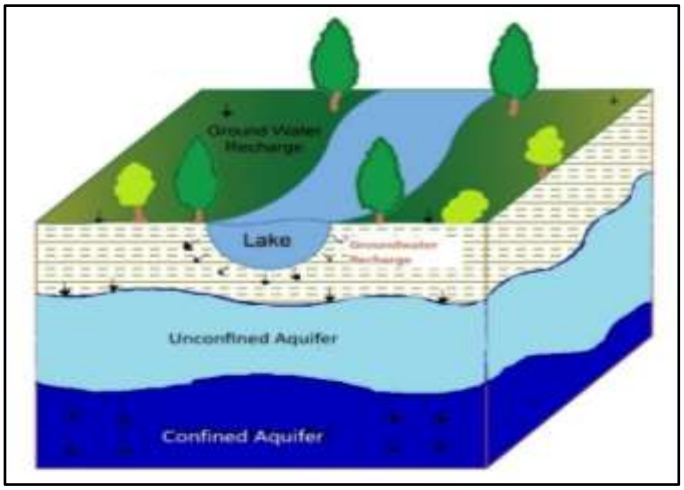


Fig. 4: Groundwater recharge by lakes

Greater storage and greater inflow in the tank have contributed to better groundwater recharging (Palanisamy & Ranganathan 2004). The rate at which the wells recharge is determined by the tank (surface) water retention. For this reason, when the tank is full, the wells overflow, and when the tank is empty, there is not enough recharging (Sakthivadivel & Srinivasan 2004). Some of the research on the role of lakes in enhancing groundwater recharge are enlisted in the Table 2 and shown in Fig. 5.

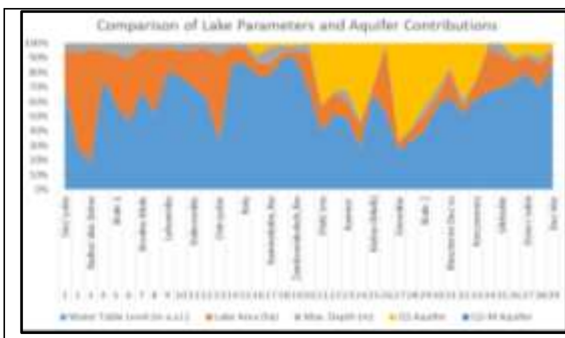
Table 2. Research on the role of lakes in enhancing groundwater recharge.

Study	**Method/ Study Outline**	**Observations**	**Findings**	**Study area**
Jaworska-Szulc B. 2015.	USGS MODFLOW model.	Lakes seepage in aquifers due to interactions.	TDS >250 mg/l-Gaining lakes; Very low TDS <100 mg/l-Losing lakes.	Kashubian lake district, Northern Poland.
Freitas et al. 2019.	Hydraulic head measured by placing Mini-piezometers	Both alkaline-saline and non-alkaline lakes function as recharge zones.	Mini-piezometers in alkaline-saline lakes demonstrated a hydraulic gradient 0.27-0.02 mm−1, indicating downward flow.	Nhecolândiasb region, central-southern Pantanal, Brazil.
Gratzer et al. 2020.	11 wells groundwater stages examination by MRVAA; pressure transducers.	Elevated water stages in oxbow lakes proved to be economical to improve aquifer recharge.	Recharge outcome in fully confined -1.7 × 10^5 m^3/year (3.9 cm/year),fully unconfined -3.2 × 10^6 m^3/year (73 cm/year).	Oxbow lake-wetland system in the Mississippi Alluvial Plain, USA.
Bhatnagar & Jain 2020.	Ponds watersheds were mapped using ArcHydro tools.	Recharge volumes from ponds were estimated with the Web-enabled semi-analyticalGroundwater Recharge model (We-GREM).	Since 2002, the built-up area amplified by 51%, ponds area shrunk by 11%. This results in 14.74% fall in pond recharge.	Roorkee tehsil/sub-district, Haridwar District in Uttarakhand, India.
Yidana et al. 2019.	Groundwater Modelling System-GMS;10.2,	The study discovered a hydraulic link of	25% less groundwater recharge till 2050 will encourage a net lake	Volta River basin Eastern

	MODFLOW	the Volta Lake, which replenishes aquifers in the Afram Plains region.	seepage of nearly 11,000 m^3/day.	Region of Ghana.

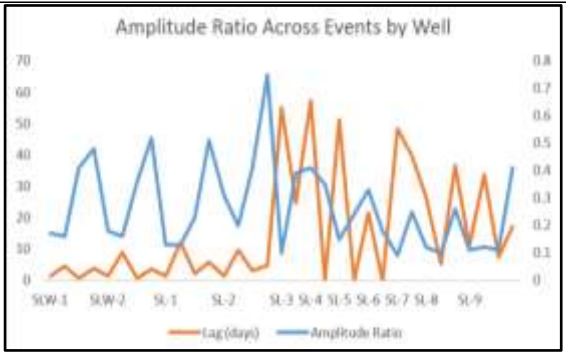
2.2 Climate change impact on groundwater resources

Lee et al. 2019, used HadGEM3-RA RCP 4.5, 8.5 climate variation projections and forthcoming groundwater consumption information gathered through the soil and water assessment tool (SWAT) to investigate act of groundwater levels in South Korea's Geum River Basin (9645.5 km^2). They discovered that future groundwater levels declined by -13.0, -5.0, and -9.0 cm at three upland locations of the five groundwater-level monitoring sites, while increasing by +3.0 and +1.0 cm at two lowland sites. Haleem et al. 2022 applied the Soil and Water Assessment Tool (SWAT) in the Upper Indus Basin, Pakistan, to investigate effects of predicted climate and land-use changes on surface runoff. They noticed that river discharge is more affected by climate change (61.61%) than by changes in land use (38.39%). Climate change (12.76-25.92%) has a bigger impact than land-use alteration (0.37-1.1%). Ferrant et al. 2014 utilised downscaled Global Climate Model (GCM) informations to create a spatially dispersed agro-hydrological model to examine the consequences of climate variation on native groundwater extraction in Kudaliar watershed (983 km2) in Andhra Pradesh State, South India. They emphasized need of taking into consideration local variables while devising mitigation strategies for CC consequences in the research area. Wang et al. 2021, utilised the constant base flow approach to evaluate groundwater recharge in 10 groundwater areas in Taiwan, taking into account historical and climate scenario parameters.

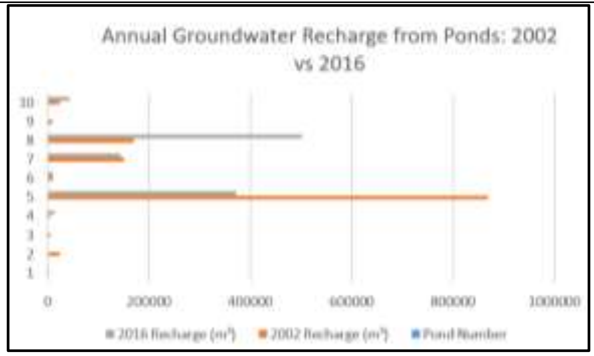


A. Comparison of lake and aquifer parameters (Jaworska-Szulc B., 2015)

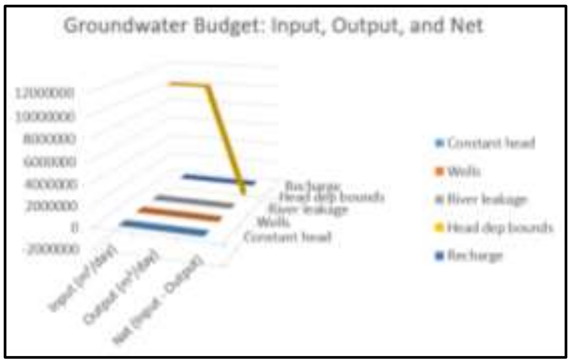
B. Monitoring wells and mini-piezometers properties (Freitas et al., 2019)



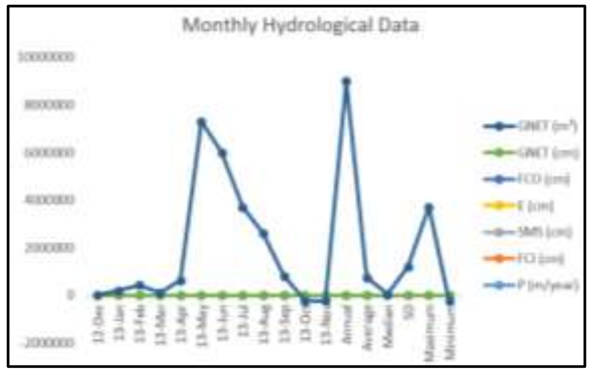
C. Amplitude ratio across events by well (Gratzer et al., 2020)



D. Annual groundwater recharge from ponds (Bhatnagar & Jain, 2020)



E. Groundwater budget: Input, Output and Net (Yidana et al., 2019.)



F. Monthly hydrological data (Lee et al., 2019)

Fig. 5: Representation of studies showing groundwater recharge by lakes.

They estimated that climate change would either boost or decrease groundwater recharge by 32.6% or 28.9% average throughout the climate scenarios compared to Taiwan's basis value.

2.3 Interlinking of lakes

Siderius et al. 2015 concluded that enhancing the combined use of rainfall, tank water, and groundwater could minimize variations, leading to increased and more consistent cropping rate, higher reasonable supply of water, and greater net agricultural income. It was also stated that optimizing the combined use of water sources could significantly lessen the impression of rainfall unevenness on tank irrigation, making it a useful tactic in the perspective of future climate variation. Ramabrahmam et al. 2023 recommended adaptation strategy for enhancing water management in the aspect of climate change is to use excess arrival to replenish downstream non-natural ponds. This can support groundwater replacement; ensure a consistent water distribution to the tail-end tanks in the tank cascade structure. Different studies addressing the interconnection of lakes and water bodies are listed in Table 3.

Table 3. Studies addressing the interconnection of lakes and water bodies

Study	Method/ Study Outline	Observations	Findings	Study area

Ambuja Cement Foundation (ACF) 2003.	Innovative project was launched that involves interlinking of local rivers/rivulets, water harvesting structures, waterbodies.	Increased water permeation has led to greater groundwater recharge.	Ability for preserving more water (12.41 MCF) has been constructed while aiding 339 wells and 1161 ha parched land with profit to 316 farmers.	Gujarat (5 villages named Mitiaz, Devli, Kadodara, Damli & Pipli), India.
Kanjani et al. 2016.	Interlinking of Kadana and Watrak dam suggested.	Alignment preferable with slightest cutting and filling depending on landscape is decided.	Proposed construction of canal (14 km length) between Kadana and Bhadar dams.	Northern part of Gujarat, India.
Peter and Pathinathan 2018.	Proposed interlinking seven lakes in Kanchipuram district, with a planned check dam at Sooradimangalam.	The excess overflow water can be stored in the proposed check dam, which further utilized for drinking and industrial purposes during periods of water scarcity.	If the lakes are interlinked then proposed reservoir/check dam can receive an inflow of 2.877 thousand million cubic of water.	Tamil Nadu, India.
Partheeban et al. 2021.	Suggested connecting five lakes in Chennai city after each lake's water standard was evaluated.	With GIS suggested the best path or canal to connect the lakes, enabling Chennai city to manage its water supply effectively.	The flow channel's designed length is 2 km, however its real length is 1.3 km.	Tamil Nadu, India.
River Linking Project Jalgaon 2011.	Proposed to interlink the Girna River/Dam with nearby rivers and ponds by utilizing existing natural streams and canals to fill the reservoir in Jalgaon district.	The interlinking project aims to recharge groundwater bodies and dry wells.	Resolve issue of drinking water (5 municipal councils, 128 villages), about 16,000 wells replenished as recognized by GSDA.	Maharashtra, India.
Sathianarayanan et al. 2017.	A study was conducted in Sivagangadistrict which is part of the Drought Prone Area Programme. The study identified regions experiencing minimal rainfall, low water levels, and high NDSI values.	Proposed interlinking ponds within identified water stress zones to create a path for redirecting surplus water from seasonal ponds.	The total length of linkage is 385.618 km and out of which 23.25 km passes through the barren land that occupied 5.8 % and more susceptiblefor drought.	Tamil Nadu, India.

2. TOOLS AND TECHNIQUES

3.1 Groundwater recharge assessment models

Evaluating groundwater recharge is crucial for maintaining a balance between groundwater recharge and extraction, estimating groundwater's contribution to streamflow, assessing its vulnerability to contamination, and understanding the sway of weather change and land use/land cover (LULC) variations on spatial; temporal scattering of recharge (Gotzinger et al. 2008, Zomlot et al. 2015). Various models are accessible for estimating groundwater restore, including one-dimensional semi-distributed numerical models like SWAP, one-dimensional lumped parametric models like EARTH, and fully distributed three-dimensional numerical groundwater flow models like MODFLOW (Gebreyohannes 2008). Some commonly used physically based hydrological models are HEC-HMS; MIKE-SHE; SWAT (Sahu et al. 2023). Different works related to groundwater recharge estimation using different methods are listed in Table 4 and shows Fig.7 and Fig. 8.

Table 4. Groundwater recharge estimation studies using different methods

Study	Method/ Study Outline	Findings	Study area	Limitations
Kisiki et al. 2023.	WetSpass model	Annual average recharge- 0–120.88 mm/year. Recharge wet season 0-120 mm/year and dry season 0-4.35 mm/year.	Makutupora basin, Dodoma city, Tanzania	Model performance may vary with land cover assumptions and seasonal data availability.
Guay et al. 2013.	CATHY	Found out recharge rate of 233 mm/year.	South western Quebec, Canada.	Limited applicability in regions with complex geology or variable recharge rates.
Loukika et al. 2020.	SWAT-MODFLOW	Monthly groundwater recharge-16.5272 mm and 17.5596 mm for January and February months respectively.	Chinatalapui Village, West Godavari district, Andhra Pradesh, India.	Requires detailed calibration and high-quality input data for groundwater interaction.
Maxwell et al. 2015.	ParFlow	Assessed prospective recharge by deduction of evapotranspiration, precipitation.	North America	Does not account for subsurface heterogeneity in fine detail.
Naima A.M. et al. 2023.	SWAT Model	Calculated slender upsurge in whole yearly average groundwater recharge-3.05 mm/y-5.12 mm/y (SSP245 and SSP585 for 2050).	Bahi (Manyoni) Catchment (BMC) in Internal Drainage Basin (IDB), Tanzania.	Climate projections carry uncertainty; recharge estimates are scenario-dependent.
Siavashani et al. 2020.	Visual BALAN v.2.0	The mean yearly aquifer recharge from rainfall-10.9mm/yr and 14.7 mm/yr, from watered land were 33mm/yr (ground) and 41 mm/yr (geospatial data).	NW part of the Lake Chad Basin Niger and Nigeria.	Assumes uniform input parameters; irrigation effects may vary locally.
Seidenfaden et al. 2023.	Metran-Transfer Function-Noise model, AquiMod- hydrological model, GARD´ENIA-lumped catchment model	Simulated groundwater heads, all three models performed admirably. GARDENIA can offer extra consistent recharge values.	10 European countries.	Model selection affects output consistency; computational load is high.
Trivedi et. al. 2023.	SWAT model calculated volume of recharge requisite to entirely reestablish the water in the basin.	Thorough restoration and peripheral stream found to be 1.33% of total rainfall. Yearly recharge diverse from 75.27 to 379.02 mm.	Kanari river, India	Depends on accurate rainfall input; results vary with spatial resolution.

Waldowski et al. 2023.	Assess the alteration of groundwater storage by a time-cumulative water balance over water table fluctuations.	Observed that fully integrated models have the capability to generate lateral flow throughout the subsurface, capture distinct spatial and temporal outlines of rejuvenating aquifer.	Deutsche Forschungsgemeinschaft, NE. Germany	Requires continuous monitoring of water table; sensitivity to surface storage dynamics.

3.2 SWAT model applications

Dekongmen et al. 2022 estimated the groundwater recharge in Afram Plains watershed, Volta Basin in Ghana by using SWAT Model (Fig. 8). The watershed was differentiated in very poor recharge area (0.58% - 20.8 km^2), poor area (22.4% -798 km^2), moderate area (60.9% -2169 km^2) and high area (16.2% -576 km^2). Hepach et al. 2024 applied SWAT the process-based infiltration model (PIM) to Mediterranean karst aquifer sited in Israel and the West Bank for assessment of groundwater recharge. They found that the range of mean annual recharge estimates was between 32.6- 34.6 % of precipitation. Jawale et al. 2024 applied SWAT model in Wakad watershed, Pune, for flood analysis. They observed that the extreme surface runoff detected is 3206 mm and the incidence of flood existences is intensifying over time. Yang et al. 2024 estimated groundwater recharge from Jiamusi, Heilongjiang Province, China by using SWAT model and remote sensing. They found that average groundwater recharge was 61.03 X 10^8 m^3.

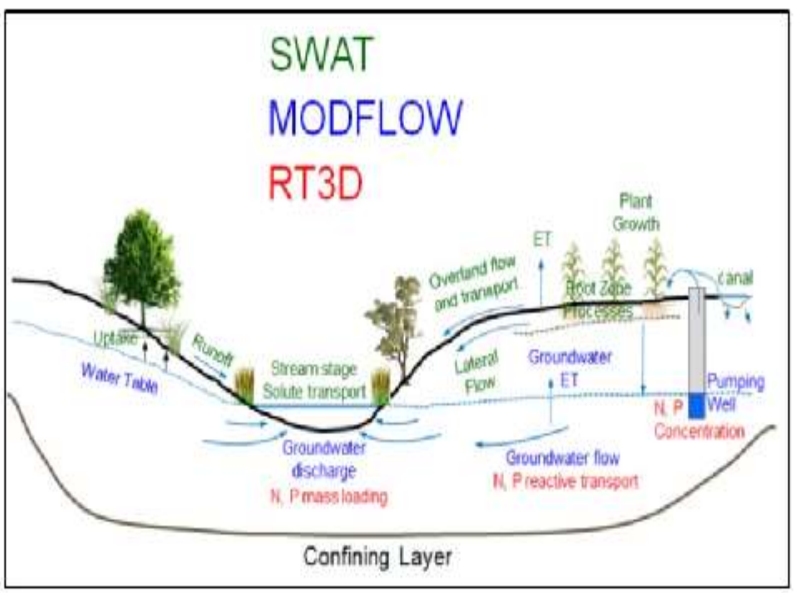


Fig.6: Process simulated by SWAT and MODFLOW model

Rath & Hinge 2024 employed SWAT model; multi-criteria decision analysis (MCDA) for assessment of potential of groundwater recharge in Dwarkeswar river basin India. They concluded that 51.57% of the study region is not appropriate for MAR, whilst the remaining zones are categorised as suitable, low, and moderate, respectively, at 0.12%, 34.59%, and 13.72%. Over the last decade, SWAT has been extensively used worldwide to carry out hydrological modeling at a watershed/basin scale under varying agro-climatic conditions (Verma

& Jha 2015). In the recent past, hydrological modeling using SWAT has emerged as a powerful tool to quantify the effects of climate change on water resources (Jha et al. 2006).

3.3 SWAT-MODFLOW model applications

SWAT-MODFLOW is a united hydro(geo)logical model that incorporates together the Soil and Water Assessment Tool—SWAT and MODFLOW (SW; GW models, respectively) to generate a comprehensive result (Fig. 6). Integrating the element models mitigates the boundaries of respective model, resulting in answer that is extra appropriate to real-world hydro(geo)logy. SWAT addresses SW hydrological routes like precipitation, temperature, river flow, surface runoff, soil water, actual evapotranspiration, and GW recharge, whereas MODFLOW handles GW processes such as saturated flow and GW release into watercourses.

Wei & Bailey 2019 implemented SWAT-MODFLOW to estimate implications of lowering irrigation on hydrological reactions and crop output in a 734 km^2 study region, Lower Arkansas River Valley, Colorado, USA. They found that reducing total applied irrigation water by about 10% reduces surface runoff by 6%, evapotranspiration by 8%, and recharge water by 4%. Aliyari et al. 2021 focused on assessing the forthcoming accessibility of surface-water and groundwater, in addition to cultivar output, in outsized semi-arid agro-urban South Platte River Basin (72,000 km^2), Colorado, USA. Under CM5A-MR-8.5 climatic situation, a 1°C upsurge in temperature and a 1.3% loss in yearly rainfall will result in 8.5% reduction-water flow, 2-5% drop-groundwater storage, and 11% lessening-crop productivity. Chinnasamy et al. 2018 adopted a hydrological model (SWAT), groundwater model (MODFLOW), and flood inundation model (HEC-RAS) in Ramganga basin, India (~19,000 km^2) to characterize the baseline hydrologic regime and evaluate circumstances with circulated managed aquifer recharge intercessions. They discovered that groundwater levels enhanced in 5years after application of MAR, causing in a groundwater rise of up to 7 m. Tolera and Chung 2021 investigated recharge of groundwater and numerical analysis using the SWAT-MODFLOW model. The analysis identified extents of interaction among the river and groundwater. The case of reduced groundwater recharge clearly highlights the significant risk to groundwater stability in the area.

In comparison to using SWAT independently, the integrated SWAT-MODFLOW model demonstrates enhanced effectiveness in representing the interactions between surface water and groundwater, as well as in assessing variations in recharge under changing climatic conditions (Table 5). For instance, while SWAT alone offers limited representation of seasonal groundwater decline, the coupled approach successfully simulates changes in baseflow and reductions in recharge under high-emission climate scenarios.

Table 5. Comprehensive Review of Hydrological Models with Limitations

Study	Model Used	Region	Climate	Scope	Key Findings	Limitations
Aliyari et al. (2021)	SWAT-MODFLOW	South Platte Basin, USA	Semi-arid	GW-SW-Crop integration	Captured climate impacts on crop yield and baseflow under 10 climate scenarios	High data and computational demand; requires extensive

						calibration for climate scenarios
Tolera & Chung (2021)	SWAT + MODFLOW	Upper Awash Basin, Ethiopia	Tropical highland	Recharge & pumping stress analysis	Simulated head changes under abstraction, enabling groundwater stress evaluation	Separate model coupling increases complexity; groundwater dynamics simplified in some cases
Yifru et al. (2021)	SWAT-MODFLOW	Rift Valley Basin, Ethiopia	Semi-arid	LULC & climate change impacts	Recharge reduced by 47–53% under RCP8.5 climate scenario	Model uncertainty under extreme climate projections; high sensitivity to input data quality
Rasheed et al. (2024)	SWAT	Global review	Various	Model sensitivity to input resolution (DEM, soil, LULC)	Accuracy of streamflow and sediment yield highly depends on fine-resolution input data	Lacks integration with groundwater components; does not address baseflow or subsurface flow
Wang & Chen (2021)	SWAT-MODFLOW	Global review	Various	Hydro-biogeochemical processes & solute transport	SWAT–MODFLOW shows great potential in simulating complex hydro-biogeochemical dynamics across regions	Model calibration is data intensive; uncertainties exist due to model structure and input data variability
Liu et al. (2020)	SWAT vs SWAT-MODFLOW	Denmark	Temperate	GW abstraction impacts on streamflow	SWAT-MODFLOW produced more realistic streamflow responses to GW abstractions than standalone SWAT	Integration of both models requires advanced calibration routines (e.g., PEST); demands high computational resources
Jafari et al. (2021)	SWAT-MODFLOW	Shiraz Catchment, Iran	Semi-arid	SW-GW parameter sensitivity and calibration	CN2 and GW hydraulic conductivity were dominant parameters; developed GW calibrator tool improved performance	Calibration of GW parameters remains complex; limited transferability of results without site-specific adjustments

4. RESULTS AND DISCUSSION

4.1 Linking of lakes

An additional source of water supply might be obtained, according to Pravin et al. 2021 by connecting storm-water flow of each level to the reachable surface water bodies. The influence of storm-water assembly on domestic convey is studied using the WEAP modelling software program. They came to the conclusion that if urban storm water is collected and stored in surface water bodies, then 100% of the residential water demand in cities can be satisfied. As noted by Long & Goethal 2019 there is a good correlation between the SDGs pertaining to environmental dimensions (Goals 6, 13, 14, and 15) and the activities taken to accomplish the longevity of lakes and reservoirs. While the effects of climate change on internal water bodies are widespread, they can also be felt locally and in various ways in different locations. Abeysingha et al. 2018 examined the impact of various tank cascade system components on enhancing the quality of the water. They concluded that restoring environmentally friendly tank structural elements and reviving the tank cascade system in the region would be beneficial in halting the spread of CKDu in Sri Lanka's dry and intermediate zones. In order to reduce water stress and accomplish Sustainable Development Goal (SDG) 2 (zero hunger) and SDG aims 6.1 (harmless; reasonable drinking water).Ahmed & Srikanth, 2023, came to the conclusion that a comprehensive strategy utilizing geospatial procedures and the MCDM system could be adopted to ILR (Inter Linking River) plans. For projected Almatti-Pennar (A-P) ILR project, they used Integrated Water Resources Management (IWRM) by include land use and land cover as key considerations in Multi-Criteria Decision-Making (MCDM) process. In order to achieve the goal of filling 115 main dams by redirecting floodwaters spilling from the Sardar Sarovar Dam along the Narmada River to the drought zones, Joshi et al. 2018, concentrated on network alignment. The 'Sauni Yojana: From Draught to life by River Interlinking in Saurashtra Region' program involved the analysis and planning of pipeline network system alignment by Remote Sensing and GIS.

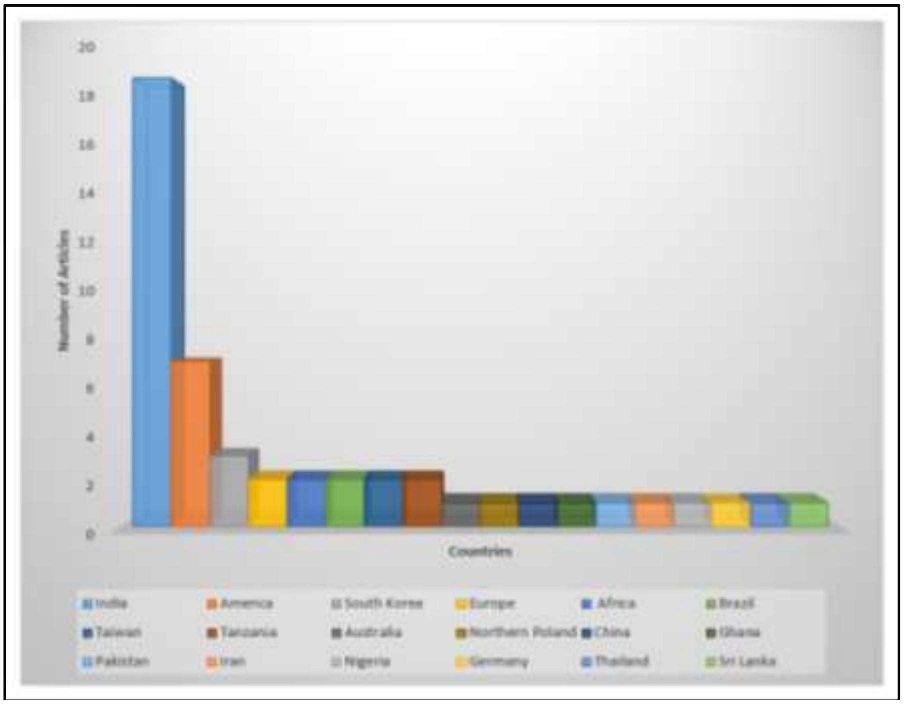


Fig. 7: Number of publications considered for reviews of different countries

Farmers would be able to access water all year round thanks to well-connected water channels, canals, and perennial rivers, according to NITI Aayog's 2022 report. It will increase the amount of water available in places that receive rain and are vulnerable to drought, ensuring more equity in the allocation of water.

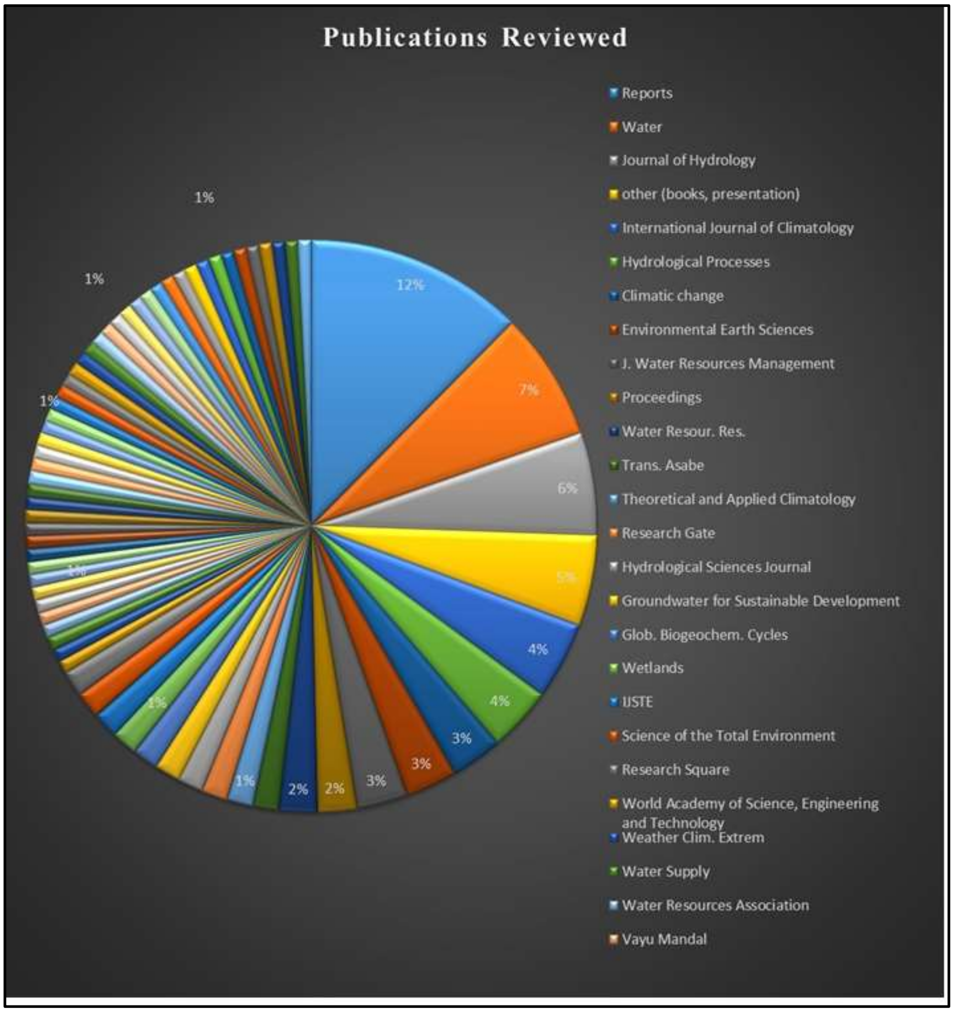


Fig. 8: Publications reviewed and cited

4.2 Impact of climate change on groundwater recharge

According to Ramabrahmam et al. 2023, the SWAT model is used in a lot of basin-level evaluations, with rare studies engaging to inspect the outcomes of climate change on reservoirs; lakes. Impact of climate change on groundwater is showing in Fig. 9. Neto et al. 2021, investigated in a Brazilian Savannah watershed the consequences of global climate change on groundwater recharge. RCP 4.5; 8.5 and future climatic predictions from climate models (Eta-HadGEM2-ES and Eta-MIROC5) were taken into account for calculating the monthly average recharges. Petpongpan et al. 2020 evaluated effects of weather change on groundwater recharge and surface water in Yom and Nan river basins, Thailand. Under RCPs 2.6 and 8.5, respectively, the total amount of water output and water percolation in basin fell by 443.98 and 316.77 million m^3/year. Different works on climate change impact in Bhandara district are enlisted in Table 6.

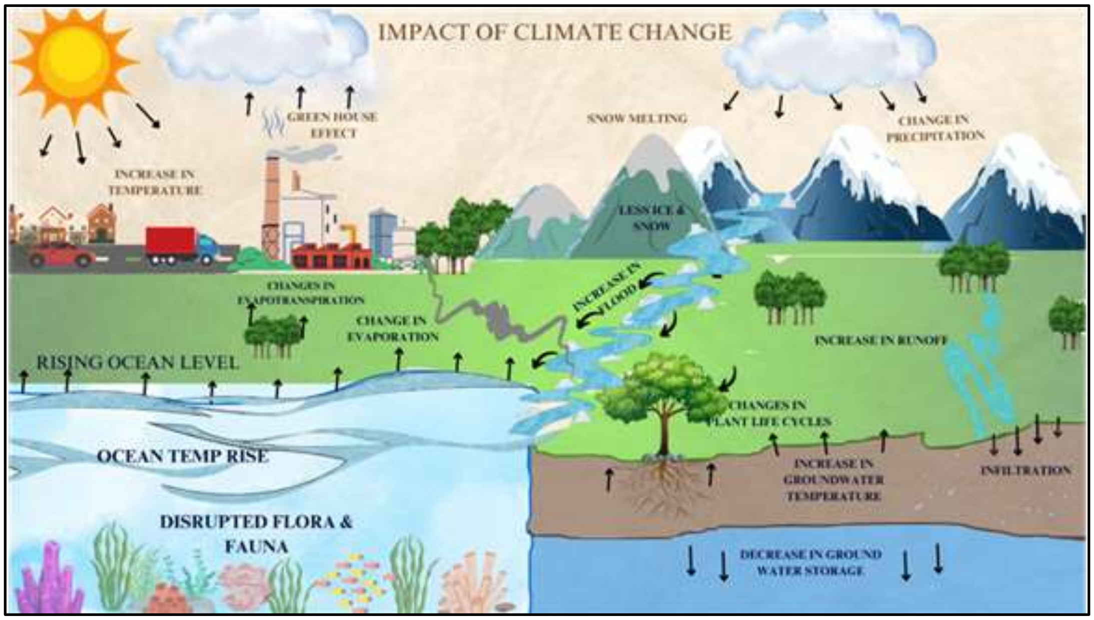
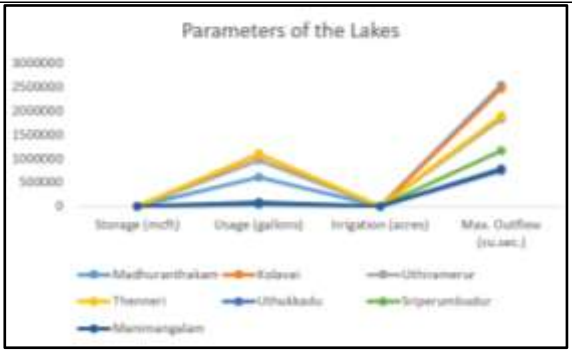


Fig.9: Impact of climate change on groundwater recharge

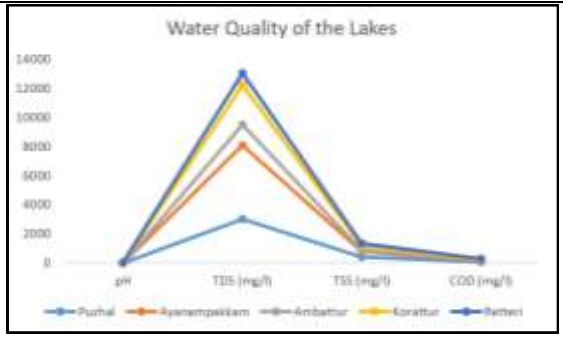
Table 6. Climate Change Impact studies in Bhandara district using different methods

Study	Method/ Study outline	Climate Scenarios/ GCM	Findings	Study area
Das & Umamahesh 2018.	Classification; regression-based statistical downscaling employed to predict monthly monsoon streamflow of Wainganga basin, India. Support vector machine (SVM) and relevance vector machine (RVM) used to execute downscaling.	40 global climate model (GCM), 4 representative concentration pathways (RCP).	Monsoon flow projections over various periods are generated using the RVM, which performs better than SVM.	Wainganga River Basin, India.
Das et al. 2018.	A macro scale, semi-distributed; grid-based hydrological model.	Focused on modelling the GCM; scenario uncertainty.	RCP 8.5 is thought to be the most ideal scenario for the streamflow projected from the MPI-ESM-LR model.	Wainganga River Basin, India.
Hengade et al. 2018.	Used variable infiltration capacity (VIC) macroscale model.	RCP 4.5 and RCP 8.5.	Although regional dispersal of hydrological factors in GRB is mostly constant, the results point to a potential rise in future rainfall.	Godavari River Basin (GRB) in peninsular India.
Kapse 2023.	The hydrological constraints evaluated and interpreted for district management.	No GCM considered	Found that the climate has affected agriculture by showing decreased in area of cultivation comparatively.	Bhandara district, Central India.

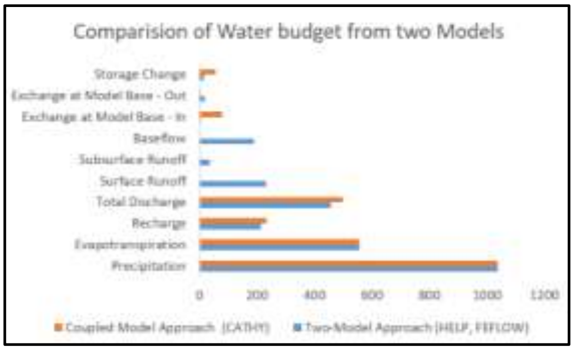
Different work related to interlinking lakes, groundwater recharge estimation and climate change impact are shown in Fig. 10.



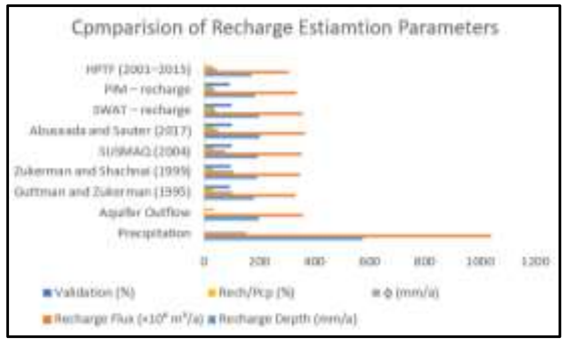
A. Parameters of the lakes [Peter & Pathinathan, 2018]



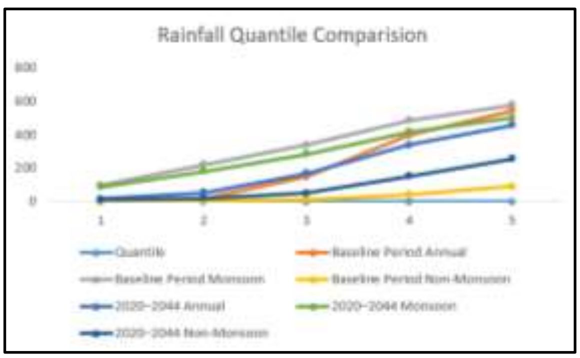
B. Water quality of lakes [Partheeban et al. 2021]



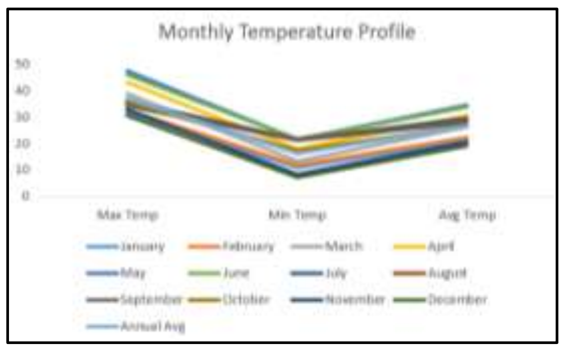
C. Comparison of water budgets from two models [Guay et al. 2013]



D. Comparison of recharge estimation parameters [Hepach et al. 2024]



E. Rainfall quantile comparison [Das & Umamahesh 2018]



F. Monthly Temperature profile [Kapse 2023]

Fig. 10: Comparative studies related to interlinking lakes, groundwater recharge estimation and climate change impact.

5. CONCLUSIONS

About 200 publications on groundwater recharge, the value of lakes, methods for evaluating groundwater recharge and the implications of weather change on groundwater recharge were reviewed in this systematic review and highlighted research trends. The strategy of interlinking lakes represents a promising and environmentally sound approach for enhancing groundwater recharge, particularly in areas facing growing water stress due to seasonal rainfall dependency and climate variability. By facilitating the movement of excess surface water between nearby lakes, especially during monsoon periods, this method can promote better water retention and increase infiltration into aquifers. When applied in geologically suitable regions, lake interconnection not only improves groundwater availability but also supports ecological stability by maintaining wetland habitats, reducing surface runoff, and stabilizing stream flows. Additionally, the approach has practical implications for improving agricultural water security and rural livelihoods, particularly in regions where groundwater forms the backbone of irrigation and domestic supply.

This review, while not offering a new theoretical model or hypothesis, provides a consolidated view of existing research, sheds light on ongoing trends, and outlines avenues for future investigation and field application. To translate the potential of lake interlinking into meaningful outcomes, a coordinated approach is required one that combines scientific tools like SWAT/SWAT-MODFLOW for impact assessment, integrated watershed management for planning. With such an approach, lake interlinking can become a valuable component of adaptive water management in the face of climate change.

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