JOURNAL OF GEOINTERFACE, Vol. 2, No. 2, December 2023, pp. 35–44 e-ISSN: 2583-6900

Facilitating water security through aquifer-based groundwater management in a typical river basin in the hard rock terrain of Peninsular India

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ABSTRACT

The Kallar Aquifer System having a total geographical area of 1691 sq.km between co-ordinates North Latitude 8°41’00”–9°10’30”, East Longitude 77°48’00”–78°15’00” is underlain predominantly by Archaean crystalline rocks and receives an annual precipitation of about 650 mm. The aquifer system is a part of the Kallar basin in Thoothukudy district of Tamil Nadu and does not have any perennial rivers/streams resulting in ground water being the major source of fresh water for various uses. Low aquifer yields, ground water sustainability issues and ground water contamination limit the prospects of groundwater development from the aquifers underlying the basin. Aquifer mapping and characterization of hydrogeological units in Kallar Aquifer System of Tamil Nadu, Southern India, was taken up with the prime objective of suggesting management interventions to facilitate water security. Studies revealed the presence of aquifer systems constituted by weathered residuum at the top and fractured crystalline rocks below with limited ground water potential. Coastal alluvial aquifers bordering the Bay of Bengal near the mouth of the basin mostly have brackish/saline ground water. Better understanding of the hydrogeologic process that control the distribution and availability of groundwater in the Kallar aquifer system is imperative for ensuring optimal resource management. The status of ground water extraction, as in 2022 is rather low at 35%, due mainly to the limitations of ground water availability rather than lack of extraction. A management plan for ensuring long-term sustainability of ground water resources in the basin to facilitate water security has been formulated by integrating all relevant data. Various combinations of measures for supply augmentation and demand reduction have been proposed depending on local hydrogeological conditions and current status of water use, which are expected to result in an additional availability of about 22 MCM of ground water every year. Implementation of measures recommended together with a sustained campaign of awareness creation and capacity building of stakeholders is expected to significantly improve the ground water regime in the basin in the years to come.

ARTICLE HISTORY
Received 1 December 2023
Accepted 18 December 2023

KEYWORDS
Kallar Basin
Aquifer Mapping
Sustainable Groundwater Management
Water Security

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1. INTRODUCTION

Groundwater is central to fight against poverty to food and water security, leading to socioeconomic development and to resilience of societies and economies to climate change (UN Water, 2013). The key determinant to water security is sustainable groundwater resources in terms of its quantity and quality metrics. Increasing and indiscriminate extraction of groundwater leading to declining groundwater levels, desaturation of aquifers and deterioration in groundwater quality are major impediments to sustained groundwater availability (Sinha Ray and Elango, 2019). Unlocking the full potential of groundwater will require strong and concerted efforts to manage the resources addressing both quantity and quality through a multidisciplinary approach.

Gauging the aquifer health by maintaining a fine balance between recharge input and discharge output forms the basis for a sound groundwater resource management. Aquifer responses to recharge inturn depends on its inherent characteristics which will either facilitate or limit the recharge.

Groundwater resources of the Kallar Aquifer System falls on a grim scale with respect to the prime attributes determining water security. Escalating water stress owing to inherent constraints of the aquifer system with 95% constituted by massive hard rocks, semiconsolidated and consolidated and the remaining 5% with coastal aquifers hosting groundwater with substandard quality bump against the limits of their replenishable capacity (Saravanan et al., 2023). This puts the aquifer systems under the cross hairs of stringent monitoring of security variables and devise management strategies to offset the fault lines.

It is in this context that the detailed study of the status of ground water regime' of a typical hard rock basin of Peninsular India has been taken up under the NAQUIM studies of CGWB (National Aquifer Mapping and Management) with special reference to the aquifer disposition and characteristics, long-term behaviour of ground water levels, which will be of great help in formulating sustainable ground water management strategies in the basin – a groundwater stimulus package involving scalable supply side and demand side management interventions.

The Kallar Aquifer System predominantly occupied by hard rocks warrants cautious groundwater development strategies because of the hydrogeological adversities manifested in the form of Poor Yielding aquifers, Drying up of shallow wells, Decrease in yield of borewells affecting the sustainability of abstraction structures, Insitu Salinity, Limited scope for Artificial Recharge Schemes in the saline tracts of the basin, Limited freshwater availability in sedimentary areas occuring as floating lenses resulting in the coastal tract vulnerable to quality issues and Pollution of groundwater due to industrial effluents.

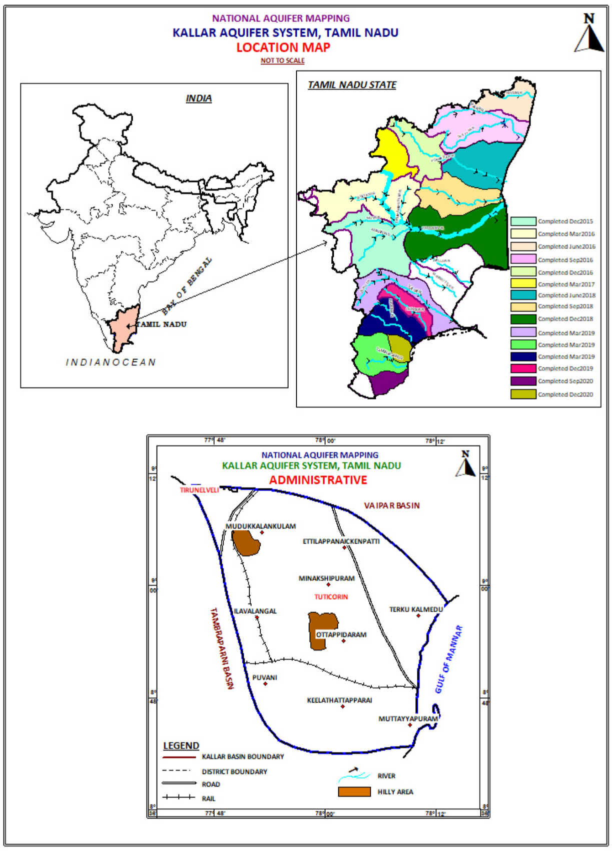

Fig. 1. Location map.

2. STUDY AREA DESCRIPTION

The Kallar Aquifer System is defined by an east flowing river basin and has its catchment defined by the Kallar river draining the northern part and the Korampallam Ar draining the southern part of the basin. The Kallar river basin (KRB) is located in Thoothukudy district of Tamil Nadu State, India and it covers an area of 1691 sq.km between co-ordinates: North Latitude 8°41'00"–9°10'30", East Longitude 77°48'00"–78°15'00" (Fig. 1). The natural flow of these rivers is seasonal and occurs only during the north east monsoon months. The Kallar River traverses a distance of 54 kms in a south easterly direction and has its confluence at Gulf of Mannar. The topography of KRB is plain with gentle slope towards southeast.

A total of 199 tanks locally known as Ooranies differentiated to 15 system and 184 non system tanks provide stress relief to the water scant regions of the basin (Sivakarun et al., 2016). System tanks are ones that collect runoff from their catchment as well as water from neighboring large streams or reservoirs. Non-system tanks are not a part of a river system and rely on rainfall. Under these tanks, a single crop is typically grown . Tanks that are not part of the system are frequently connected to one another to form a group of tanks. The excess water from the higher tank will flow to the lower tanks during periods of intense rainfall (Palanisami and William Easter, 2019). An area of 21 sq km is occupied by the tanks of which the Korampallam tank, a system tank nourished by the Tamiraparni river stand out as the superlative in the basin with an ayacut area of 916 ha holding a capacity of 228.56 Mcft.

The study area experiences a semi arid climate with 2 monsoon periods southwest (June to Sept) and northeast (Oct to Dec). The south west monsoon has only a marginal contribution whereas the north east monsoon contributes to the major precipitation together making 650 mm rainfall which ranks among the lowest in the state (Rangarajan et al., 2019).

The Aquifer System (Fig. 1) located in the southern part of Tamil Nadu, represents a typical Precambrian metamorphic terrain, comprising of gneisses and charnockites (NAQUIM report on aquifer mapping and management of Kallar aquifer system, 2022). The gneisses occupy a major part of the basin with a small area occupied by the charnockites. Towards the coast the crystalline rocks are overlain by sedimentary formations ranging in age from cretaceous to Recent.

Groundwater occurs under phreatic condition in the weathered crystalline formations and in the shallow fractures in hydraulic continuity with them. It occurs under semi confined condition in the fracture zones of crystalline rocks and deeper granular zones in the sedimentary formations. Due to high heterogeneity in the hard rock, especially in terms of fracture system, the aquifer characteristics vary from place to place and therefore the water holding capacity of these rocks also vary drastically in space.

3. MATERIALS AND METHODS

A total of 19 bore wells have been drilled by Central Ground Water Board (CGWB) in the basin representing the Kallar Aquifer System as part of its groundwater exploration program during 2000- 2010 of which 15 were drilled in the hard rock areas and 4 drilled in the coastal sedimentary terrain under brine water studies undertaken by CGWB. During the NAQUIM studies data gaps were identified and 55 VES were conducted through outsourcing evenly spread across the basin and addressing the data gaps. A comprehensive analysis of these data characterized the aquifer systems in terms of its disposition and its lateral and vertical extent which were the key input data for its conceptualization and formulation of aquifer management plan.

As per the latest ground water resource estimation (2015 methodology) the stressed units were identified based on the stage of development of the groundwater resources which is the ratio of the extracted resources to that of the replenishable resources in the aquifer system/basin ie Stage of Extraction (SoE) more than 70%. Under 2015 methodology the assessment involves computation of Annual Ground Water Recharge and Annual Extractable Ground Water Resources, Total Annual Ground Water Extraction (utilization) and the percentage of utilization with respect to Annual Extractable Ground Water Resources (Stage of Extraction). The assessment units (blocks/taluks/mandals/tehsil/firkas etc.) are categorized based on the Stage of Extraction (SoE) i.e 'Safe' if SoE $< 70\%$; 'Semi-critical if SoE > 70 and $<= 90\%$; 'Critical' if SoE > 90 and $<= 100\%$ and 'Over-exploited' if SoE $> 100\%$. The latest assessment as in 2022, the basin has one assessment unit under critical category (Parivalikottai firka) and the remaining falling under safe. However groundwater exploration through Down The Hole Hammer (DTH) drilling rigs and survey of the study area over the years conducted by Central Ground Water Board has explained that the basin which is predominantly a hard rock basin has inherent challenges reflected as deep water levels and poor sustainability due to limited groundwater storage available in the thin discontinuous aquifers and erratic behavior of rainfall. Geospatial technologies were also employed which have become an important tool in water studies due to their capability in developing spatio-temporal information and effectiveness in spatial data

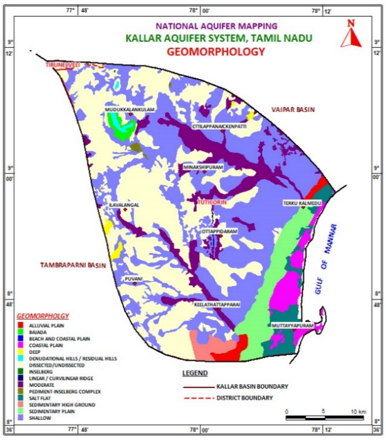

Fig. 2. Geomorphology.

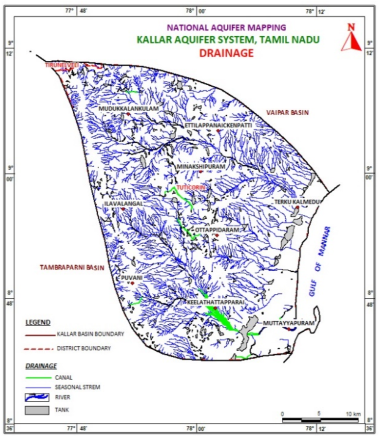

Fig. 3. Drainage.

analysis and prediction (Preeja et al., 2011). Thematic maps like geomorphology, drainage and land use/land cover (LULC), Lineament were obtained from Institute of Remote Sensing, Chennai. These were processed from high resolution satellite data IRS (Indian Remote Sensing) P6- LISS (Linear Imaging Self Scanning) III and validated through field verification. Geology map was obtained from Geological Survey of India. All these data were georectified and projected in Geographic co ordinate system -World Geodetic System 1984 for smooth usage in GIS environments. The 3D representation of the aquifers are acquired by ROCKWORKS 17 software.

4. RESULTS AND DISCUSSIONS

4.1. Geomorphology and drainage

The Kallar Aquifer System lies in the eastern parts of the Thoothukudi district and covers an area of 1691 sq.km. The following three major landforms have been identified based on the genesis and morphological characteristics. Denudational landform, Fluvial landform and the Coastal landform. (Fig. 2) The topography of the Kallar Aquifer System is plain with gentle slope towards southeast.

The rivers namely Kallar (Malattarodai), Korampallamaru (Upparodai) and Chalikulamaru drain the study area. There are two big tanks in the basin viz., Eppothumventran tank located in Kallar (Malattarodai) sub basin and Korampallam tank which received water from Tamiraparaniriver, from North main canal of Srivaikundam Anicut (Fig. 3).

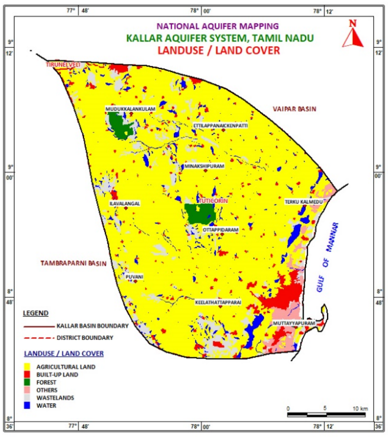

Fig. 4. Land Use/Land Cover.

4.2. Land Use and Soil

The land use and soil provides information on infiltration, soil moisture and vegetation. Remote sensing and GIS offer dependable and precise baseline information for land use mapping. Predominantly the area is characterized by the plantation and dry crops and accounts for 45% of the total area of the aquifer system. Water intensive crops like paddy, sugarcane and banana occupy 25% of the study area. The predominant soil types found in this river basin are Inceptisols, Alfisol, Entisol and Vertisol. Due to different stage of weathering of parent material, the above soil types are met within combination (Figs. 4 and 5).

4.3. Hydrogeology

The major swathes of the Kallar Aquifer System (95%) is underlain by the crystalline Gneisses and

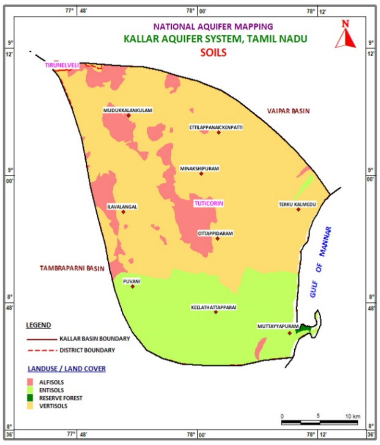

Fig. 5. Soils.

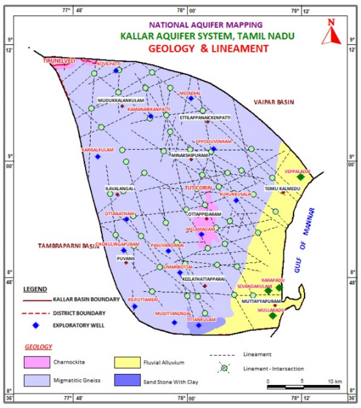

Fig. 6. Geology and Lineament.

Charnockites with 5% along the south eastern border occupied by alluvium. The geology with lineament map is shown below. The frequency of lineaments is more in the area covering in between Ettaiyapuram, Veppaolodai, Mel Arasadi and Ottapidaram. The NW-SE and NNW-SSE trending lineaments are predominantly traversing in these areas. East-West trending lineaments are cutting across the above two sets of lineaments and developed more number of lineament intersection points. The geology and lineament map generated in the GIS environ show positive ways to develop groundwater in this semi-arid dry belt of Kallar (Fig. 6).

Groundwater occurs within the weathered and fractured gneiss rocks under phreatic condition. The 3d Aquifer disposition is deciphered through the bore hole lithologs which aided in interpreting the weathered zones (Fig. 7).

The weathered zone is found to occur upto 40m below ground level. The depth of wells in the hard rock area generally ranges from 6 to 20 m and the water levels in this area vary from 3m to 7m, during winter and in summer the level goes down from 15m to 18m from ground level. The wells in hard rock area are sustainable for pumping 3 to 5 hours in a day in winter months and about 2 hours of pumping in summer months.

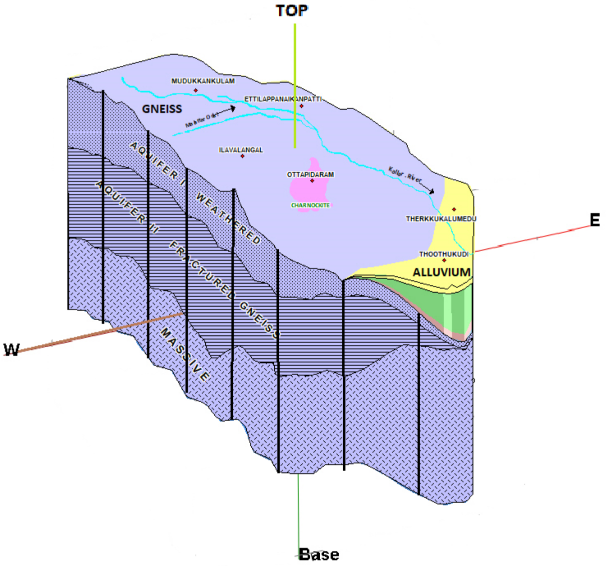

Fig. 7. 3d aquifer disposition.

The exploratory wells drilled in the basin by CGWB depicts and validate this grim situation wherein 98% of the drilled wells have yield less than 0.5 lps.

The sandstones of Tertiary formation is very hard and compact in nature and groundwater occurs under water table conditions, the yield is fairly good though the quality of groundwater do not fall within the drinking water standards stipulated by WHO. Occasionally continuous pumping is reported in certain pockets with yield ranging from 400 to 500 lpm in normal monsoon period.

Alluvium is restricted and occurs along the river courses only. In the alluvial area, groundwater occurs in phreatic conditions and in the coastal alluvium the groundwater occurs under perched watertable conditions. The average depth of the well is about 8m. The ground water level during winter in the wells generally reaches to ground level and in summer it goes down upto7m from ground level (Fig. 8).

To comprehend the average groundwater level variations, a decadal mean of the groundwater level for the premonsoon and postmonsoon was studied. Most locations have groundwater levels more than 10 m bgl during the premonsoon most have groundwater levels less than 10 m bgl during the post monsoon. The post monsoon water level scenario in

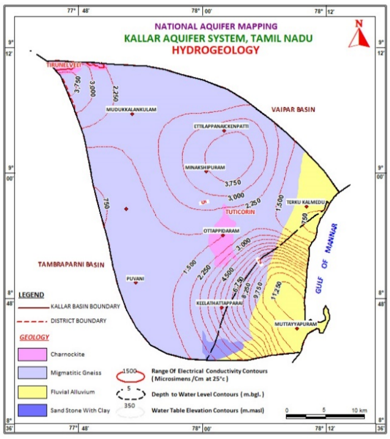

Fig. 8. Hydrogeology.

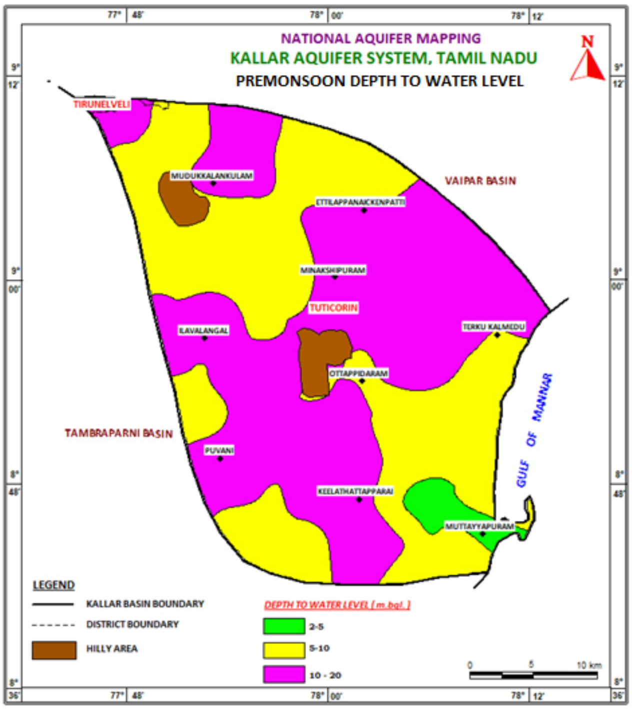

Fig. 9. Premonsoon Depth to water level.

the Kallar Aquifer System is interpreted to infer the subsurface storage potential of the Aquifer System (Figs. 9 and 10).

4.4. Groundwater potential

The groundwater potential in an area is governed by a host of factors of which the key determinants are the rainfall and consequent recharge. Other interdependent factors determining the potential are geomorphology, geology, drainage, lineament and land use land cover pattern . The spatial distribution of these attributes across the basin were prepared in the GIS platform Groundwater potential zones as well as sites feasible for managed aquifer recharge were identified. (Fig. 11) The results were then corroborated with water level behavior primarily those areas showing a declining trend (0.10 m/year) and the long term post monsoon water level were considered which is a prime indicator to recharge areas. Integration of these thematic layers with spatial distribution of the analytical data of groundwater samples has also been interpreted to fine tune the recharge worthy areas.

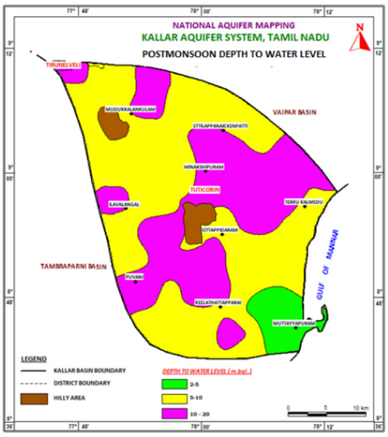

Fig. 10. Postmonsoon Depth to water level.

A collective assimilation and analysis of the thematic maps and the groundwater resource assessment in the basin resulted in demarcating areas suitable for Artificial Recharge (Report on dynamic groundwater resources of the State of Tamil Nadu, 2022).

i. Areas of all over exploited, critical and semi critical firkas. In the study area only one firka falls under the semicritical category. (Table 1)
ii. Water scarce areas of the basin wherein the assessment units are categorized as safe with stage of development >50% and where the post monsoon Water level >3 mbgl
iii. Coastal aquifers qualifying the condition mentioned above were excluded from the recharge interventions due to the insitu salinity and the attendant soil texture being an impediment to recharge interventions. (Fig. 11)
iv. Urban area in the basin earmarked for Rooftop rainwater harvesting.

4.5. Management Plan

With all the adversities addressed, a groundwater management plan is proposed. It requires a comprehensive assimilation of the groundwater potential zones and areas feasible for aquifer recharge which

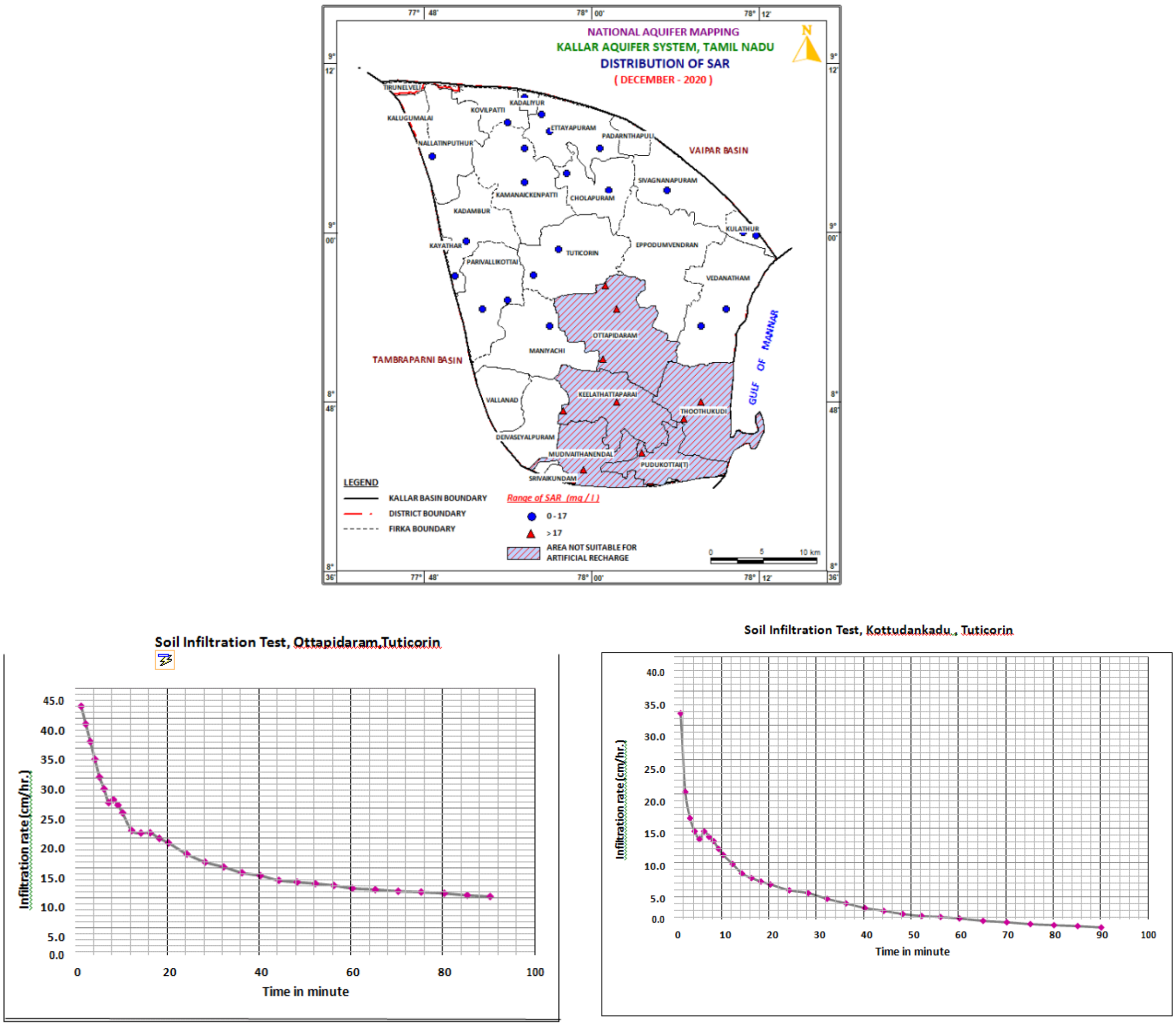

Fig. 11. Area not suitable for recharge demarcated based on SAR values and soil infiltration tests.

Table 1. Groundwater Resources in the assessment units identified for recharge interventions.

Firka	Area	Net Annual Extractable GW Resources (ha m)	Extraction for irrigation (ha m)	Extraction for Domestic/Industrial (ha m)	Total extraction (ha m)	SGWE (%)	Category
Parivallikottai	119	912	869	27	896	95.5	Critical
Kadambur	130	1095.78	664.2	19.72	683.92	61	Safe
Kamananpatti	105	1072.69	534.4	27.94	562.34	55	Safe
Ottapidaram	138	772.03	425	50.26	475.26	65	Safe
Nallathinputhur	96	800.72	344.35	35.43	379.79	51	Safe
Thoothukudi (Urban)	74	193.56	15.2	57.01	72.21	37	Safe

is a precursory requirement for proposing site specific management interventions for stimulating the aquifers and rejuvenating the groundwater resources of the basin. A synchronized integration of identifying potential and recharge zones with resultant management interventions to define water security in the basin forms the highlight of the study.

4.6. Source water availability

The availability of non committed source water is one of the main requirements for any artificial recharge scheme. The rainfall received during the northeast monsoon between October – December is the principal source water for artificial recharge schemes. The surface water resources have been calculated firka wise using Strange's Table showing depth of runoff as percentage of total monsoon rainfall and yield of rainfall per square kilometer in MCM for average catchment (Master plan for groundwater recharge, 2022). The total water requirement for recharging the unsaturated zone below 3 m from surface is 379 MCM. In some of the firkas the non committed runoff is more

Table 2. Firka wise area identified, Volume of water required for recharge , uncommitted runoff and surplus volume available for recharge.

Sl. No	Firka	Area (Sq.km)	Normal Rainfall (mm)	Average Post-monsoon Water Level (m bgl)	Suitable Area for AR (sq.km)	Un-Saturate Zone (m)	Un-Saturated volume (mcm)	Sub-surface storage (mcm)	Sub-Surface water required (mcm)	Runoff (mcm)	Un committed runoff available for recharge (mcm)
1	Kadambur	130	772	7.05	130.0	4.05	526.50	105.3	140.05	31.2	9.36
2	Kamanaickanp	105	759	5.26	104.0	2.26	235.04	47.01	62.52	25.1	7.54
3	Ottapidaram	138	556	6.80	138.0	3.80	524.40	104.8	139.49	33.2	9.95
4	Nallatimputhu	96	788	5.26	96.00	2.26	216.96	43.39	57.71	23.1	6.92
5	Parivalikottai	119	556	6.80	119.0	3.80	452.20	90.44	120.29	28.6	8.57
	Total	**588**	**686.2**	**6.23**	**587.0**	**3.23**	**1898.36**	**379.6**	**504.96**	**141.0**	**42.31**

than the water requirement, whereas in some other firkas it is less than the requirement. Considering the water requirement and the availability **42.31**MCM water is proposed to be utilized for artificial recharge (Table 2).

4.7. Available subsurface storage potential and surface water requirement

The thickness of the available unsaturated zone (below 3 m bgl) of the above categories is estimated by considering the different ranges of water level. Thus the total volume of unsaturated zone calculated is 1898 MCM. This volume was then multiplied by average specific yield on area specific basis to arrive at the subsurface storage potential ie 380 MCM. After assessing the volume of water required for saturating the unsaturated zone (subsurface storage potential), the actual requirement of source water is estimated based on these field inputs. An average recharge efficiency of 75% of individual structure is feasible. Therefore to estimate the total volume of source water actually required at the surface, the volume of water required for artificial recharge is calculated by multiplying the estimated storage potential with 1.33 (ie reciprocal of 0.75) which is 504.96 mcm. Firka wise areas identified for recharge, volume of water required for recharge, non committed run off, surplus volume available for recharge are all presented in Table 2.

5. SUPPLY SIDE INTERVENTIONS

A total of 321 artificial recharge structures exist within the study area established by various State government agencies. Based on the availability of space and unutilized surface water, an additional 36 masonry check dams and 59 nala bunds can be constructed in moderate to high recharge potential zones. These structures can contribute 14 MCM of water to the aquifers. (Fig. 12) The existing ponds and tanks have lost their storage capacity and the natural groundwater infiltration from these water bodies have become negligible due to siltation and encroachment by farmers for agriculture purposes.

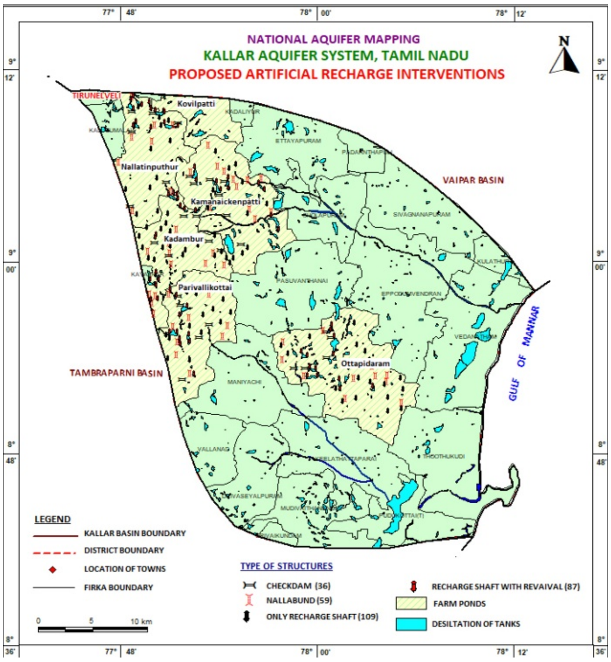

Fig. 12. Groundwater Management Plan.

There are several such villages where ponds/tanks are in dilapidated condition. These existing village tanks which have high siltation and damaged can be repaired/modified to serve as recharge structures (percolation tanks). Desilting coupled with provision of proper waste weirs will convert the village ponds/tanks into recharge structure. Several such types of village ponds/tanks are available in the study area, which can be converted for augmenting groundwater recharge. About 199 tanks/water bodies have been identified in the study area wherein 109 recharge shafts and 87 RRR (Revival and repair along with recharge shafts) need to be constructed so as to harness the surplus water (Table 3). Thus a total of 8MCM of runoff can be harvested by revival of ponds/tanks with recharge shafts.

Photo 1. Farm pond.

Table 3. Proposed Structures.

Masonary Check Dams	36
Nala Bunds	59
Recharge Shafts	109
RRR ponds with recharge Shafts	87
Farm ponds	150

5.1. Water conservation measures through Farm ponds

A farm pond is a huge dugout, usually square/rectangular in dimension, which collects rainwater and stores it for future use (Senthilkumar et al., 2019). (Photo 1) The size and depth of the recharge pond are directly proportional to the size of the land holding, the type of soil, water requirements, affordability of the excavation, and the possible usage or disposal of the excavated material. For farmers of large farm holdings the size of a farm pond is typically 30 x 30 x 1.5 m dimension. Water from the farm pond is conveyed to the fields either manually or by pumping.

5.2. Roof Top Rainwater Harvesting in Urban Areas

Thoothukudy corporation is spread in an area of 90.66 sq km hosting a population of 376550 (2011 census). The normal rainfall is 612 mm. The water requirement is 51 MLD and the source is the Thambraparni river. During lean period if 30% of the area is taken as the rooftop then water harvested will be 1350 million litre which can sustain for 26 days at the rate of 51 MLD.

6. DEMAND SIDE INTERVENTIONS

Management of Groundwater Resources cannot be achieved in isolation, the supply side measures need to go in tandem with the demand side measures to bring about the desired impact on the resources which would ensure sustainable water security. The effective measures proposed in the basin are increasing the irrigation efficiency through an overhaul of the conventional techniques of flooding to SRI method (System Rice Intensification: for Paddy) and drip irrigation for Sugarcane and Banana (Satyanarayana et al., 2007). For flooding practice a water column of 1.4 m is required for paddy cultivation and 0.6 m for Sugarcane and Banana. By shifting to the proposed efficiency in irrigation practices in Kallar Aquifer System the volume of water saved is figured at 2.97 MCM and 4.95 MCM for 30% and 50% of the irrigated area practising the shift. Table 3 elaborates the calculated conservation figures for Paddy cultivated in an area of 2500 ha and Sugarcane & banana cultivated in 500 ha (Table 4).

Table 4. Water conserved through shift in irrigation.

	Area Ha	30 percent area	50 percent area	draft for 30% area (Area x1.4 for paddy and 0.6 for Sugarcane)	draft for 50% area	SRI 30% water saved/MI	SRI 50% water saved/MI
Paddy	2500	750	1250	900	1500	270	450
Sugarcane & banana	500	150	250	90	150	27	45
			Total	990	1650	297	495
water saved					MCM	2.97	4.95

7. CONCLUSIONS

The Thoothukudy district of Tamil Nadu, which receives the state's lowest average rainfall of 650 mm is home to the Kallar Aquifer System. Hard rocks comprising of Gneisses and Charnockites occupy almost the entire study area except along the coastal fringes. The crystalline landscape have inherent challenges reflected as deep water levels and poor sustainability due to limited groundwater storage available in the thin discontinuous aquifers and erratic behavior of rainfall. A collective assimilation and analysis of the thematic maps and the groundwater resource assessment in the basin have prioritized the areas suitable for artificial recharge interventions. Those assessment units which were water stressed based on the degree of development were identified for management interventions. Also regions with post monsoon water level greater than 3 m bgl and a long term decline in water level were demarcated as area suitable for Artificial recharge. Urban areas in the basin were identified for roof top rainwater harvesting.

Based on the availability of space and unutilised and uncommitted it is proposed to construct 36 masonry check dams, 59 nala bunds, 109 recharge shafts and 87 percolation ponds (repair, renovation and restoration). This shall create additional groundwater resources of 22 MCM through Artificial Recharge/Rooftop Rainwater harvesting techniques and through changes in irrigation practices 4.95 MCM water can be saved. Thus construction of these structures at various locations identified shall rejuvenate the aquifer system of the study area and increase the sustainability of the groundwater abstraction structures. Increasing the irrigation efficiency through shifting the conventional practices of flood irrigation to MI techniques can save 2.97 to 4.95 MCM corresponding to the area for which MI is practiced.

ACKNOWLEDGEMENTS

The authors would like to express their deep gratitude to the Chairman, Central Ground Water Board, Faridabad for publication of the research findings. Authors also extend sincere thanks to the scientists from CGWB for giving valuable suggestions and technical guidance to carry out the study. Special thanks to Dr A.Asokan, Regional Director, CGWB, SECR, Chennai in providing guidance and support for the documemtation of the study.

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