Aquifer Unit Management Plan (AUMP) For Groundwater Resources Management of Multi-layered Coastal Aquifer System

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Abstract

To address the vulnerability of coastal aquifer to over exploitation and sea water intrusion, a groundwater resources management plan titled as Aquifer Unit Management Plan (AUMP) is designed to provide valuable guidance for groundwater management of a multi-layered cuddalore coastal aquifer system located east coast of South India. The aquifer unit management plan is based on the summative examination of the aquifer unit disposition, response of hydraulic heads to recharge and discharge and effect of increased pumping on aquifer hydraulics. The safe hydraulic heads and annual exploitable potential were considered as the guiding factors to manage fresh groundwater resources of the coastal aquifer. The results show that the process of sea water intrusion has already started and with the present rate of pumping (1034.86 mcm^{-1}), the sea water intrusion risk has increased manifold all along the coast. The salient management strategies recommended are; restricting pumping to 695 mcm^{-1} , stepping up recharge activities in recharge zone, adopting water use efficiency methods and regulation in the coastal zone. AUMP is simple and can guide water managers to plan for sustainable groundwater withdrawal and safe guard the coastal aquifer from sea water intrusion and ensure sustainability of groundwater abstraction structures.

1. Introduction

The management of multilayered coastal aquifers are challenging due to its vulnerability to sea water intrusion along the coastal zone. The fragility of the multilayered coastal aquifers and their sensitivity to excessive groundwater withdrawal (Hoori 2020) demands a comprehensive aquifer management plan for holistic understanding of the coastal aquifer system and management of its precious groundwater resources in a sustainable manner (Aristotelis 2003, Manivannan and Elango 2019). Studies on groundwater management in coastal aquifers have been carried out by various researchers (Cendrero and Fischer 1997; Gnanasundar and Elango 2000; Reichard and Johnson 2005; Siaka et al 2017). Flow in coastal aquifers is very complex processes (Bear 1999) but management plans that identifies issues and provide less complex strategies to protect fresh groundwater resources is necessary. Due to muddled groundwater development and in absence of groundwater management plan, a multi-layered coastal aquifer (called as Cuddalore Coastal Aquifer System - CCAS) located at east coast of South India is vulnerable to over exploitation and faces threat of sea water intrusion. In lieu of the above, the authors had conceived a management plan named as Aquifer Unit Management Pan (AUMP) that can provide valuable guidance for groundwater management of multi-layered CCAS.

2. Description Of Study Area And Location

The Cuddalore coastal aquifer system is one of the most prolific coastal aquifer located 200 North of Chennai, India lying between the latitudes $11^{\circ}30'$ to $11^{\circ}55'$ and longitudes $79^{\circ}15'$ to $79^{\circ}50'$ and covering an area of 2100 Km^2 . The length (N-S) of the aquifer is 32 kilometer and width (W-E) is 58 kilometer approximately. The northern boundary is defined by up dip along the Ponnaiyar River and the southern boundary by Vellar River (Fig. 1). The archeans (Biotite Hornblende Gneiss forms the western boundary and Bay of Bengal Sea constitutes the eastern boundary. Along the west, sandstones crop out and underlie towards the east coast and dip gently eastward beneath the Bay of Bengal. The topographic elevation is at 120 m mean sea level (msl) in the west and gradually slopes towards east where at coast the elevation is at msl. The mean annual precipitation for the years 1999 to 2018 is 1290 mm. This region is intensively irrigated by groundwater with dominant land use consists of cultivated crops (almost 80 % of the area) such as rice, sugarcane, groundnut, banana, cashew, millets and vegetables. Cuddalore and Neyveli and are the prominent towns and Asia's largest open cast lignite mine (Neyveli lignite mine) is operational within the study area since 1956.

3. Materials And Methods

The Aquifer Unit Management Plan (AUMP) constitutes 7 steps, the description; salient outcome of each step is given as Table 1. An aquifer system constitutes one or many major aquifers and several aquifer units within (CGWB, 2017). For management of coastal aquifers, the dispositions of the aquifer units are to be explored and its hydraulic characteristics are to be assessed. The exploratory drilling data (78 nos), geophysical resistivity logging data (36 nos) generated from the aquifer mapping study of Central Ground Water Board (CGWB) were used to decipher hydrostratigraphic units, delineate major aquifers/aquifer units and develop conceptual model. The hydraulic head data (57 nos) used in the study for analyses are from the groundwater monitoring program of Central Ground Water Board (CGWB 2020). The practical knowledge gained by the authors during field hydrogeological studies between 2011 and 2014 were applied to arrive at logical assumption wherever necessary.

Table 1
Steps or Methodology of the Aquifer Unit Management Plan (AUMP)

Steps	Description	Salient outcome
I	Decipher/establish the aquifer units	The hydrostratigraphic units, major aquifers and aquifer units within the aquifer system are deciphered and named.
II	Develop conceptual model	The basinal, hydraulic features of the aquifer units are figured out and conceptual model of aquifer system is developed.
III	Assess recharge to the aquifer units	The pumping history, groundwater withdrawal for irrigation, industry and drinking water sectors are estimated.
IV	Assess discharge from the aquifer units	The recharge zones, rate of rainfall recharge, source of recharge and artificial recharge to the aquifer units are estimated.
V	Status of the aquifer units	The response of the hydraulic heads (annual and long term) to hydraulic stress, comparison of current hydraulic head elevation with historic head elevation. Projection of the scenario from long term pumping rate, hydrograph and numerical modelling.
VI	Sensitizing public on status of the aquifer units	Sensitizing farmers and people on user aquifer units and appraise issue on decline in hydraulic heads and issues that threatens the sustainability of dug wells and tube wells.
VII	Aquifer management strategies	Governing aquifer hydraulic principles, comprehensive aquifer unit management plan that includes pumping limit, safe hydraulic heads, and management measures to be taken in stressed aquifer unit's including administrative measures.

4. Results And Discussion

4.1 Step I Decipher/establish the aquifer units

Table 2. Stratigraphic correlations between Geologic, Hydrostratigraphic units and aquifer units of CCAS.

Table 2
Stratigraphic correlations between Geologic, Hydrostratigraphic units and aquifer units of CCAS.

Stratigraphic correlations between Geologic, Hydrostratigraphic units and aquifer units of CCAS.								
Era	Period	Series/Epoch		Geologic Unit/Formation	Hydrostratigraphic Unit (detailed)	Major Aquifer	Aquifer Units	
Cenozoic	Quaternary	Holocene/Pleistocene		Alluvium sand	Upper Cuddalore Aquifer	Cuddalore Aquifer	Unconfined Aquifer Zone	Cuddalore Coastal Aquifer System
	Tertiary	Mio-Pliocene	late	Cuddalore Formation			(Aquifer Unit – I)	
			early	(Cuddalore sandstones)	Lower Cuddalore Aquifer		Confined Aquifer Zone	
			Unconformity					
	Eocene	late	Neyveli Formation (Neyveli sandstones)	Upper Neyveli Aquifer	Neyveli Aquifer	Confining Aquifer Zone		
						(Aquifer Unit – III)		
		middle		Middle Neyveli Aquifer		Confining Aquifer Zone		
				(Aquifer Unit – IV)				
		early		Lower Neyveli Aquifer		Confining Aquifer Zone		
						Aquifer Unit – V		
						(exists beyond 400 mbgl)		
Unconformity								
Mesozoic	Cretaceous	Late		Puvanur Formation	Fossiliferous siliceous Limestone			
					Calcareous sandstone and marls			
Unconformity								
Proterozoic	Archaean	Intrusives		Granitoid Gneiss	Basement			

The CCAS has a layered sequence of aquifers composed of sandstones that thicken and deepen to the east towards the Bay of Bengal Sea. The basement exposed in the western part has not been encountered in the eastern and southwestern part due to thickening of the tertiary sedimentary sequence from west to east (Subramanyam 1969). The hydro-stratigraphic units and aquifer units were deciphered by the authors after analysis of borehole lithology, geophysical electrical logs and from previous studies (Paul and Subramanyam 1961, Subramanyam 1969, Mandaokar and Debi 2014, Elayarajaa and Kumarasamy 2019,) to establish coherence between the geologic period, series/epoch, geologic unit/formation, hydro-stratigraphic unit and aquifer units (Table 2). The CCAS constitutes two major aquifers (Cuddalore and Neyveli aquifers) and five aquifer units (Aquifer Unit I, II, III, IV and V) down to the depth of 400 m below ground level (bgl). The aquifer units exist throughout the CCAS and pinches in northwestern and western boundaries. Lignite seam of 10 to 22 meters coexists along with a discontinuous clay layer of 3 to 7 m between the Cuddalore and Neyveli aquifers. The Cuddalore aquifer comprises of argillaceous sandstone, pebble bearing sandstone, ferruginous arkosic sandstone, gravel, grits and clay beds. They are friable, whitish, pinkish, and reddish in color deposited under continental, fluvial and near by shore environment. The Neyveli aquifer comprises of friable calcareous sandstones, lignite seam, sandy limestones, clay and carbonaceous clay. They are more compact than the Cuddalore aquifer and are deposited in fluvio-marine, paralic, deltaic, near shore to inner shelf environment (Selvaraj and Ramasamy 1998).

4.3 Step II Develop Conceptual model

The sandstones of CCAS have strike along NNE to SSW direction with a dip of 20° to 25° towards ESE or SE direction. Clay as intercalations occur within the sandstones and is predominant near the coast (Paul and Subramanyam 1961). The clay layer (aquitard) occurring at top and bottom of the sandstones hydraulically separates the aquifer units. The varying hydraulic head elevations (Fig. 2) substantiate that the aquifer units function as multi-layered aquifer system (Anandan et al 2009, CGWB 2015). The vertical leakage (upward or downward flow) exists among the aquifer units where clay is minimal or absent. The hydraulic conductivity (K) ranges from 18 to 115 m/day. The degree in sorting, cementing and compaction

accounts for varying permeability among the units. The tube wells tapping these units have yield varying between $18 \text{ m}^3\text{h}^{-1}$ and $220 \text{ m}^3\text{h}^{-1}$ sustaining for 10 to 12 hours of pumping with 3 to 5 m drawdown. The groundwater flow is from northwest to southeast direction, pre-dominantly horizontal and finally seeps into Bay of Bengal Sea. In region around Neyveli lignite mine, the regional groundwater flow is distorted. Fresh groundwater water discharge through sea bottom occurs as CCAS is a part of Cauvery basin extends into the sea for several kilometers (Nagendra and Nallapa A 2017, Twinkle et al 2016). The conceptual model of CCAS is given as Fig. 3.

4.3.1 Aquifer Unit I

The Aquifer Unit I is the top most aquifer unit composed of sandstones of late mio-pliocene age, alluvium and Laterite formations. The alluvium formation (sand and sandy clay) overlies the sandstones towards east. Clay as intercalations occurs within the alluvium sand and its thickness increases towards coast as well as towards south west of Vellar River. The thickness of this aquifer unit I is 30 to 110 m. The groundwater in aquifer unit I is fresh and occur under unconfined conditions. Groundwater development is by dug wells and few dug cum-tube wells. The dug wells have diameter of 1 to 3 m and are lined by bricks or perforated concrete concentric rings. The depth of the dug wells ranges from 3 to 35 m bgl and their water level ranges between 1.5 and 26 m bgl. Perched water table occurs at 3 to 10 m bgl formed by the presence of thick clay in the central region. The Electrical conductivity (EC) of the groundwater ranged between 350 and 1500 $\mu\text{S}/\text{cm}$. Rainfall is the major source of aquifer replenishment. Apart from rainfall, groundwater recharge also occurs from irrigation return flow, ponds/tanks and by recharge through artificial recharge structures. The yield of the aquifer unit varied between 10 and $65 \text{ m}^3\text{h}^{-1}$. The transmissivity (T) of the aquifer I ranged between 450 and $940 \text{ m}^2/\text{day}$ (Paul and Subramanyam 1961) and the specific yield (Sy) ranges between 9 to 17 %.

4.3.2 Aquifer Unit II

The aquifer unit – II lies below the Aquifer unit I and is composed of sandstones of early Mio-Pliocene age. The top of the aquifer - II lies at 10 to 120 m bgl. The thickness of the Aquifer Unit II varies from 30 to 55 m. The groundwater abstraction from the aquifer is by tube wells ranging from 40 to 100 m bgl. Groundwater occurs under confined conditions with the hydraulic head of the aquifer II ranging between 14 and – 24 m msl. Apart from rainfall, groundwater recharge occurs from vertical leakage from aquifer I. The yield of the aquifer unit varied between 43 and $102 \text{ m}^3\text{h}^{-1}$. The EC of the aquifer ranged between 450 and 1200 $\mu\text{S}/\text{cm}$. The transmissivity (T) of the aquifer II range between 780 and $1980 \text{ m}^2/\text{day}$ and the storativity (S) ranges between 1.2×10^{-3} to 4.1×10^{-4} (Paul and Subramanyam 1961).

4.3.3 Aquifer Unit III

The aquifer unit - III underlies the Aquifer unit II and is composed of sandstones of late Eocene age. Lignite (Brown Coal) occurs on top of the sandstones and is considered as marker bed. Lignite seams also occur within the sandstones at depths. Clay as intercalations occurs within the sandstones lignite seams. The top of the Aquifer unit III lies at 90 to 160 m bgl. The thickness of the Aquifer Unit III varies from 30 to 100 m. The groundwater in the aquifer unit III occurs under confined conditions with the hydraulic head ranging between 7.0 and – 28.5 m msl. The yield varies from 72 and $170 \text{ m}^3\text{h}^{-1}$. The EC of the groundwater ranged between 300 and 1000 $\mu\text{S}/\text{cm}$. The T of the aquifer III range between 670 and $2100 \text{ m}^2/\text{day}$ and the S ranged between 1.6×10^{-4} and 2.9×10^{-5} (Paul and Subramanyam 1961).

4.3.4 Aquifer Unit IV

The aquifer unit IV constitutes middle Eocene sandstone and lies below the Aquifer III. The top of the Aquifer IV lies at 50 to 280 m bgl. The aquifer unit IV is thicker than the other units and extends beyond 400 m bgl near the coast. The thickness varies from 50 to 130 m. The groundwater occurs under confined conditions with the hydraulic head ranging between 9.0 to -30.5 m msl. The aquifer IV is highly potential aquifer and its yield varies from 64 to $158 \text{ m}^3\text{h}^{-1}$. The EC ranged between 500 and 1300 $\mu\text{S}/\text{cm}$. The T of the aquifer IV range between 980 and $2700 \text{ m}^2/\text{day}$ and the S ranges between 4.3×10^{-4} to 9.1×10^{-5} (Paul and Subramanyam 1961).

4.3.6 Step III Assess Recharge to Aquifer Units

The recharge to the CCAS occurs through a) infiltration of rainfall on the outcrop in the western margin covering an area of 220 km^2 (Anandan et al 2010). b) an area covering 350 km^2 between Ponnaiyar and Gadilam River) area of 110 km^2 between Manimuktar and Vellar river d) subsurface inflow across north western boundary d) return flow from irrigation activity and e) seepage from the tanks, ponds and artificial recharge structures. Approximately 58 percent of total rainfall (1290 mm) is by the north-east monsoon (October, November, December and January) and 30 percent of rainfall is contributed by the south-west monsoon (July, August and September). Rainfall occurs almost in every month of a year and the rainy day accounts for 45 to 63 days in a year. The month March to May has the minimum number of rainy days in any year and the period October to January has the maximum number of rainy days. Rangarajan et al 2005 in their study concluded high recharge rate of 24 to 40 percent of rainfall occurs along the western part of the region covering an area of 650 km^2 . In the remaining region, rainfall accounts to 8 to 16 % of the annual recharge (CGWB, 2015). The estimated recharge rate is 772 mcm y^{-1} for 1290 mm of rainfall. The natural recharge occurs in all the four aquifer units during monsoon, but recharge to aquifer unit I is comparatively high than the other aquifer units as 72 percent of its formation is exposed to the ground surface.

4.3.5 Step IV Assess discharge from the aquifer units

The groundwater withdrawal from the aquifer units prescribes the aquifer unit management plan. The discharge from Cuddalore coastal aquifer system occurs as (a) withdrawals by irrigation, industrial, mining activity (depressurization) (b) public supply wells and c) free flowing wells (artesian condition). Before 1960, discharge was mainly by pumping from about 145 flowing wells to the south of Cuddalore, apart from the underflow towards Gadilam and Vellar rivers (Paul and Subramanyam 1961). The energisation of the dug wells during early 1970's led to increase in groundwater withdrawal for irrigation (Fig. 4). The total annual groundwater withdrawal during early 80's was estimated at 350 to 400 million cubic meters (mcm). Presently (2019) the estimated annual withdrawal by pumping is estimated at 1034.86 mcm (Table 3). About 84 % of groundwater withdrawals are from aquifer unit I and II of which irrigation accounts to ~ 97 %. The large scale groundwater pumping or depressurization activity in aquifer unit III for safe mining of lignite deposits commenced during 1961 and is confined in and around Neyveli lignite mines (Anandan et al 2009, 2010). Presently about 133.10 mcm of groundwater is pumped annually. The Metro-water of state department withdraws 12.79 mcm of groundwater annually from Aquifer unit IV during lean periods (April to July). The groundwater pumped is transported 200 km through pipelines to cater drinking water supply of Chennai city.

4.3.7 Step V Status of the aquifer units

The status of the aquifer units reflects the hydraulic functioning of the coastal aquifer wherein the response of the hydraulic heads to stress (recharge and pumping) and its vulnerability to over exploitation and sea water intrusion is brought out. The sensitivity and magnitude of the stress abide within the aquifer units need to be figured out to impute corrective measures in the management plan. The change (lowering) in the hydraulic heads of the aquifer units in the recharge (western), intermediate (Central) and coastal zone (eastern) portray the impact of heavy pumping and vulnerability to seawater intrusion. The magnitude of the aquifer stress is difference between the annual discharges by pumping with annual recharge. Considering natural recharge and groundwater discharge by pumping, the groundwater budget was negative by late 1980. Currently the total recharge is ~ 26 percent less than the estimated total extraction which is alarming and this percent difference is likely to increase in the coming years. For convenient sake, the western and central region together is denoted as Inland zone. In the central and eastern region, the hydraulic heads of the aquifer unit I almost remain the same or decline is insignificant with the average hydraulic head fluctuation (annual rise and fall) of 4 to 9 m. (Fig. 5). However, the western region is de-saturated by 45 m due to decline in hydraulic heads. The hydraulic heads of aquifer unit II in the western margin lowered from positive hydraulic pressure head (+ 60 to + 80 m) to negative hydraulic pressure head (-24 m msl). Similarly, the hydraulic heads of aquifer unit III and IV lowered from positive hydraulic pressure head (+ 60 and + 80 m) to negative hydraulic pressure head (-28.5 and - 30.5 m msl) respectively. The cumulative long term negative imbalance between recharge and discharge (discharge > recharge) has lowered the hydraulic head in the aquifer units. The historic hydraulic heads of aquifer units II, III and IV in the central and eastern region were above mean sea levels and the tube wells tapping these aquifers were under artesian conditions (Paul and Subramanyam 1961) and artesian conditions existed until mid-1980 (CGWB, 2015). The present status and the hydraulic features of CCAS is given as Table 4.

Table 3 Groundwater withdrawal (Year: 2019) from the aquifer units for domestic, agricultural and Industrial activities

Formation	Aquifer Units	Irrigation	Industrial (mcm/year)	Domestic/Drinking
Sand/sandstone	Aquifer I	315.0	0.8	29.50
Sandstone	Aquifer II	517.32	1.2	
Sandstone	Aquifer III	25.15	133.10	
Sandstone	Aquifer IV			12.79
Sandstone	Aquifer V	(no groundwater withdrawal)		
Total (mcm/year)		857.47	135.10	42.29

Table 4
Hydraulic features and status of the aquifer units

Parameters	Aquifer unit I (unconfined)	Aquifer Unit II (Confined)	Aquifer Unit III (Confined)	Aquifer Unit IV (Confined)
Usage	Domestic/drinking and Irrigation	Irrigation and Industrial	Mining activity and irrigation	Drinking water supply
Hydraulic head (pre-development)	Above msl	Auto-flowing Up to late 80's	Auto-flowing Up to early 90's	Auto-flowing Up to early 90's
Hydraulic Head (pre-monsoon 2019) inland (m msl)	1.5 to 26	14.0 to - 24.0	7.0 to -28.5	9.0 to -30.5
Hydraulic Head (pre-monsoon 2019) Coastal zone (m msl)	0.5 to 1.5	- 2.0 to - 7.0	msl to - 3.0	msl to - 2.0
Long term Decline in Hydraulic head (meter per year)	No decline in the central and coastal zone but decline in the western margin	0.20 to 0.30	0.10 to 0.30	0.10 to 0.20
Impact of pumping since 1970	De-saturated in western and central region by 45 m	Drop in hydraulic head Sea water intrusion near Cuddalore town	Drop in hydraulic head and Cone of depression around Lignite mine. Upward vertical leakage in places where clay is absent	Drop in hydraulic head Upward vertical leakage in places where clay is absent
Status	Threat of sea water intrusion if hydraulic head lowers below msl in the coastal zone.	Threat of sea water intrusion if hydraulic head lowers below - 3 m in the coastal zone		
Threat of sea water intrusion	Coastal zone vulnerable to sea water intrusion from coast to 10 km inland.			

Figure 5 Long term (Period: 1973–2018) hydraulic head fluctuation and trend of aquifer unit I.

Table 4 Hydraulic features and status of the aquifer units

Continuous and heavy withdrawal of groundwater ($\sim 865 \text{ mcm y}^{-1}$) for irrigation in the last 2 decades induced decline in hydraulic heads (western and central region) of the aquifer unit II at the rate averaging 0.20 meter per year. The hydraulic heads of aquifer unit III and IV decline around lignite mines at $\sim 0.20 \text{ m y}^{-1}$ for pumping that accounts for just 14 % ($\sim 170 \text{ mcm}$) of total pumping. The aquifer unit III with high hydraulic pressure infuses water into aquifer unit II by upward vertical leakage (Anandan 2010) thereby losing water in its storage apart from annual discharge of 130 mcm by pumping. Similarly, the aquifer unit IV infuses water into aquifer unit III by upward vertical leakage from its storage apart from annual discharge of 12.79 mcm by pumping. In the region within and around the lignite mine, the hydraulic heads continue to decline (Ravikumar et al 2010) at 0.20 to 0.30 m/year. The average hydraulic fluctuations (annual rise and fall) of aquifer unit III and IV are less ($\sim 0.5 \text{ m}$) than the above aquifer units (~ 1 to 2.5 m). These situations roughly provide us an understanding (hydraulic functioning) that recharge to deeper aquifer units (III and IV) could be less than 22 % ($\sim 170 \text{ mcm}$) of total annual recharge (772 mcm).

The hydraulic continuity of CCAS with the salt water (Bay of Bengal Sea) poses constant threat to the freshwater resources and vulnerable to sea water intrusion in the coastal zone. The coastal zone functions as hydraulic barrier between the salt water wedge and fresh water wherein the hydraulic pressure is mounted over the years. The hydraulic heads at mean sea level reflects equilibrium condition and thus the fresh and salt water interface are left undisturbed (Woo-Dong, 2019). Numerical modeling of CCAS unveil the region between coast and 10 km inland is highly sensitive even to 5 percent increase in pumping and hydraulic head of the confined aquifer units at -5 msl reverses the recharge velocity flow direction towards

the coastal aquifer or inland which in ideal condition (hydraulic head at msl) should be pointing towards sea (CGWB, 2015). Thus, it is crucial to maintain hydraulic heads (hydraulic equilibrium) of each aquifer units at mean sea level as decrease in hydraulic pressure or negative hydraulic pressure (hydraulic disequilibrium) induced by pumping in any one of the aquifer units initiate reversal of hydraulic gradient. The change in hydraulic head dynamics (from positive hydraulic pressure to negative hydraulic pressure) facilitates the salt water wedge (Holland, 1998) to move inland. To maintain hydraulic equilibrium, equivalent freshwater head that represents the column of fresh groundwater is required to balance the hydraulic pressure at a particular depth and groundwater density (Costall, 2020). The present hydraulic heads of the aquifer units III and IV in the coastal zone ranged between - 3 and - 5 and msl to -2 m respectively. Even though the hydraulic heads of the aquifer units (II, III and IV) exists above the aquifer unit (top layer), hydraulic heads below mean sea level has the potential to trigger salt water wedge to march into the coastal aquifer (Sherif and Vijay1990, Woo-Dong 2019). The simulated results of numerical modelling studies (CGWB 2019a) for scenarios with increased pumping showed the recharge flow velocities deflected towards inland in regions where the hydraulic heads of confined aquifer units (Aquifer II, III and IV) dropped below - 3 m msl. It can be precisely concluded that the confining aquifer units of CCAS will be subjected to sea water intrusion if the hydraulic heads lowers below - 3 m msl. The low hydraulic head of -7 m msl (negative hydraulic pressure) in aquifer unit II (CGWB 2019a) along northeastern region (negative hydraulic pressure area with recharge flow velocities towards inland or landward) thus indicate the process of sea water intrusion has started. Despite disadvantageous hydraulic conditions the groundwater in the aquifer units are presently fresh with electrical conductivity (EC) ranging between 330 and 1250 $\mu\text{S}/\text{cm}$ (CGWB 2019b) except at northeast corner (near Cuddalore town) where, EC is 7200 $\mu\text{S}/\text{cm}$. By 2022, the annual pumping (projected from the present rate of pumping) would be around 1090 mcm and the hydraulic head would decline further in absence of intervention or management strategy. Thus, CCAS is at high risk of being intruded by seawater all along the coast in near future. Senthilkumar et al 2017 reported due to heavy and continuous pumping of similar type of coastal aquifer system (Chennai coastal aquifer system), sea water intrusion has occurred up to 9 to 16 km inland and pumping was discontinued as reclaiming the intruded zone is a daunting task.

4.3.8 Step VI Sensitizing public on status of the aquifer units

Aquifer management plan that involves change in pumping pattern, crop pattern can be successful only when such type of plan is discussed with public by water managers, local administrators through Public interaction programme (Jadeja et al 2015, Amrtha, 2016). About 94 % of the pumping wells in the region are privately owned and thus it is relatable to earn the favor of public in adhering to management options designed for implementation by the local authorities. The method of public interaction programme primarily depends on urban/rural mass and socio-economic conditions of the region. The major thrust is to expose or share people on the present status of the aquifer units and the consequence of over exploitation of groundwater resources in near future. The sensitive information on aquifer units thus shared with public raises scope for effective implementation of management strategies so as to ensure sustainability of the groundwater abstraction structures and protect the coastal aquifer from the threat of sea water intrusion.

4.3.9 Step VII Aquifer Management Strategies

The hydraulic characteristics of the aquifer units, groundwater development between withdrawal and discharge, response of hydraulic head to recharge and pumping over a period of time and the consequence of increased pumping on existing users were the criteria considered for AUMP. Numerical modelling which takes into account of the above criteria has guided to develop aquifer management plan (Gnanasundar and Elango, 2000, Senthilkumar and Elango, 2004, Barazzuoli, 2008). The simulation model results (CGWB, 2015) of existing and proposed groundwater management schemes was used to establish the safe yield, sustainable groundwater exploitation quantity and a reasonable groundwater exploitation scheme for the future. (Table 5). The numerical modeling study carried out by Gnanasundar and Senthilkumar (CGWB 2019a) established that hydraulic heads between ms land- 3 m msl has the potential to overcome the hydraulic pressure exerted by salt water front and therefore hydraulic head above msl upto- 3 m msl is considered as safe hydraulic heads. The efficacy of the Aquifer Unit Management Plan lies in the evaluation of natural and artificial recharge to the aquifer units, pumping and present scenario of the hydraulic heads in comparison with the historical heads. AUMP for coastal aquifer is based on the following aquifer management principles a) Pressure-head component of hydraulic head to exceed the elevation-head component in the discharge zone or coastal zone and create artesian conditions of the confined and unconfined aquifer unit. b) Maintain hydraulic equilibrium of the aquifer units.

Table 5
Aquifer management strategies for Cuddalore coastal aquifer system.

Aquifer Units	Safe hydraulic heads (m msl) In coastal zone	Present Pumping Year: 2019 (1034.86 mcm/year)	Pumping limit (690 mcm/year)	Aquifer management strategies					
				Reduction in pumping					Increase in recharge
				Recommended Optimum pumping per well (m ³ /day)	Recommended usage	Regulatory Measures in the coastal zone	Change in method of Irrigation	Artificial recharge activity	
Aquifer I (unconfined)	above msl	345.30	200	80	45	Domestic, drinking and irrigation	Drinking water supply, domestic and irrigation wells operational only	Flooding method for paddy should be changed to System of Rice Intensification method	Stepping up of recharge activity* in the up dip region or recharge zone.
Aquifer II (Confined)	Above msl to -3	518.52	320	80	45	Domestic, drinking and irrigation			
Aquifer III (confined)	Above msl to -3	158.25	150	120	No pumping	Depressurization for safe mining of lignite	Withdrawal restricted for existing and new industry.	Interaction with Public through Public Interaction Programme.	between Ponnaiyar and Gadilam River & Manimuktar and Vellar River
Aquifer IV (Confined)	Above msl to -3	12.79	20	120	No pumping	Drinking water supply in the event of drought to Chennai city and region nearby.	Telemetric water level and quality monitoring with high frequency.		

Table 5 Aquifer management strategies for Cuddalore coastal aquifer system.

Pressure-head component of the hydraulic head in the discharge zone or coastal zone can be enhanced by stepping up of recharge activity in the up dip region and recharge zone (western region). The solution to arrest lowering and further raise the hydraulic heads in the coastal zone lies in recharging the recharge zone as confined aquifer units are technically less feasible to be recharged even by injection wells in the coastal zone. Percolation pond with recharge shaft/recharge well and check dam are the effective artificial recharge structures in the up-dip and recharge zone as sand and gravel with high hydraulic conductivity ($K = 40$ to 115 m/day) facilitates high recharge (Marrykutty and Mohan 2019). In all possibility, it estimated that roughly 85 to 100 mcm of water could be additionally recharged annually and this has the potential to increase the hydraulic pressure of confined aquifer units (Aquifer unit II, III and IV) in the coastal zone.

Maintaining hydraulic equilibrium of the aquifer units can be achieved by minimizing the percent difference between recharge and discharge (presently 31 %) and operating the aquifer system wherein the present hydraulic heads equals the safe hydraulic head. This is achievable by reducing pumping in a way to match the estimated permissible yield. The permissible yield (Koch 2012) is the annual exploitation potential (E_{pr}) of the aquifer based on recharge or the total pumping rate that guarantees the average hydraulic head in each aquifer unit does not fall below safe hydraulic head (a vertical distance of -3meters from the mean sea level in the next 10 years). The annual exploitation potential (E_r) of the aquifer based on recharge to the aquifer in m^3 / area is calculated using the following formula:

$$E_{pr} = A \cdot R \cdot D \text{ eq.... 1}$$

Where, A = the area over which recharge to the aquifer take place (m^2) R = rainfall recharge to the aquifer (m/a) D = abstractable proportion of rainfall recharge. Approximately 10 % of annual rainfall recharge is assumed to discharge from the coastal aquifer system as base flow/seepage to sea. D is computed as follows;

$$D = 90 \% \text{ of Recharge (R) eq....2}$$

As per Eqs. (1) and (2) the annual exploitation potential (E_{pr}) of an aquifer is computed as 695 mcm y^{-1} . Thus the permissible yield of the entire CCAS should be lesser than 695 mcm y^{-1} .

Limiting annual groundwater withdrawal at $\sim 200 \text{ mcm}$ against 345.30 mcm in aquifer unit I and $\sim 320 \text{ mcm}$ against 518.52 mcm in aquifer unit II is the way forward and operate the aquifer system with total pumping not exceeding the annual exploitation potential (695 mcm y^{-1}). This can be partially achieved by stepping up recharge activities ($\sim 100 \text{ mcm/year}$) as discussed earlier and by switching over to water use efficiency methods (Sudhir et al. 2013) like the System of Rice Intensification (SRI) method (Verma 2017) instead of flooding method for paddy, drip and sprinkler irrigation for other crops like sugarcane, groundnut and ragi. Water Use Efficiency method (Golam Rasul 2011, Ram Fishman, 2015) has the potential to reduce pumping approximately by 15 to 20 % (~ 150 to 200 mcm annually). Cautious depressurization in aquifer unit III for safe mining of lignite along with periodic monitoring of hydraulic heads in all the four aquifer units around the lignite mine as well as near coast is required. Tube wells in aquifer unit IV can continue to tap drinking water supply to Chennai city if the reservoirs feeding Chennai city has poor storage. Also in an event of drought by monsoonal failure drinking water supply in the region can be met from aquifer unit IV.

Based on the guidelines recommended by National Green Tribunal (<https://greentribunal.gov.in>), declaring coastal zone as 'Notified area' (from coast to 10 km inland) to regulate pumping wherein registration of existing groundwater abstraction structures, permission to operate wells for drinking and irrigation activity only and restrict new wells are few management strategies that can bring down groundwater withdrawal by $\sim 50 \text{ mcm/year}$. In 2020, the National Green Tribunal (NGT) recommended that there must be no general permission for withdrawal of groundwater, particularly to any commercial entity, without an environment impact assessment of such activity and restricted groundwater extraction in over exploited areas for industries except for drinking water (<http://cgwb.gov.in/CGWA/NGT-orders.html>). Such permission should as per Water Management Plans to be prepared, based on mapping of individual assessment units. The plan strategy to limit pumping by 690 mcm y^{-1} with optimum pumping of 1.85 mcm/day and pumping per well as $40 \text{ m}^3/\text{day}$ in the coastal zone (maximum well depth 50 m bgl) and 80 to $120 \text{ m}^3/\text{day}$ in the inland zone is the controllable hydrogeological environment to protect CCAS from sea water intrusion. Monitoring is inclusive part of AUMP; hence specially built piezometers fitted with telemetric automatic water level and water quality recorders would enhance monitoring mechanism. Finally, involving stakeholders mainly farmer's would sensitize people to achieve desirable results.

Table 5 Aquifer management strategies of Cuddalore coastal aquifer system.

5. Conclusion

Sustainability of the coastal groundwater resources has been a critical issue as pumping-induced hydraulic head draw down has the potential to reverse the hydraulic gradient into the coastal aquifer. The Aquifer Unit Management Plan (AUMP) is a groundwater resources management plan designed for Cuddalore coastal aquifer system to understand and manage its resources in a sustainable way. AUMP is decisive as it cogitates annual groundwater withdrawal limit, annual recharge, and hydraulic heads of the aquifer units, management strategies and administrative measures. With complex aquifer hydraulics and processes within, aquifer unit wise management interventions can guide water managers to initiate action plan and act swiftly to protect the coastal aquifer system from sea water intrusion. As many coastal aquifers in the sub-continent lack management plan citing its complexity, AUMP designed for Cuddalore aquifer coastal system can be broadly amended to single as well as multi-layered coastal aquifers of the sub-continent.

Declarations

Availability of data and material

There are no linked research data sets for this submission. The following reason is given: Data will be made available on request

Competing interests

No competing interests exists.

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Authors' contributions

Authors contribution both the authors have made equal contribution in the study and also in the preparation of the manuscript.

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Figures

Map showing the location, boundary and regional geology of Cuddalore Coastal Aquifer System, India

Scale

100 m

msl

-100 m

-200 m

-300 m

-400 m

Vertically exaggerated

Flow direction

Recharge Zone

Intermediate zone

Coastal Zone

Neyveli

msl (Sea)

clay

clay

clay

Lignite

sandstone

sandstone

sandstone

sandstone

sandstone

Aquifer unit - I

Aquifer unit - II

Aquifer unit - III

Aquifer unit - IV

Aquifer unit - V

Basement

Basement 4500 m (approx)

Salt water wedge

Hornblende biotite gneiss

Escarpment

Explanation

Model orientation : West to East

Distance (West to East) : 58 km (approx.)

msl : Mean sea level

m : Meter

Conceptual model of Cuddalore coastal aquifer system, South India.

Figure 4

History of groundwater withdrawal from the cuddalore coastal aquifer system

Figure 5

Long term (Period: 1973 – 2018) hydraulic head fluctuation and trend of aquifer unit I.