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Assessing the impact of groundwater abstractions on aquifer depletion in the Cauvery Delta, India

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ABSTRACT

Many of the world's deltas are highly productive areas for agriculture as well as important places of socio-economic development but are currently under stress. This study assesses the impacts of stresses on groundwater pumping, changing cropping patterns, and saltwater intrusion on groundwater resources in the Cauvery Delta in Tamil Nadu, India. A transient groundwater flow model of the delta was constructed for this assessment. The historical changes in groundwater resources in response to decreasing irrigation canal flows and increasing groundwater abstractions were assessed for the past 30 years. Furthermore, the model was used to formulate and analyze future sustainable groundwater development scenarios. Farmers' narratives about a drying delta, as they experience water scarcity and quality issues most closely, were ascertained in the research. Farmers have abandoned many shallow wells in their fields. The model simulation shows groundwater levels are decreasing and aquifer storage depleting. Furthermore, salinization has increased, with continuous declining groundwater levels in the deep aquifer from 1990 to 2019. A more robust hydro-chemical assessment and further modeling of seawater intrusion are needed to better assess the sources and distribution of groundwater salinity. The pathway for future sustainability requires enhancing groundwater recharge in the shallow aquifer and controlling groundwater abstraction in the deep aquifers.

1. Introduction

Deltas around the world are under threat. Recent research shows that around 85% of the deltas of the world are shrinking (Loucks, 2019). Deltas are often highly fertile and densely populated areas across the world and their water resources have suffered increasing impacts from the economic growth around the 21st century (Syvitski et al., 2009). Over-abstraction of freshwater in these systems distorts the natural equilibrium of recharge and discharge, resulting in depletion and salinization (Praveena and Aris, 2010). The Nile Delta's coastal aquifer is experiencing increased salinity levels (Mabrouk et al., 2018; Armando and Negm, 2018; Nam, 2017). Rising salinity due to sea-level rise and decline in freshwater flows from upstream are also common problems. The increase in the number of dams constructed upstream of the Krishna and Godavari rivers and the increased groundwater pumping has led to seawater intrusion and ecosystem disruption (Saxena et al., 2004).

Climate change is expected to impose further adverse impacts on coastal groundwater resources, including groundwater depletion and seawater intrusion (Verkooijen and Ki-moon, 2021; Polemic and Walraevens, 2019). Due to heavy canalization and flood control measures, the entire Mississippi River Delta is experiencing land subsidence and reduced sediment flows (Loucks, 2019). While these exogenous biophysical drivers threaten deltas, human responses to them are exacerbating the problem further. The Ganges-Brahmaputra-Meghna Delta of Bangladesh is seeing a shift in practices of rice cultivation to aquaculture and there is the additional pressure of building salinity in the Delta (Essink, 2017).

To address these concerns and their effects on deltas, understanding the complex interaction of groundwater (GW) and surface water (SW) and the way they are affected by groundwater over-abstractions and agricultural activities (including canalization for irrigation) is crucial (Tian et al., 2015). For better management, quantifying and modeling

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[1] The datasets generated and/or analyzed during the current study are available from the corresponding author (Ankita) upon reasonable request at prayagankita@gmail.com.

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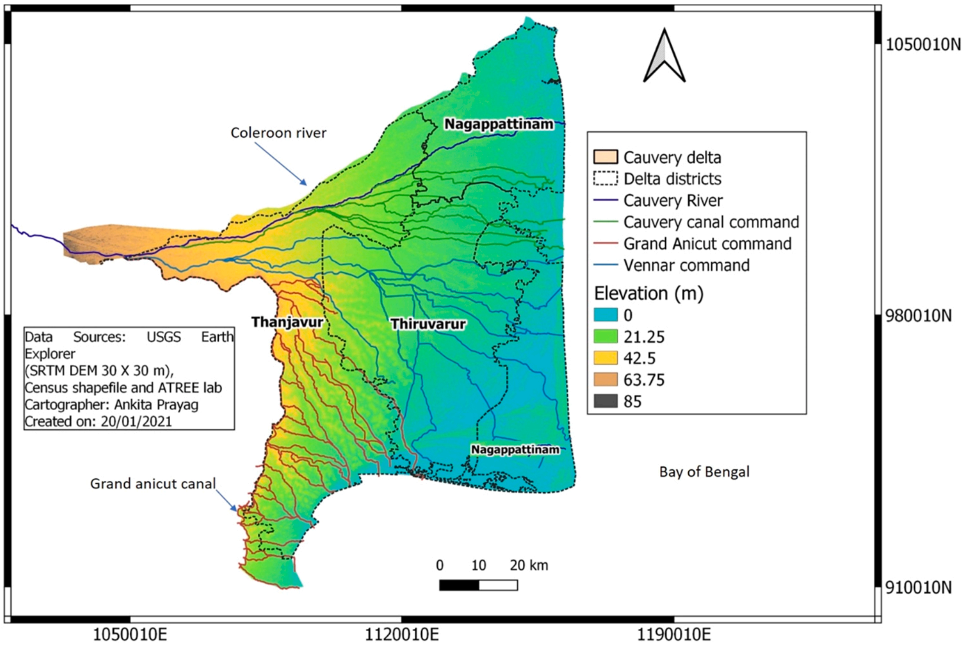

Fig. 1. The digital elevation map of the Cauvery Delta with canal network and districts.

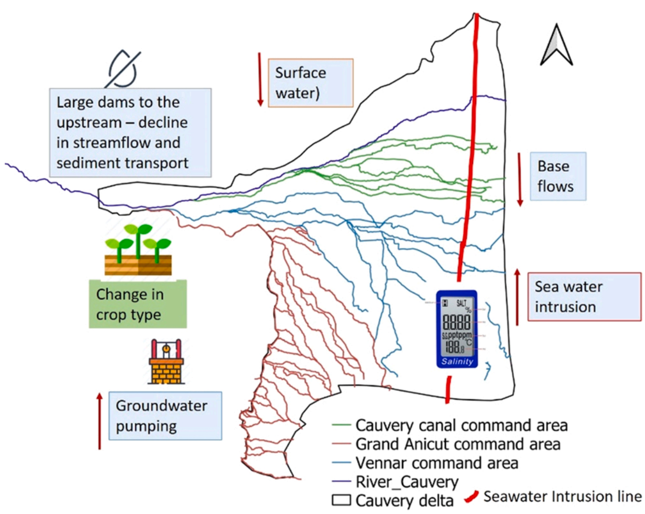

Fig. 2. The conceptual model for the problem description of the Cauvery delta (not to scale).

the cause and effect of the various components, coupled with the uncertainty and human responses, requires attention and further research (Li et al., 2017).

Groundwater models are useful in this sense and have previously been used to study and understand these effects. For example, in the Mekong Delta, various scenarios of increasing abstraction and reduction in recharge were simulated, which helped in the understanding of groundwater dynamics as well as the possibilities for sustainable water resources management (Nam, 2017). Groundwater sustainability is addressed globally using a modeling approach (Mulder, 2018; Casillas-Trasvina et al., 2019; Weerasekera, 2017; Gopinath et al., 2016; Jusseret et al., 2009). Nevertheless, in much of the Global South, collecting the necessary information for model implementation is challenging and comes with a large degree of uncertainty (for instance, Candela et al., 2014; Aghlmand and Abbasi, 2019; Mende et al., 2007; Chinnasamy and Agoramoorthy, 2015; Majumdar, 2010). Characterizing human responses and potential management pathways poses an additional challenge.

The objective of this research is to assess groundwater availability and the impacts of abstractions in the Cauvery Delta by building conceptual and numerical groundwater flow models. The models were used to analyze historical changes in groundwater resources in response to increasing abstraction and decreasing upstream inflows. The models were further used to formulate and assess two scenarios of groundwater development: business-as-usual (BaU) and a reduction in abstraction rate, with the latter representing a future pathway towards a sustainable Cauvery delta.

2. Data and methods

2.1. Study area description

The Cauvery river basin is one of the largest river basins in Southern India. The river basin is around 81,155 km^2 and is spread over the states of Karnataka (42.23%), Kerala (3.53%), Puducherry (0.2%), and Tamil Nadu (54.04%). The river disembogues into the Bay of Bengal after traveling around 800 km. Part of its course forms the border with Karnataka until it reaches the Mettur dam (constructed in 1934) (Nature, 1934), which stores Tamil Nadu's water for use in the Cauvery delta (ADB, 2011b).

A long-standing conflict between Karnataka and Tamil Nadu existed regarding the proportion of the water shared between the two states. It started in 1892 (Singh et al., 2007), flared up after the withdrawal of the British government and subsequent re-organization of states in 1956 (Schmidt et al., 2018), and was eventually settled in 2007 after a tribunal verdict was delivered by the Government of India that ordered Karnataka to release water into Tamil Nadu every year (Singh et al., 2007). However, the amount of water that Tamil Nadu receives is lower than its 1970 share.

The 2000-year-old Grand Anicut barrage is generally regarded as the beginning of the delta. Here, the Cauvery splits into several branches. The northern branch is the Coleroon river, which is the north boundary of the delta in our model (Fig. 1). The other three branches are the Cauvery and Vennar rivers, and the Grand Anicut main canal, the latter forming the western boundary. The command areas of the branches consist of dense canal networks and are referred to as the Old Delta (Cauvery command area), Vennar Delta (Vennar command area), and

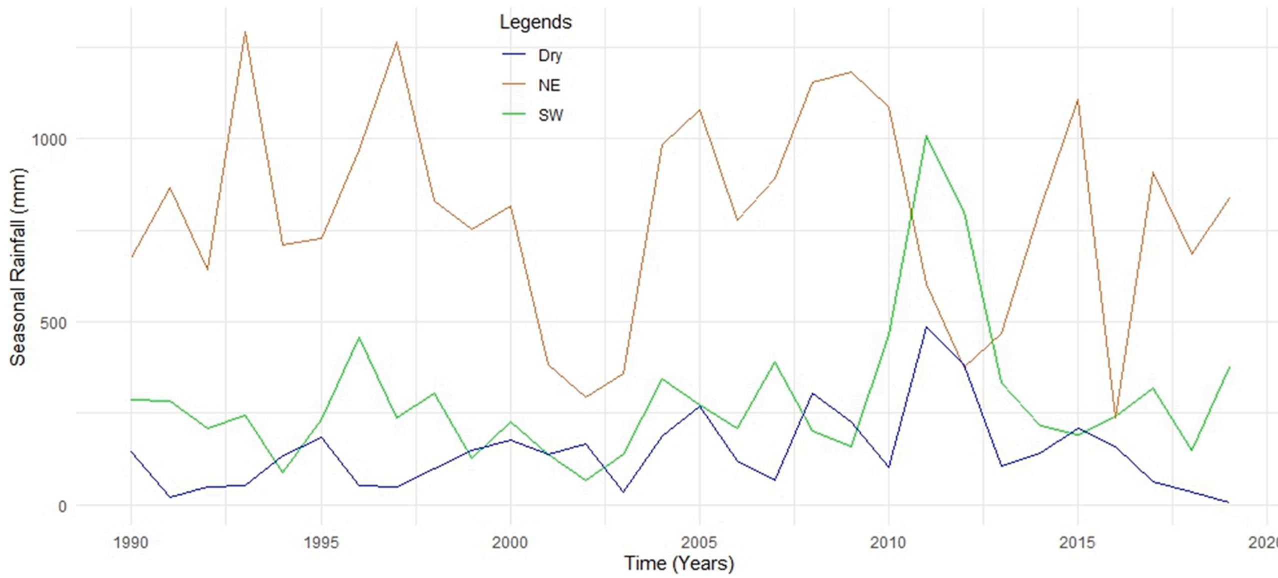

Fig. 3. Seasonal rainfall (mm) over the past 30 years in the delta.

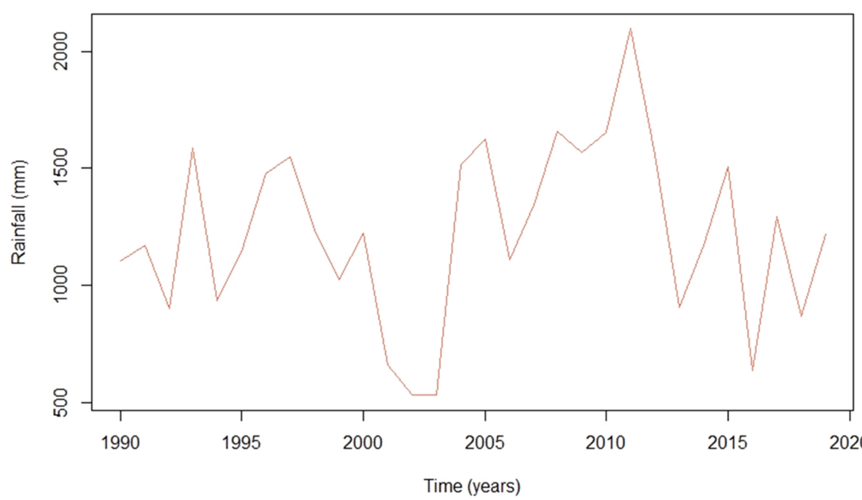

Fig. 4. Annual average rainfall (mm) over the past 30 years in the delta.

Table 1
Aquifer properties of the delta (ADB, 2011a).

Aquifer properties	Sediment properties	Depth ranges (m)
Quaternary alluvial	Sand, silt, and clay superimposed sand	0–45
Pliocene aquifer	Clays, weathered formations	30–100
Miocene aquifer	Sedimentary and metamorphic rocks	100–200
Cretaceous aquifer	Yellow-red sandstones, clay, limestones	150–300

New Delta (Grand Anicut command area), respectively (Fig. 1).

The Cauvery Delta of Tamil Nadu has been affected by reduced freshwater inflow, floods, and increased salinity (ADB, 2011c). Rainfall in the region has become more erratic and uncertain, triggering a change in river flow regimes and a lower surface water availability. This puts the Delta at risk of salinization and creates the possibility of a reduction in crop productivity (Srinivasan, 2019). The Asian Development Bank summarizes the issues of the Delta, which highlights mentioning diminished surface water from the southwest monsoon and water-logging caused by the more irregular and intense north-east monsoon; changing land use and cropping patterns due to: 1) salinity in the region—forcing farmers to shift from rice cultivation to aquaculture, and 2) a decline in canal water—forcing farmers to shift from two short-duration rice varieties into a single, extended one (ADB, 2011a, 2011b). The various interlinked problems are presented in a conceptual model of the Cauvery Delta in Fig. 2.

Field interviews with farmers were conducted to obtain a better understanding of their issues regarding surface and groundwater availability, quality, as well as changing cropping patterns. Their general response was one of severe water shortage, due to uncertain rains, reduced inflows, over-extraction of groundwater, and salinity issues. This has led farmers to abandon shallow wells to drill deeper ones and to shift from paddy crops to saline-tolerant crops, such as cotton. The scarcity situation has been causing distress among farmers—their memories of destructive cyclones (e.g. in 2018) and disastrous droughts (e.g. in 2016 and 2017) were still fresh. Many shared the sentiment that their delta is drying. Beyond these accounts of farmers, the drying delta narrative is found in the media and among policymakers. Yet, it is found that hydrological evidence of impact on groundwater storage and salinity, such as from developed groundwater models, is currently lacking for the Cauvery Delta (see also ADB, 2011c).

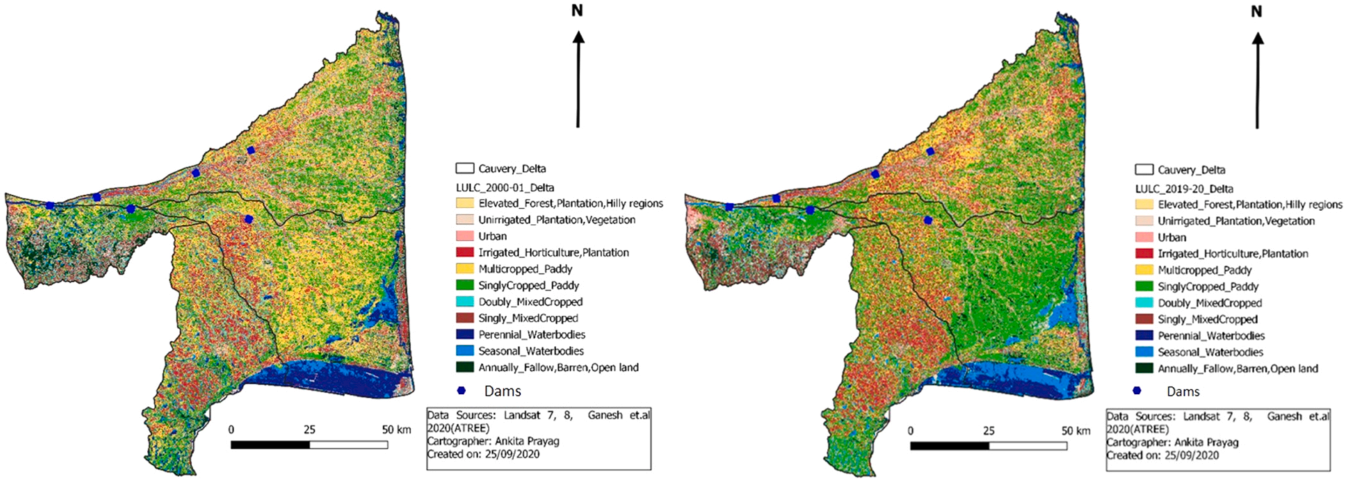

Fig. 5. Land use map comparison for the years 2000–01 and 2019–20.

Table 2
Details of the datasets involved during research with the data sources.

Attributes	Collected data type	Data sources
DEM	30 m x 30 m resolution SRTM	https://earthexplorer.usgs.gov/
Precipitation, evapotranspiration	Annual/seasonal precipitation, ET	IMD (http://imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html), ATREE India WRIS (https://indiawris.gov.in/wris/#/evapotranspiration)
Hydrogeology and parameters	Aquifer type, depths, hydraulic conductivity, storage coefficient	ADB publications, CGWB district reports
Change in land use and cropping pattern	Land use maps	Google Earth Engine, Landsat 7 and 8 (ATREE lab)
Mettur dam releases	For the period from 1974 to 75–2016–17	Information in Common Format of Tamil Nadu
Recharge and abstractions	Shallow and deep aquifers	CGWB 2017 Yearly Water Budget (this is the only latest water budget published)
The water-level trend over a period	Monitored groundwater levels	Tamil Nadu PWD (http://www.groundwatertnpwd.org.in/data_availability.htm)
Shapefiles	Canal network, administrative boundaries	ATREE

2.2. Data collection

The data used in this study were collected from primary and secondary sources to characterize the hydrogeology of the Cauvery delta.

2.2.1. The digital elevation model (DEM)

The SRTM DEM was accessed using the USGS Earth explorer. The highest elevations were found towards the west. The coastal zone is less than 5 masl. with parts in the southeast being below sea level (see Fig. 1).

2.2.2. Rainfall

The gridded-based rainfall data published by the Indian Meteorological Department (IMD) was used for the analysis of seasonal and annual trends from 1990 to 2019. The delta receives rains from the southwest monsoon (SW) from June to September while the northeast monsoon (NE) brings the highest rainfall to the delta from October to December. The lowest rains are noticed during the dry season from February to May as shown in Fig. 3. There is a large inter-annual variation in annual rainfall. In this century, the delta experienced prolonged dry spells in 2002–03 and 2016–17; after that, there was a recovery in rainfall; see Fig. 4.

2.2.3. Hydrogeology

Conducting a hydrogeological analysis of the aquifer and setting up the model was a challenge due to the absence of borehole data. Instead, combined data from various sources and reports, such as the India-WRIS (Water Resources Information System), the Geological Survey of India, and a Citizen Science program of the ATREE team, was used to enrich the data set. It was observed that there is a mixture of permeable and impermeable geological settings across the delta, especially for shallow depths. Most of the delta has alluvium deposition (Raju, 2016) and the area is subjected to aquifer characterization of the cretaceous Eocene, Pliocene, Miocene, and Quaternary alluvial aquifers (Ghosh, 1999). Table 1 shows the list of aquifer properties present in the delta along with the depth ranges.

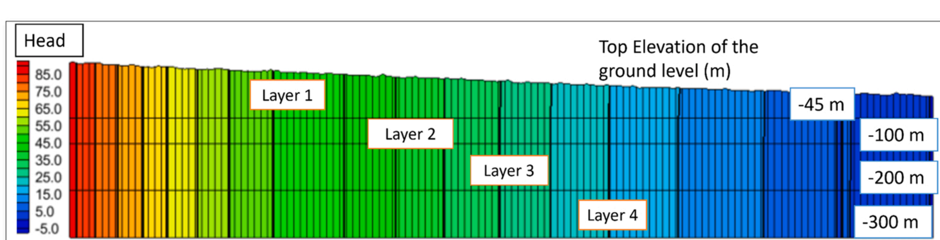

Fig. 6. Cross-section of the aquifer layers (negative sign indicates level below the mean sea level).

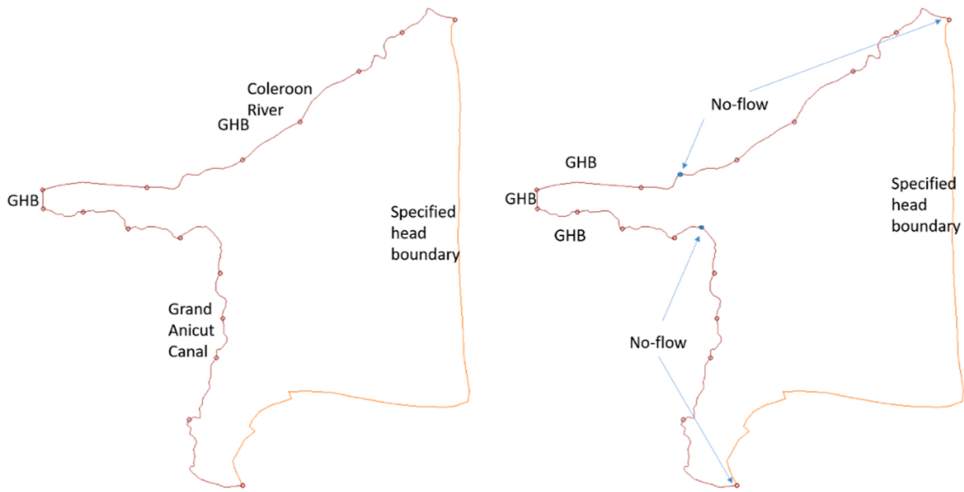

Fig. 7. Boundary conditions for layer 1 (left) and layers 2–4 (right).

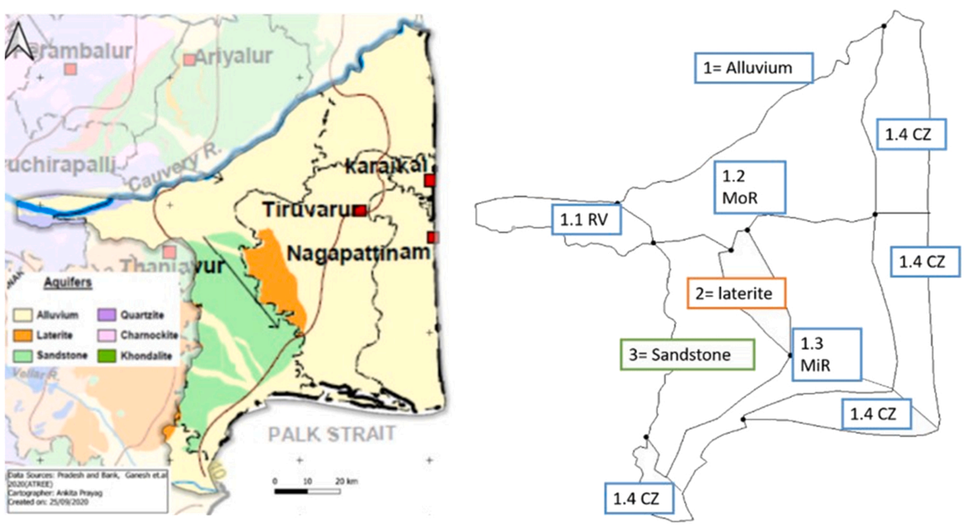

Fig. 8. Hydrogeological parameters zones.

Table 3
Zoning with the nomenclature for the hydrogeological zones.

No.	Type	Zones	Nomenclature
1	Alluvium	River valley zone	1.1 RV
		Major river zone: This is the main Cauvery river zone	1.2 MoR
		Minor river zone: This is the Vennar river zone	1.3 MiR
		Coastal zone	1.4 CZ
2	Laterite	—	—
3	Sandstone	This is lined Grand Anicut canal zone	—

Table 4
Recharge percentages from rainfall as an input to the steady-state models.

Recharge zones	Natural condition	With abstractions: Before calibration	With abstractions: After calibration
Zone 1	7%	11%	6%
Zone 2	6%	11%	6%
Zone 3	7%	14%	9%
Zone 4	6%	8%	7%
Zone 5	3%	7%	8%
Zone 6	13%	11%	6%
Zone 7	3%	8%	8%
Zone 8	11%	10%	4%
Zone 9	11%	25%	16%
Zone 10	21%	31%	18%

2.2.4. Cropping

The primary crop in the study area is rice, however, a range of other crops, such as groundnuts, banana, maize, cashew, coconut, and cotton, are also cultivated depending on the water availability during growing seasons. Recently, changes have been noticed in cropping patterns across the delta districts. Using Landsat 7 and 8 images, members of the ATREE project team made a comparison of land use classification (see Ganesh et al., 2020) while following the command areas of the Old Delta, Vennar Delta, and New Delta. The maximum land-use coverage in 2000–2001 shows a multi-cropped paddy in the Vennar Delta area. In recent years, the cropping pattern has changed and shifted from multi-crop to single-paddy crop as shown in Fig. 5.

2.2.5. Groundwater levels

Data on groundwater depths are collected from Government data sources such as the CGWB (Central Groundwater Board) and the PWD (Public Works Department). Various government agencies are responsible for managing the data, such as groundwater levels in the

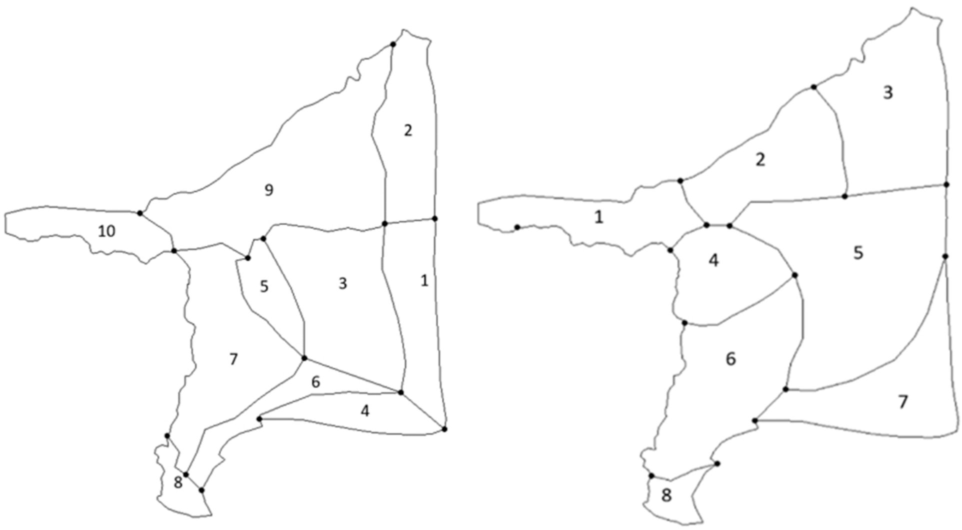

Fig. 9. Recharge zones (left image) and ET zones (right image).

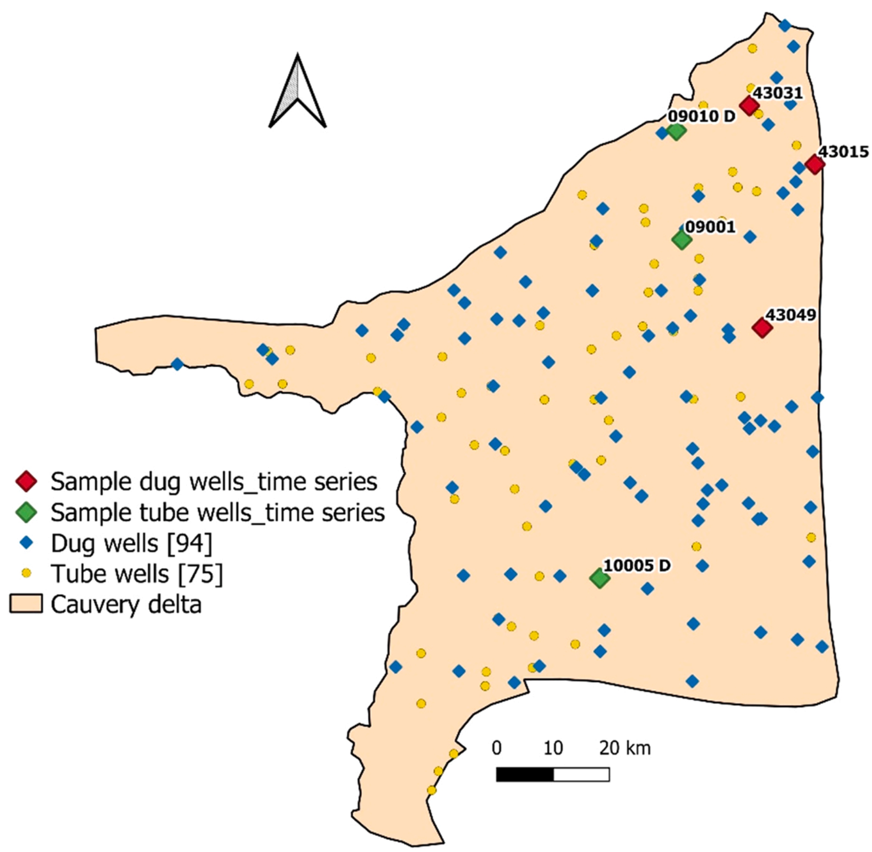

Fig. 10. The location map of the monitored dug and tube with sampled wells discussed in this paper.

observation wells at various depths and locations. The delta is divided into three districts (see Fig. 1) and the monitored data was then requested from the state department to be shared for 30 years (from 1990 to 2019) for dug and tube wells. The data analysis is discussed in Section 3.1.

2.2.6. Dam releases data

Data from outflows through the Mettur dam were collected from the PWD Tamil Nadu, for the period between 1974 and 75 and 2016–17. The data summarizes the monthly canal withdrawals from the Mettur dam in the 43 years (as furnished by the Tamil Nadu state department).

All the data collection for the various attributes listed with their sources are summarized in Table 2.

2.3. Construction of the conceptual model

Model conceptualization was performed in the map module tool of groundwater modeling software (GMS). Tamil Nadu WGS 84 EPSG 7785 (unit: meters) was used as the coordinate system in GMS. The model set up units in GMS 10.4.8 and used meters for length and days for time. The

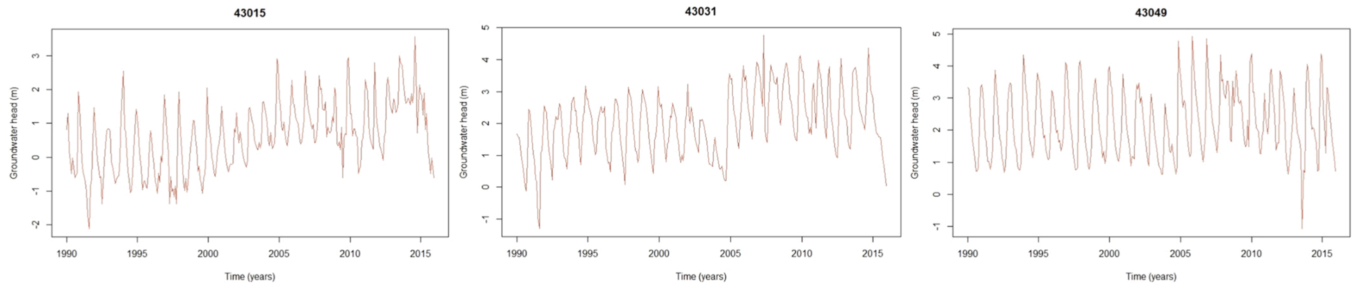

Fig. 11. Groundwater level time series from the dug wells.

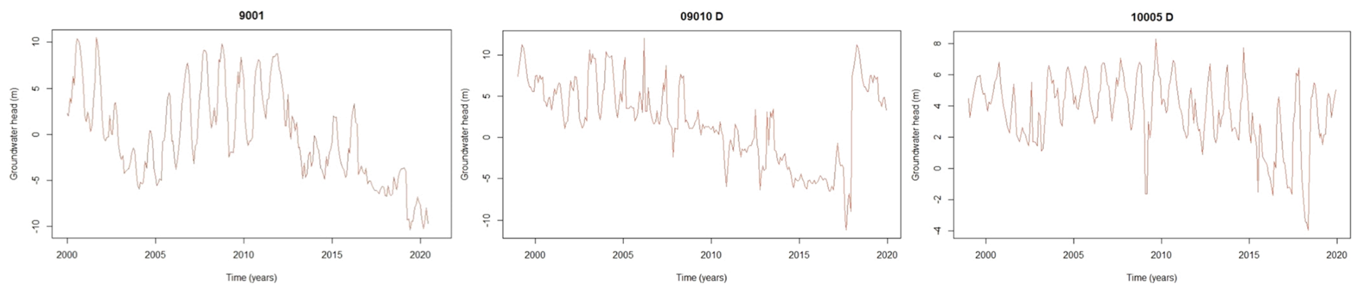

Fig. 12. Groundwater level time series from the tube wells.

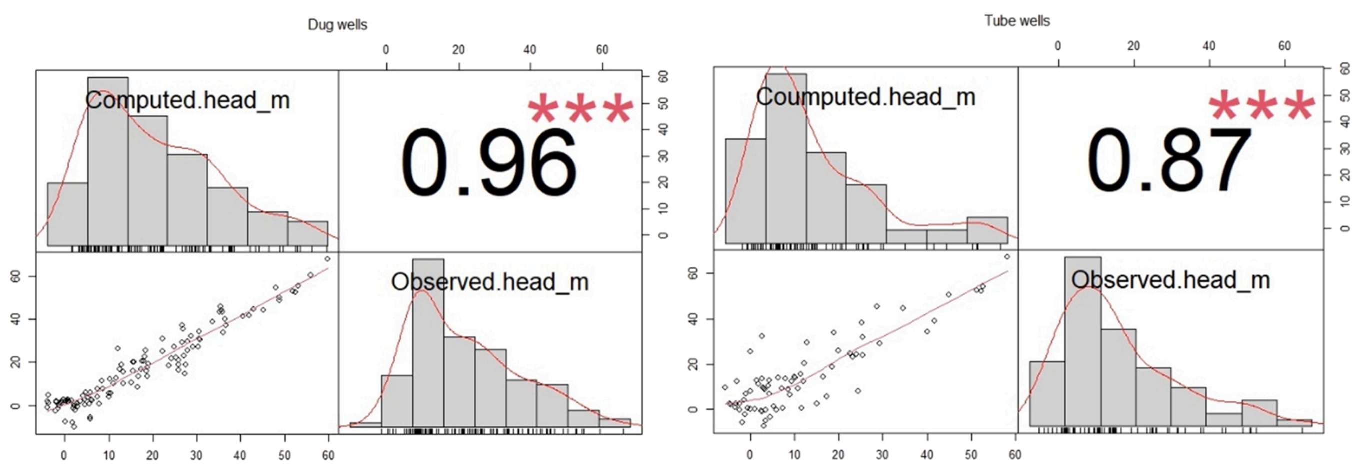

Fig. 13. Scatter plot of the computed head versus the observed head of the steady-state model.

elevation from the DEM was assigned to the top layer of the model, which represents the surface elevation.

Aquifer types and layers were identified from the literature and data on geological formations. The top aquifer consists of Quaternary alluvium formations that are unconfined. The lower three aquifer layers are sandstone and laterite type and confined in nature (CGWB, 2020; ADB, 2011a). Fig. 6 shows the cross-section of the delta with the aquifer layers and the respective bottom elevations. The groundwater head is indicated with colors.

For the first layer, the east side of the Cauvery Delta is bounded by the coastline and, thus, assigned as a specified (constant) head boundary for all layers, as shown in Fig. 7. The Coleroon river and the Grand Anicut canal are considered general head boundaries in the top layer of the model. For the second to the fourth layer, it is assumed that there is no flow across the boundaries see Fig. 7.

The stresses in the steady-state and transient-state models were assigned with the recharge and abstraction rates (discharge) components. Recharge rate was assigned as an area property, which is the percentage of the rainfall in m/d, whereas abstraction rates were assigned to a tube well/open well. The abstraction rate was assigned as a negative value with the volumetric unit of m^3/d. Recharge and discharge components were estimated from the annual water budget across the delta districts developed by CGWB.

The dense network of irrigation canals (Fig. 1) is conceptualized as rivers and simulated with the River package in the MODFLOW model.

2.4. Construction of the numerical model

The objectives of modeling were to assess groundwater resources and the impacts of groundwater abstractions over a period of time by building both the steady-state and transient groundwater flow models. The steady-state model was constructed using average recharge and discharge values based on the groundwater resources assessment water budget, published by the Central Groundwater Board (CGWB, 2019) for the year 2017. The transient simulation model is from 1990 to 2019, with a yearly stress period since most time-dependent data are available yearly.

MODFLOW code was used to construct the numerical model. The

Table 5
Groundwater flow budget components from the calibrated steady-state model (MCM= Million cubic meters).

Flow terms	Flow rate (MCM/year)	Percentage
Seawater intrusion	35	3%
River/canal leakage	152	14%
Inflow from boundaries	14	1%
Rainfall recharge	860	81%
Total inflow	1061	100%
Discharge to the sea	22	2%
Well abstractions	739	70%
Discharge to river/canal	85	8%
ET	165	16%
Outflow through boundaries	51	5%
Total outflow	1061	100%

uniform model grid was used with a cell size of 1000 m x 1000 m. This resulted in 163 rows and 146 columns. Four model layers were chosen corresponding to four aquifer layers (see Fig. 6). The top model layer is unconfined, and the rest are confined. Semi-permeable layers were not simulated explicitly in the model since there were no borehole data to classify aquifers and aquitards. The vertical resistance due to the presence of aquitards is accounted for with small values of vertical hydraulic conductivity.

2.4.1. Model packages

The layer property flow package (LPF) was chosen to compute horizontal and vertical groundwater flows. The top elevation of the first model layer is the surface elevation derived from the DEM data. The elevations of the rest layers were specified as constant values as shown in Fig. 6. Hydrogeological parameter zones were delineated with the hydrogeological map to define parameter values (Fig. 8). The Cauvery Delta is divided into three major hydrogeological zones. Most area is covered by alluvium deposits, which consist of sands and silts. The yellow color of the hydrogeological map is of alluvium, which is subdivided into four types based on the topographical features.

Zones with the nomenclature in Fig. 8 are provided in Table 3.

The horizontal hydraulic conductivity values were estimated from lithologies and conductivities were calibrated during the model calibration. The vertical hydraulic conductivity anisotropic factor was assumed as 1/20 to take account of the aquitards present in the aquifers.

The groundwater resources assessment report (1997) adopted the water level fluctuation method and rainfall infiltration method (CGWB, 1997). The recharge rate was determined by the terrain type. Recharge zones were developed based on hydrogeological settings as shown in Fig. 8. Based on alluvial or hard rock settings, the infiltration coefficient as the percentage of the annual precipitation was assigned as suggested by CBWB norms (Table 4). The percentages for various aquifer systems are within the recommended values as per the groundwater estimation committee (Kumar et al., 2020). Zones 9 and 10 are in the alluvium settings and, thus, the percentage recharge from rainfall is the highest. The recharge is simulated with the recharge package (RCH).

The evapotranspiration was simulated with the ET package. The ET zones were delineated with the land use map (Fig. 5) as shown in Fig. 9. The extinction depths were specified according to major crops in the zones. The dense network of irrigation canals and rivers was simulated with the river package (RIV). The spatial distribution of canals and rivers was mapped from digitized data provided by the ATREE lab. River/Canal width was estimated using QGIS plugins and the head stage was estimated using the DEM (selection of each arc node used in the head stage in meters). Rivers and canals were defined as arcs with varying conductance. Canal conductance values were assigned based on their lined or unlined condition.

Groundwater abstractions from dug/tube wells in the delta were not metered and there was no record of the groundwater used for agriculture demands (ADB, 2011a; Chinnasamy and Agoramoorthy, 2015). The gross yearly groundwater draft was calculated for irrigation, domestic and industrial uses by the CGWB methodology (CGWB, 1997). There was no data available for the pumping well locations, the number of pumping wells, and the depth at which those are placed, and groundwater is extracted. There was no data for the abstraction rate of the pumping wells either. Groundwater abstraction rate was assigned to dug/tube wells and simulated with the wells package.

For the transient model, abstraction from layer one was assumed constant while abstractions in layers 2 and 3, which are critical for abstractions, were considered with an increased rate over time. From the census data, it was found that there are 2000 villages/towns present in the delta, and 2000 drinking water wells are distributed in various zones and depths with calibrated abstraction rates.

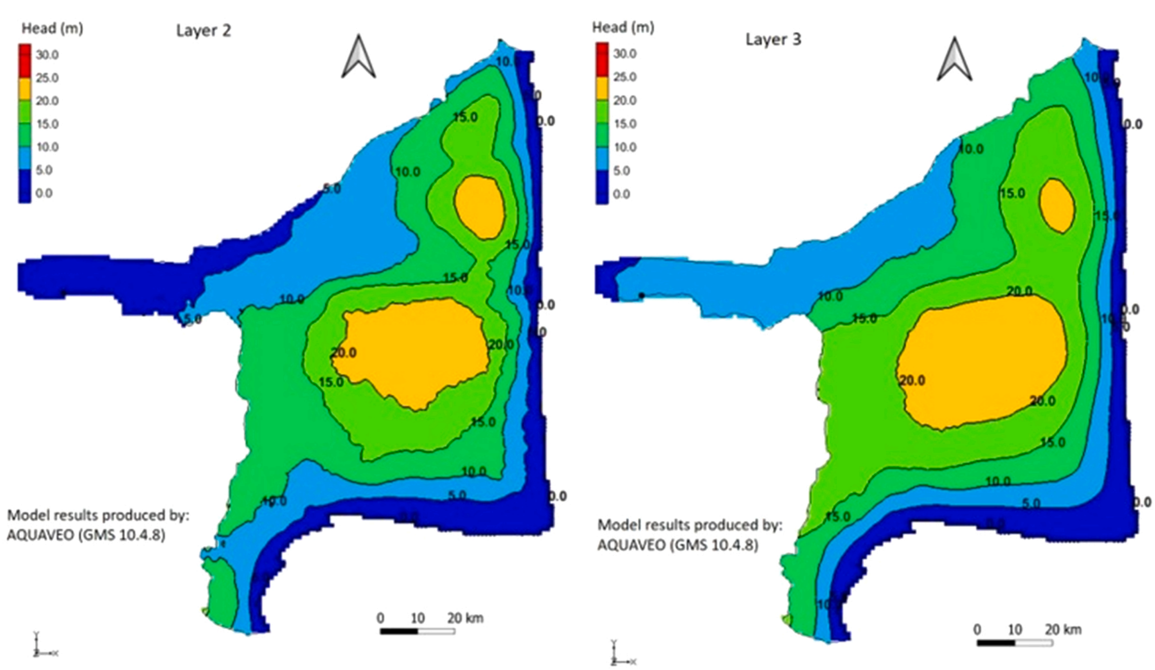

Fig. 14. Contour map of drawdown caused by abstraction in the model layers 2 and 3.

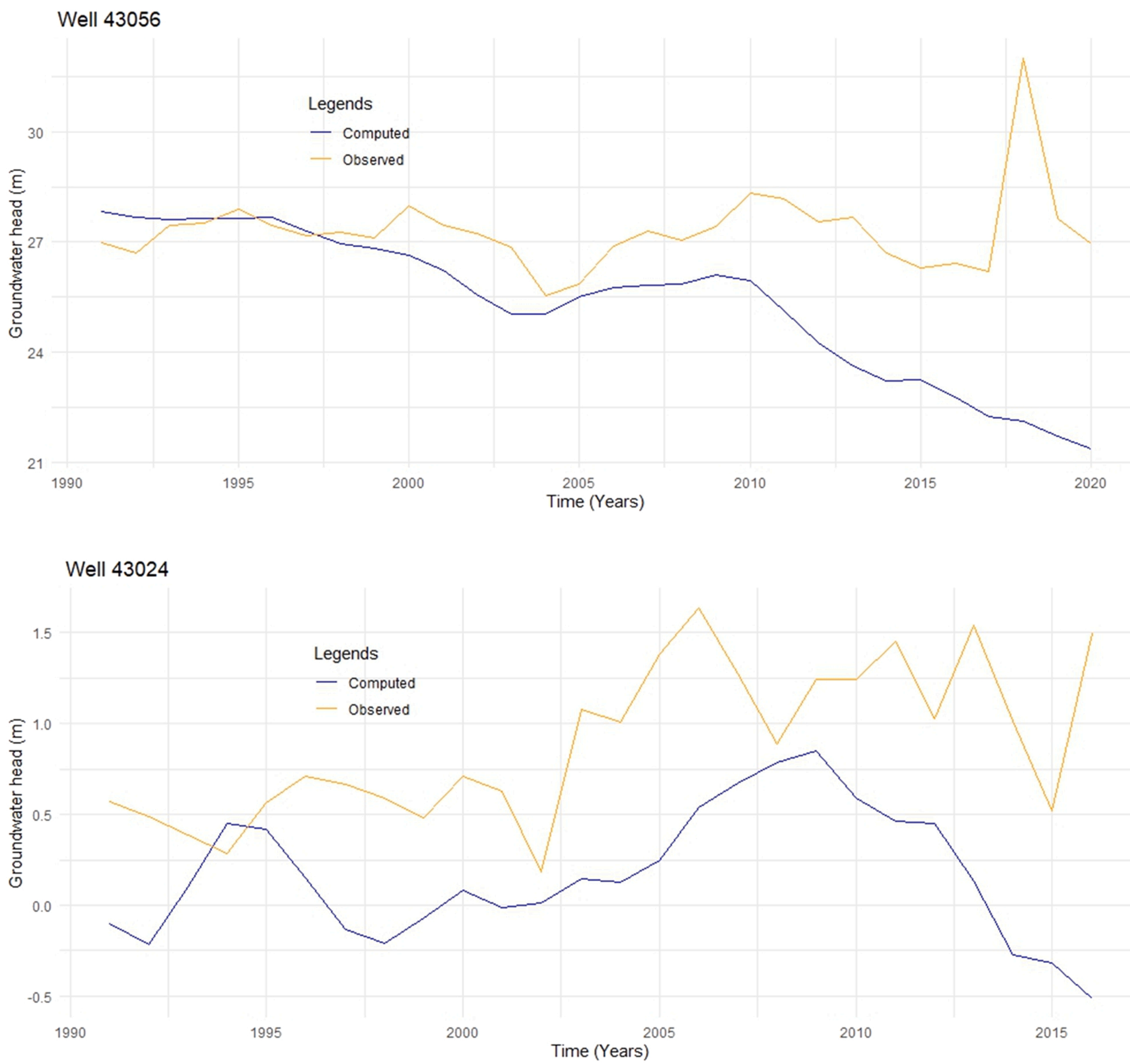

Fig. 15. Time series plots of computed versus observed heads from dug wells 43056 and 43024.

2.5. *Scenario formation*

This research considers the scenarios for estimating the future groundwater resources to indicate pathways to sustainability in terms of controlling water use, canal water supply, and groundwater abstraction of the Cauvery Delta. Two scenarios were formulated and simulated for the simulation period of 2020–2050. Changes in groundwater heads and water budget were computed and compared for each scenario. The original calibrated transient model was termed a benchmark model for comparison.

Scenario 1: Business-as-Usual (BaU).

The business-as-usual scenario assumes that current irrigation practices and groundwater development will continue in the future. Groundwater recharge was estimated for a normal water year; no extreme wet and dry years were considered. The boundary conditions also remained the same.

Scenario 2: Reduction of abstraction.

All inputs were kept the same as in the first scenario while groundwater abstraction was reduced by 50%. Groundwater abstractions must be reduced by 50% by 2050 to mitigate groundwater depletion. The reduction of the abstraction was applied in deep aquifers (model layers 2 and 3) where large aquifer depletion was found.

3. Results

3.1. *Monitored groundwater levels*

The current study analyzed the time series of the monitored groundwater levels of dug and tube wells. The measured groundwater levels in 94 dug wells and 75 tube wells are collected, analyzed, and used for model calibration as shown in Fig. 10. Sampled wells are selected based on the maximum number of observations.

Fig. 11 plots the monthly groundwater level series from three dug wells. Groundwater levels from the dug wells (located in the first aquifer layer) show intra-annual seasonal variations corresponding to wet and dry seasons and inter-annual changes in response to dry and wet years. The magnitude of seasonal variations ranges from 2 to 3 m. Groundwater levels in the dry season drop below sea level because of increased pumping in the wells. There are no obvious trends found in shallow groundwater levels. Fig. 12 represents the monitored groundwater level

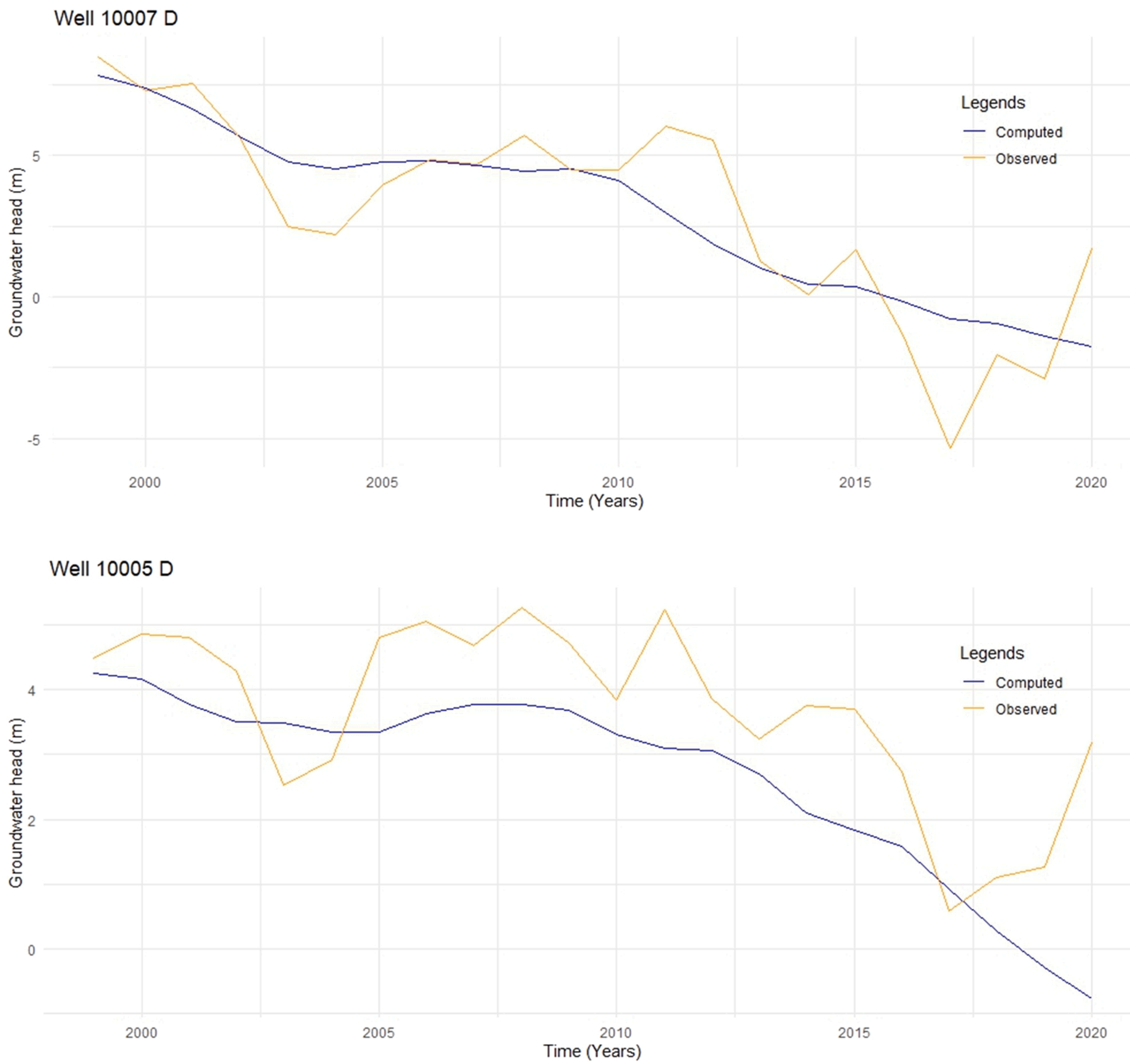

Fig. 16. Time series plots of computed versus observed heads from tube wells 10007 D and 10005 D.

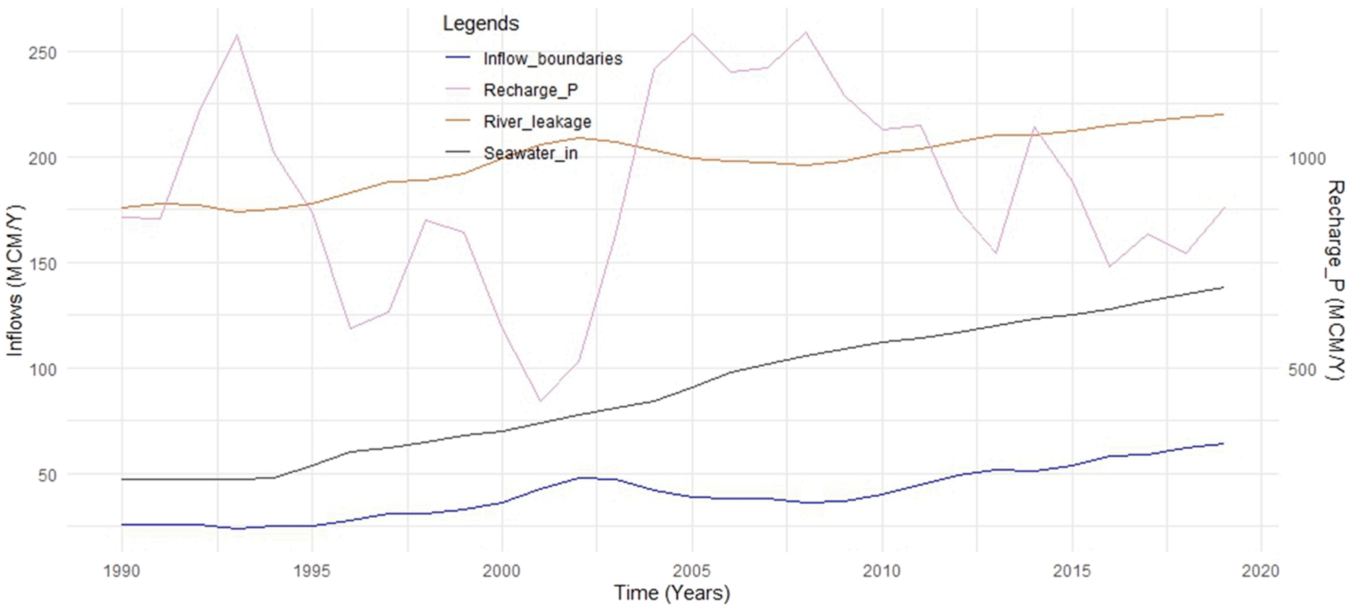

Fig. 17. Inflow from boundaries, rainfall recharge, river leakage, and seawater intrusion from transient model.

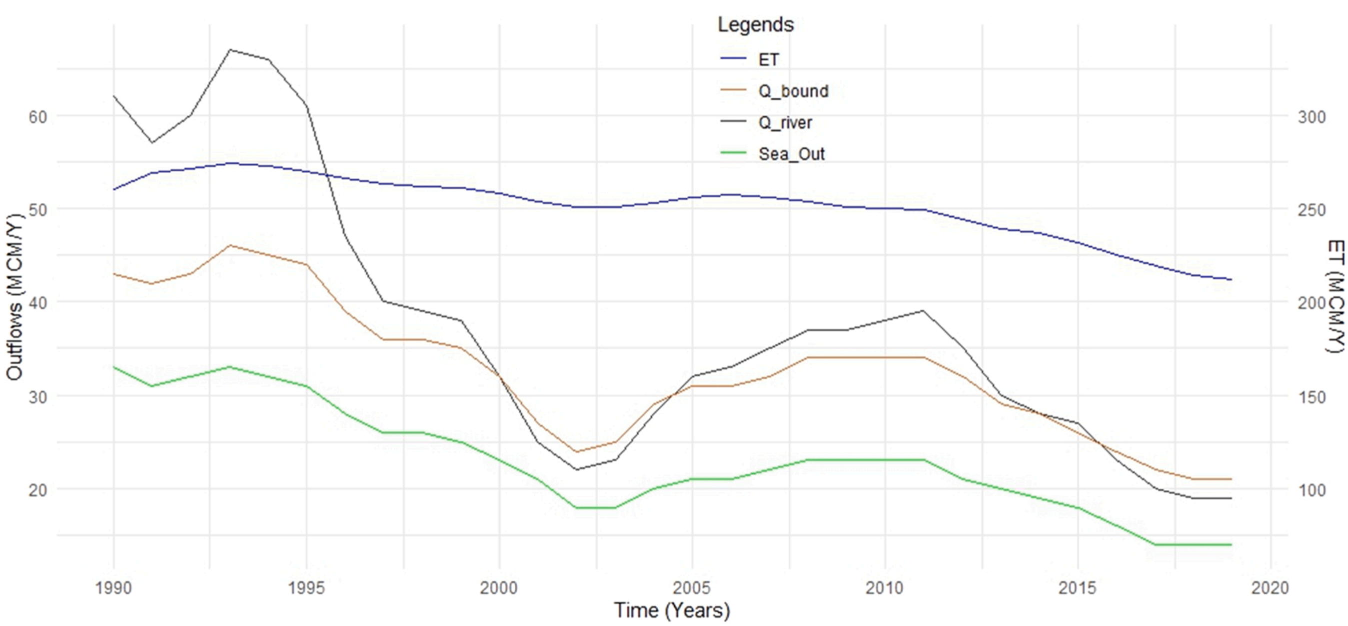

Fig. 18. Outflow from ET, boundaries, river leakage, and seawater from the transient model.

series from tube wells. Groundwater levels show a clear trend of decrease on top of seasonal fluctuations. The lowest water levels occurred in the dry years of 2002–05 and 2016–2019.

3.2. Model calibration

3.2.1. Calibrated steady-state model

Fig. 13 shows the scatter plots of the computed heads versus observed heads. In general, the computed heads resemble the observed heads. In dug wells, the mean residual error is − 0.015 m, the root mean squared error is 4.95 m, and the correlation coefficient between the computed and observed heads is 0.96. In tube wells, the mean residual error is − 3.04 m, the root means the squared error is 8.68 m, and the correlation coefficient is 0.87. The accuracy of the model calibration is better for dug wells than for tube wells.

Table 5 presents the water budget components. Recharge from precipitation dominates the inflow with 81% of the total inflow while leakage from irrigation canals accounts for 14%. Inflow from the sea accounts for 3% of the total. Inflow from the north and west boundaries is limited. Abstraction dominates groundwater discharge with 70% of the total outflow, ET accounts for 16%, followed by discharge to rivers and canals. A small amount of groundwater discharges to the sea and the north and west boundaries were observed.

The differences in the computed heads between the natural condition and under the abstraction provide estimates of drawdowns. Fig. 14 plots the contour maps of drawdowns in the deep aquifers 2 and 3. Cones of the depression are formed in the intensive abstraction areas for irrigation with a drawdown of about 25 m.

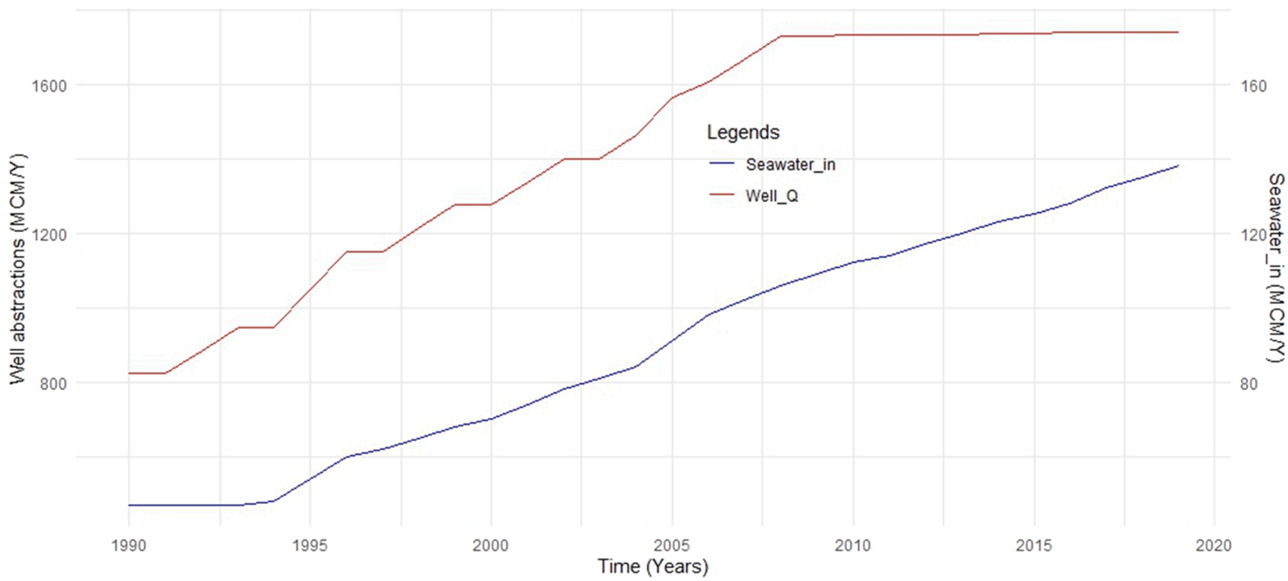

Fig. 19. Seawater intrusion versus well abstractions from transient model results.

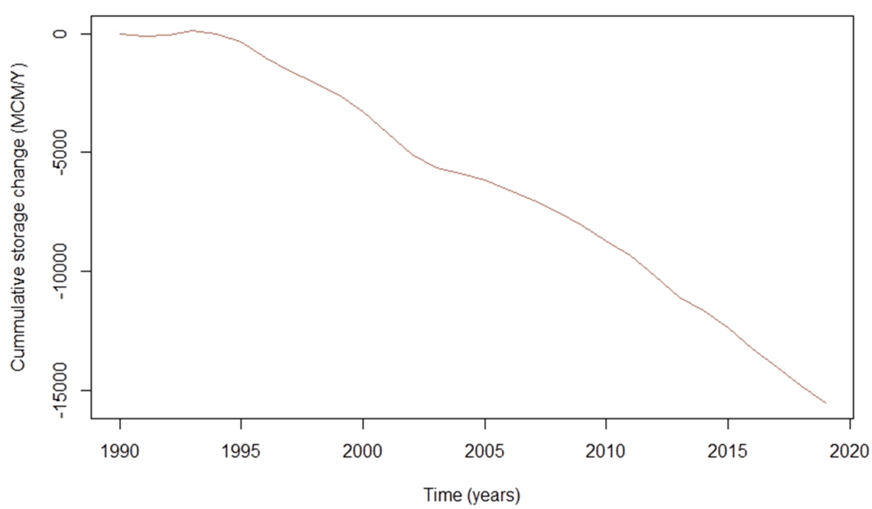

Fig. 20. Cumulative storage changes from 1990 to 2019.

3.2.2. *Historical changes in groundwater resources from the transient modeling*

Fig. 15 plots the computed heads and measured heads in two dug wells. Large differences can be found after 2010. Computed groundwater levels showed a decreasing trend while the observed groundwater levels fluctuated in response to dry-wet years. This trend of decrease in groundwater levels is caused by increasing abstractions in deeper model layers. Since separate aquitards were not included in the model, the model could not compute stable water levels in the first model layer.

The computed heads fit better with the observed heads in tube wells (Fig. 16). Both computed and observed heads show decreasing trends.

Fig. 17 plots inflow components. Recharge from precipitation varied largely depending on annual precipitation. In the dry years of 1996–2003, recharges from precipitation are the lowest. In recent years, recharge from precipitation is modest. Seawater intrusion has increased in recent years and amounted to 1.37×10^8 m^3 in 2019 (Fig. 17).

As far as the outflows discharge to boundaries, rivers (baseflows), and the sea are concerned, they show a similar trend over a period of time, with a peak drop during the dry years 2002–2003 and 2016–2019 (Fig. 18). Groundwater abstraction is estimated to gradually increase from 8.22×10^8 m^3 in 1990–1.73×10^9 m^3 in 2008 and remain constant afterward (Fig. 19). Fig. 19 shows that increasing well abstractions caused an increase in seawater intrusion.

The cumulative storage change (Fig. 20) indicates continuous groundwater storage depletion amounting to 15.5×10^9 m^3 by the end of 2019.

Fig. 21 shows that cones of depression had developed where drops of groundwater levels reached 20 m in layer 2 and about 30 m in layer 3.

3.3. *Scenario analysis*

Scenario 1 shows that the continuation of current abstractions will greatly impact the groundwater budget and storage depletion. Table 6 indicates that seawater intrusion will increase by 39 % by 2050, compared to the benchmark model (calibrated transient model). Discharges to the river/canal will be reduced significantly: by 51 % of the benchmark model. Inflow from boundaries will increase by almost 83% and outflows to the boundaries will be reduced by 53 %.

Large drops in groundwater levels can be seen in Fig. 22, which shows the contour maps of groundwater level decreases in layer 2 and layer 3 from 1990 to 2050. Fig. 23 shows the time series of the decrease of groundwater levels in layers 2 and 3 for zones of the Vennar Delta and

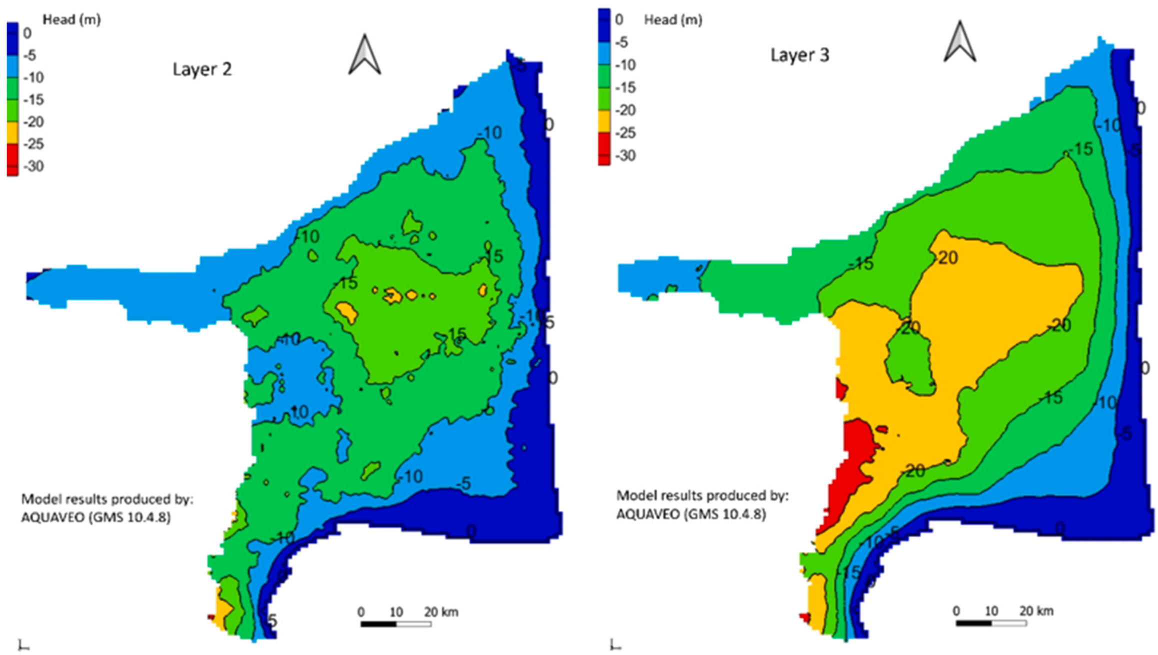

Fig. 21. Head difference map between 2019 and 1990 in layers 2 and 3 computed from the transient model.

Table 6
Groundwater flow budget for scenarios in 2050 compared to the benchmark model.

Budget components	**Calibration model** 1/1/2019	**Business as usual (S1)** 1/1/2050	**Reduction of abstraction (S2)** 1/1/2050	**Percentage of change** S1	S2
Seawater intrusion	124	172	61	39%	-51%
River/canal leakage	217	234	203	8%	-6%
Recharge from boundaries	57	117	44	104%	-23%
Rainfall recharge	996	996	996	0%	0%
Total Inflow	**1395**	**1519**	**1304**	**9%**	**-6%**
Discharge to sea	23	15	31	-35%	36%
Well abstractions	1651	1651	825	0%	-50%
Discharge to river/canal	22	11	36	-51%	63%
ET	250	209	318	-16%	27%
Discharge to boundaries	22	11	32	-53%	43%
Total outflow	**1968**	**1896**	**1243**	**-4%**	**-37%**
Change of storage	**-573**	**-377**	**61**	**-34%**	**-111%**

Grand Anicut area. The cones of depression extended to the whole aquifer. The groundwater level decreases at about 30 m below the sea level at the center of the cones (Zone 3).

Fig. 24 shows cumulative storage change. Under BaU, the accumulated storage depletion amounts to thirty billion cubic meters by 2050.

In scenario 2, after minimizing the abstractions, seawater intrusion was reduced by 51 % (Table 6). Discharges to canals/rivers increased and recovered by almost 63 %. Fig. 24 shows a slow recovery of storage, implying that the storage depletion is reversed under scenario 2.

Fig. 25 shows the difference in the groundwater heads for scenario 2 between 2050 and 1990. The cones of depression are reduced in both layers. Fig. 26 shows a slow recovery of groundwater levels in layer 2 and the rate of decrease of ground levels in layer 3 is reduced.

4. Discussion and concluding remarks

The current situation of the Cauvery Delta is complicated and subject to complex and interconnected issues concerning water use, availability, and quality. Groundwater models were applied to analyze field observations as well as the feedback from farmers that the delta was drying, as they experienced growing water scarcity and felt the necessity to drill deeper boreholes. Steady-state and transient flow models were constructed under a data deficiency situation to research: 1) the impact of groundwater abstraction on shallow and deep groundwater storage, 2) the critically affected zones in the delta with historical changes in groundwater levels, and 3) the current and future extent of seawater intrusion by mobilizing two scenarios of groundwater development. Some of the key findings of the paper contribute to the view that the Cauvery Delta is at a tipping point. Canal flows are reduced, rains are more irregular, and groundwater extractions are intensifying.

4.1. Data and model uncertainty

Due to the lack of essential data, the model contains uncertainties in the conceptualization of the aquifer system, layer properties, and recharge and abstractions. Recharge estimation and estimation of groundwater abstraction have uncertainties (CGWB, 1997, 2009, 2017). CGWB estimated recharge using a percentage of annual precipitation which does not differentiate between extremely dry and wet years. The groundwater abstraction data were collected from states as a total sum,

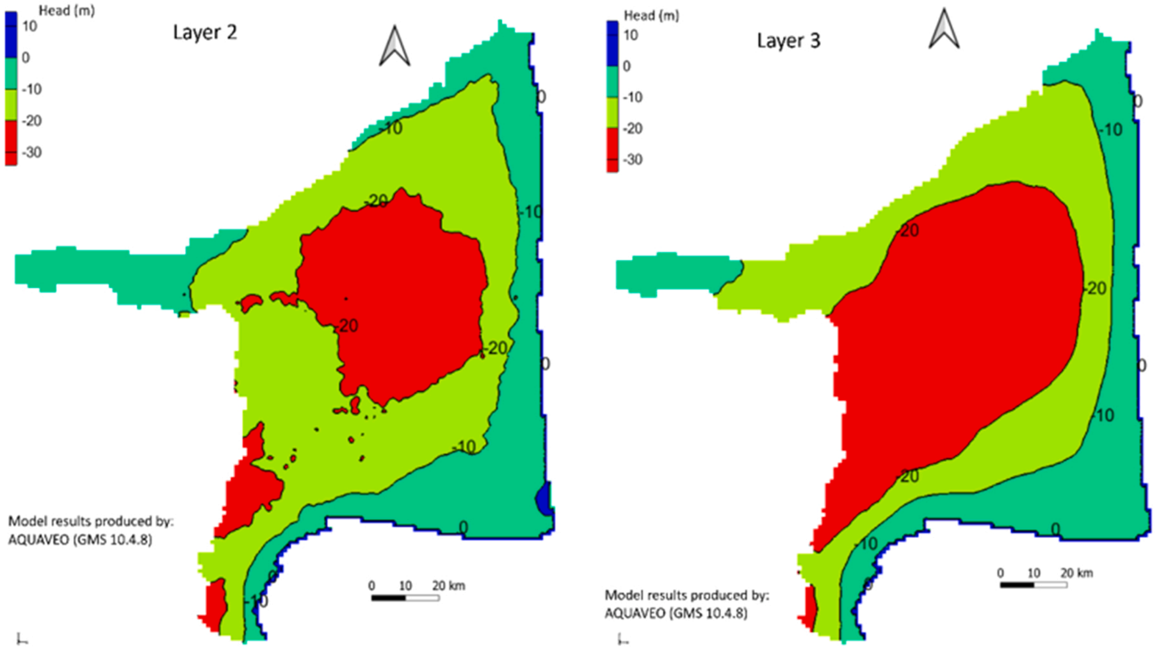

Fig. 22. Head difference map between 2050 and 1990 for model layers 2 and 3: Scenario case 1; BaU.

as no data was available about the number of wells, their locations, depth, and rates. There are uncertainties about groundwater level measurements as well. Groundwater levels were measured mostly from production wells. A significant uncertainty was associated with long-term groundwater level trends (Hora et al., 2019; Fishman et al., 2011). The accuracy of the steady-state model calibration is better for dug wells than for tube wells. The accuracy of the transient model calibration is affected in the absence of information from separate aquitards, abstractions, ET, aquifer types and depths, and canal/river flows.

4.2. Model conclusions: supporting field observations

Deeper aquifers show a decrease in groundwater levels with a cone of depression in the Vennar and New Deltas. There are specific zones, like the tail end of Grand Anicut Canal (Zone 7) or the central part (Zone 3), that show a continuous decline in groundwater levels, depletion of groundwater storage, and induced seawater intrusion. While the steady-state model suggests that seawater intrusion is just 3% (despite abstractions of around 70% of the total natural inflows), the transient model indicates that seawater intrusion has increased three times from 1990 to 2019. This is deteriorating the groundwater quality. Indeed, a water quality analysis (Cl and EC concentrations) of CGWB state department data (historical purchased data) indicates inland salinity, which was also found during field observations in Zones 7 and 3 of the deltas, where the groundwater was of the brackish-saline type.

Interestingly, the model shows the trend ofdecreased groundwater level in the shallow aquifer over the last decades. These results agree with farmers' stories of a drying delta and the abandoning of shallow wells for deeper boreholes. Farmers drill deeper wells because of the insufficient reach to the surface water during the annual dry period, while in the coastal area, the use of shallow wells for irrigation is almost nil, because of salinity.

Overall, the model results indicate that the (deeper) aquifers are heavily exploited every year, especially during years when groundwater levels were dropping significantly. We also conclude that the increased pumping coincides with the dry months of pre-monsoon summer and also during the drought years. The key finding of this study is that the aquifer has already reached its maximum groundwater development, that is, overexploited—where an aquifer has reached an unsustainable situation of exceeding abstractions than the rate of replenishment in current times—and there is no room for increasing the abstractions in the future. On the contrary, groundwater abstraction must be reduced to achieve long-term sustainability.

4.3. Pathways for groundwater sustainability

Scenario 1, or the business-as-usual simulation, shows that under the current abstraction regime, groundwater levels will continuously decline, which will result in large depletion of groundwater storage and induced seawater intrusion. For developing pathways for groundwater sustainability in the Cauvery Delta, key insights were gained from scenario 2, or the reduce-abstraction-by-50%, simulation. One of these insights refers to the targeting of the deeper aquifer layers for reduction while simulation improved recharge for the shallow aquifer. For that path, there is a need for robust chemical data and saline modeling to better assess seawater intrusion and current inland salinity and to understand the mechanism and distribution of saline water at shallow and deeper aquifers.

Current research fulfills the requirement of developing an understanding of the realistic availability of groundwater resources in given space and time to address the delta water management issues. Two crucial transformations are needed for groundwater sustainability in the delta. First, to execute a far-reaching and large-scale groundwater recharge campaign to raise awareness and aid the recovery of water levels and water quality. Practices to this end can already be observed, led by both government agencies and grassroots initiatives. Second, to create a robust spatial and temporal groundwater monitoring system, mobilizing both water quality and quantity data samples to assess the current groundwater regime and future trends.

Considering the data limitations at various stages of the modeling, there is scope for scaling and building data sets on hydrogeology (aquitards and their properties), groundwater abstractions, and dense monitoring of water resources in the delta. The current models can lead to building more robust future modeling by mobilizing citizen science campaign data of the delta, such as the one we have recently set up. Despite uncertainties in the data and the model, the constructed groundwater models provided useful insights for the control of groundwater abstractions and seawater intrusion that will hopefully be

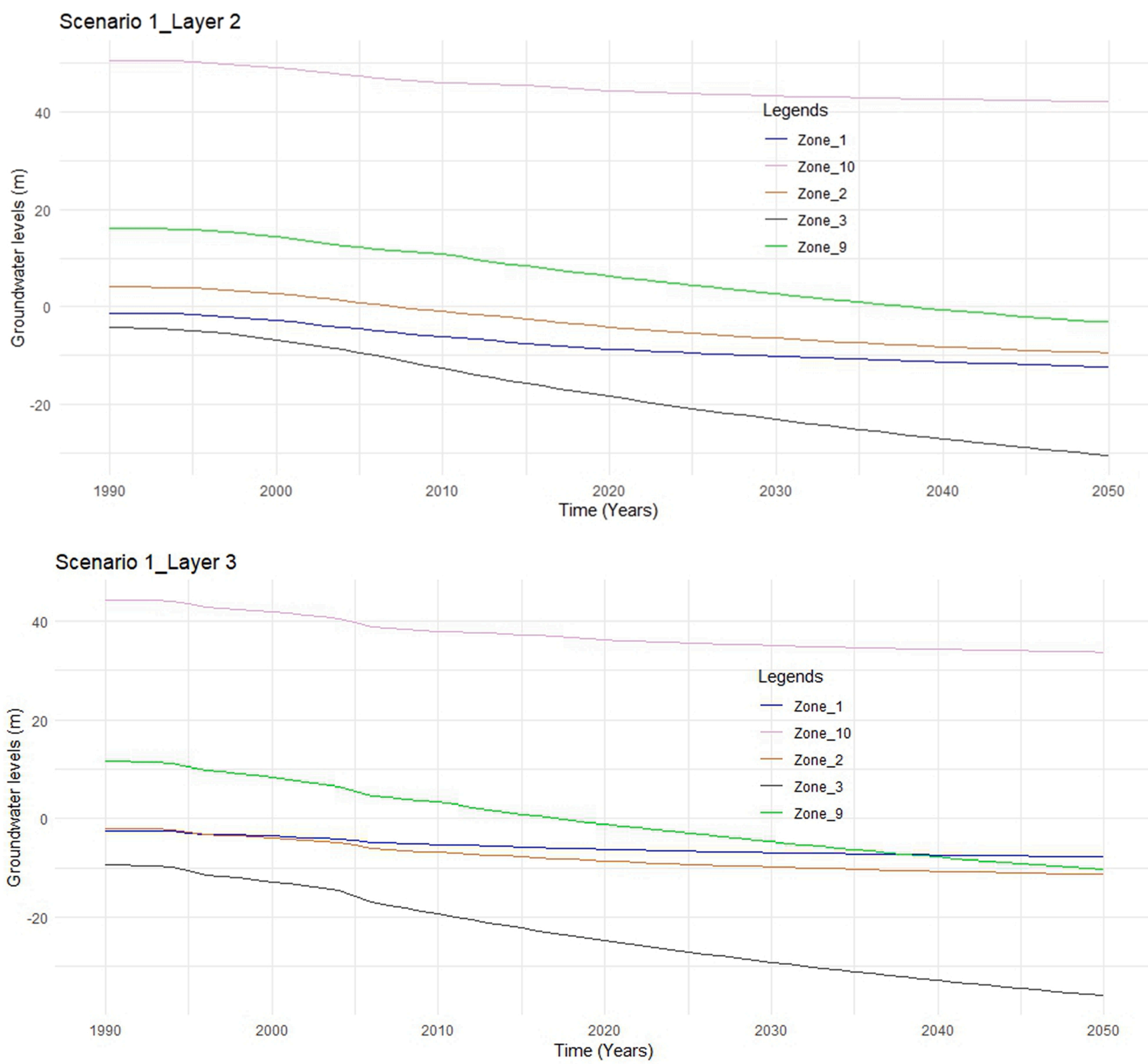

Fig. 23. Groundwater level time series for key zones in layers 2 and 3 from Scenario 1.

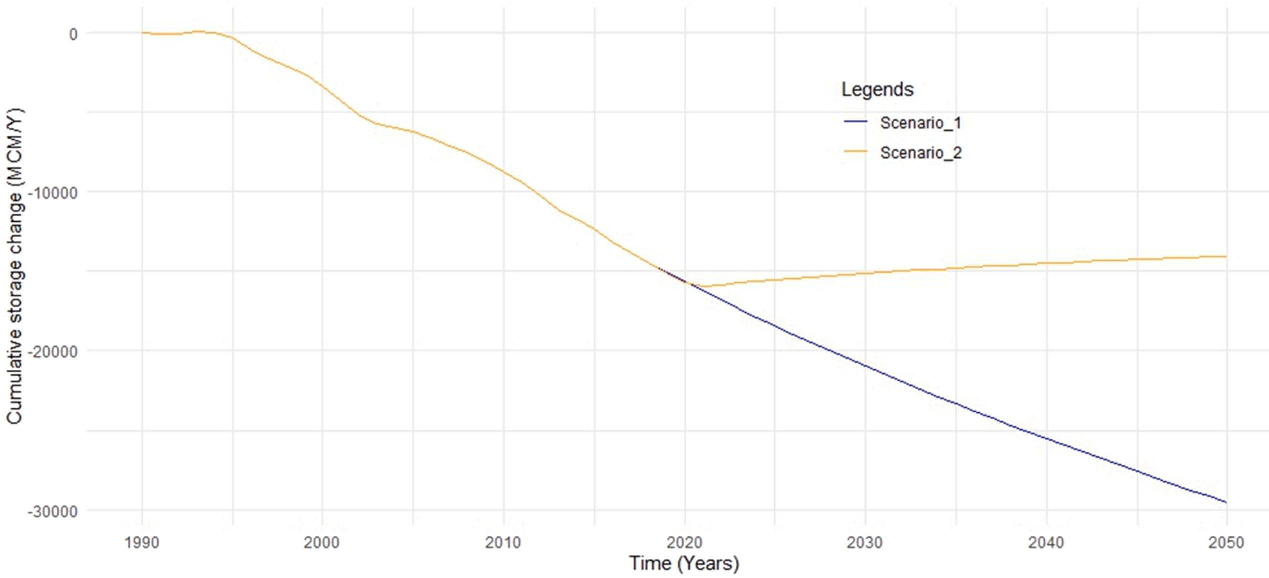

Fig. 24. Cumulative storage changes under scenarios 1 and 2.

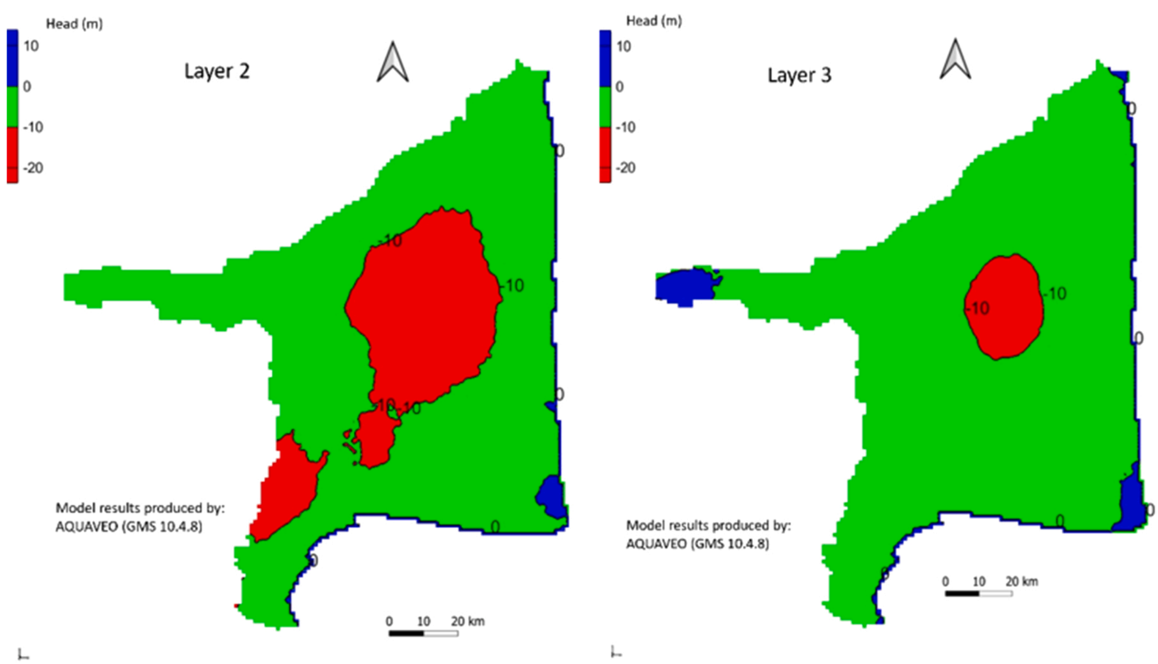

Fig. 25. Head difference map between 2050 and 1990 for layers 2 and 3: Scenario 2.

taken up by policymakers and other water professionals to come to the aid of the delta farmers and their future.

Ethical Approval

This material is the authors' original work, which has not been previously published nor considered for publication elsewhere. The research and analysis are truthful and complete.

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CRediT authorship contribution statement

All authors contributed to the study and paper from conception to submission. Model preparation, data analysis, and calibration were performed by Ankita Prayag and Yangxiao Zhou. Veena Srinivasan and Tibor Stigter provided critical revisions to the modeling work. Andres Verzijl helped with model reflection and interpretation of fieldwork stories. The first draft of the manuscript was written by Ankita and all co-authors contributed to the writing and editing of later drafts and approved the final manuscript.

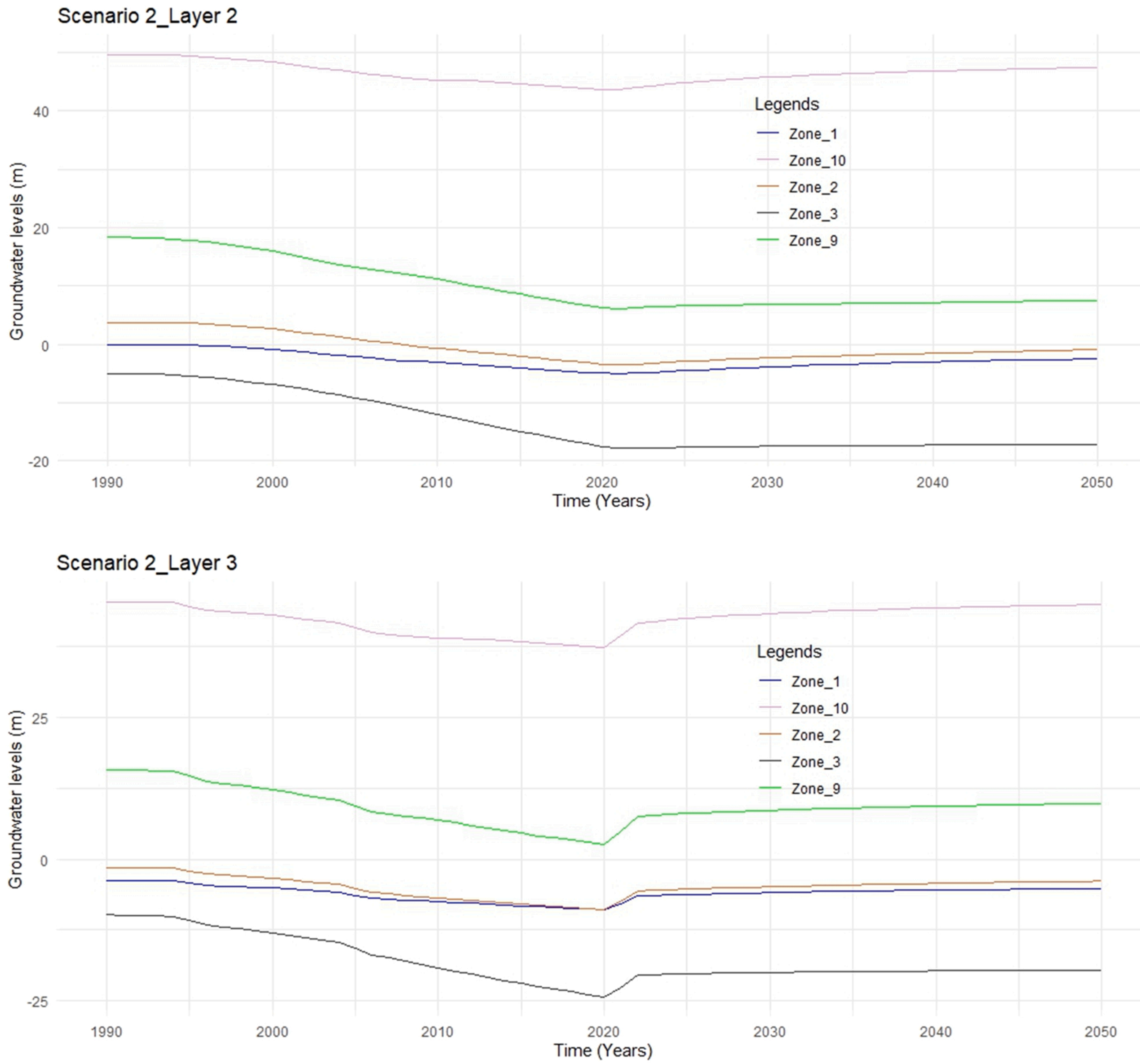

Fig. 26. Groundwater level time series for key zones in layers 2 and 3 from Scenario 2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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