Modelling Small-scale Storage Interventions at the Basin Scale

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Key Points:

- In this study, the farm bunds do not have any measurable effect on the streamflow but however the farm bunds increase the groundwater level.
- The cumulative effects of the interventions on streamflow are less than the individual effects of tanks and check dams due to model conceptualisation.
- Effects of interventions on streamflow varies between catchments of varying geology and flow regimes.

Abstract

Recently, there has been renewed interest in the performance and functionality of traditional small-scale storage interventions (check dams, farm bunds and tanks) used across India for the improvement of local water security. The Central Groundwater Board of India is encouraging the construction of such interventions for the alleviation of water scarcity. It is of critical importance to understand the hydrological effect of these interventions at basin scales to maximise their effectiveness. The quantification of small-scale interventions in hydrological modelling is often neglected, especially in large-scale modelling exercises. A bespoke version of the GWAVA model was developed to assess the impact of interventions on the water balance of the Cauvery Basin and two smaller sub-catchments. Model results demonstrate that farm bunds appear to have a negligible effect on the estimated average annual streamflow at the outlets of the two sub-catchments and the basin whereas tanks and check dams have a more significant effect. Interventions generally were found to increase evaporation losses across the catchment. The model adaption used in this study provides a step-change in the conceptualisation and quantification of the consequences of small-scale storage interventions in large- or basin-scale hydrological models.

1. Introduction

Water resources management is becoming increasingly challenging (Cleaver, 2017) with rapid population growth (Loucks, 2017), a changing climate (Wang, et al., 2016) and increasing competition over limited natural resources (Smith, 2018). For centuries, local communities and municipalities have altered the landscape and built informal structures to increase local water security. In semi-arid regions of the world, people have relied on large-scale infrastructures, such as dams and water transfer schemes, and small-scale infrastructures, such as check dams, farm bunds and tanks, to provide and store water for urban and rural use.

In India, the shortfall in renewable water resources to meet the increasing demand has resulted in aggressive abstraction of the deep groundwater stores and the construction of small surface-water storage structures (Ramaswamy, 2007). The Government of India and State governments have actively encouraged the construction of interventions, such as check dams, farm bunds and tanks, as the primary policy response for alleviating water scarcity (Goyal & Sivanappan, 2017). There are now millions of such structures across India (Agoramoorthy & Hsu, 2008) and, recently, there has been renewed interest in their effectiveness for improving local water security. It is of critical importance to understand the hydrological effect of these interventions at the local- and basin-scale to inform sustainable water resource management.

Interventions are generally constructed, within rural and urban settings, to assist in the replenishment and maintenance of local groundwater resources (Renganayaki, S.P. and Elango, L., 2013). The most prolific types of interventions in Southern India are check dams, farm bunds and tanks (Shah, 2008). There is limited knowledge of the hydrological dynamics and performance of interventions (Van Meter, et al., 2015) and little research has been undertaken to quantify the hydrological effects of interventions at a basin-scale (Xu, et al., 2013). Some studies have modelled the local impact of interventions on streamflow with different perspectives, including: the impact on the water balance (Van Meter, et al., 2015); as a possible use to treat wastewater (Vidya, et al., 2015); and the impact on river flows in headwater catchments (Garg, et al., 2012; Penny, et al., 2018). Additionally, many studies have focussed on the effects of interventions on sediment transport and local groundwater level (Doolittle, 1985; Armanini, et al., 1991; Boix-Fayos, et al., 2007; Boix-Fayos, et al., 2008; Mishra, et al., 2007; Renganayaki & Elango, 2013; Polyakov, et al., 2014; Dashora, et al., 2018; Wei, et al., 2017; Díaz-Gutiérrez, et al., 2019) The upscaling of small-scale storage interventions is of high interest because it is becoming increasing popular for water resource management and planning approaches to focus on the basin as an entity (Krois & Schulte, 2013). A basin-wide approach is important in semi-arid regions and particularly important in closed and closing basins, where water is a scarce commodity and upstream interventions directly affects downstream water availability (Krois & Schulte, 2013).

There are concerns regarding the effects and functionality of interventions in Peninsular India. The underlying fissured hard-rock geology of Peninsular India differs from the alluvial deposits Northern India, where most previous studies have been undertaken. Fissured hard-rock has a medium to low permeability and contain aquifers with modest water resources compared to porous, karst and volcanic aquifers. The Cauvery Basin was chosen to be representative of many other basins in Peninsular India. These basins are under pressures of urbanisation, population growth and agriculture intensification. The Cauvery is additionally a contentious river with concern over sharing of water between Karnataka and Tamil Nadu (Salman, 2002). With water resources in the Cauvery Basin under severe stress and the abundance of small-scale interventions, it is important to understand the effect of interventions on the spatial and temporal hydrological patterns (Xu, et al., 2013). There are constraints and uncertainty identified in the current modelling of interventions at the basin scale:

- The hydrological functioning of each type of intervention is uncertain.
- Proxy values and parameter adjustments have been utilised in an attempt to quantify the functioning of interventions.
- Data on the location and characteristics of interventions are scarce, and not well documented when available.

The impacts of such changes and interventions on local hydrological processes, such as streamflow, groundwater recharge and evapotranspiration, are poorly understood, and knowledge of how these diverse local changes cumulatively affect water availability at the broader basin-scale is very limited.

Over recent decades, the hydrological functioning of the Cauvery Basin has been altered by drivers including urbanisation, land use change, increased groundwater use, and the proliferation of small-scale surface water storage interventions (Sreelash, et al., 2020). The Cauvery Basin is predominantly situated in the federal states of Karnataka and Tamil Nadu, although it crosses into Kerala and Puducherry (Sharma, et al., 2020). The basin is highly water-stressed (Hoekstra, et al., 2012) and the current water use exceeds the renewable water resources within the basin (Moore, 2018). All the water resources, associated with a “normal” rainfall year, are currently allocated by tribunal (Salman, 2002) and surface water flows only reach the Bay of Bengal in years of strong monsoons (Falkenmark & Molden, 2008). The agricultural activities across the basin require 90% of the total water resources (Bhave, et al., 2018). However, rapidly developing urban and industrial centres are creating increased inter-sectorial and inter-state competition for limited renewable resources (Jamwal, et al., 2014). The four states have different water policies, traditional water harvesting techniques, water use prioritisation and value associated with the natural environment. A common technique throughout the four states is the use of small-scale storage structures to assist in the alleviation of local water stress in non-monsoon periods (Kumar, et al., 2006).

Several hydrological modelling exercises have already been carried out in the Cauvery Basin or sub-catchments thereof. Remote sensing methods (Patel & Ramachandran, 2015), an ANN model (Patel & Ramachandran, 2015) and the SWAT model (Kumar & Nandagiri, 2015) have been utilised in various sub-catchments of the Cauvery. At a basin scale, SWAT (Gosain, et al., 2006; Singh & Gosain, 2011; Bhuvaneswari, et al., 2013; Mandal, et al., 2016), SCS-CN (Geetha, et al., 2008; Parvez & Inayathulla, 2019) and VIC-MHM (Raje, et al., 2014) have been used to simulate streamflow. However, none of these previous studies are understood to have considered the inclusion of small-scale interventions.

The Global Water Availability Assessment Tool (GWAVA) is a large-scale gridded water resources model developed by the UK Centre for Ecology & Hydrology (Meigh, et al., 1999). The model incorporates natural processes (soils, land use, lakes, etc) and anthropogenic influences (crops, domestic and industrial demands, reservoir operations, transfers, etc). The model estimates surface flows and recharge using a conceptual rainfall-runoff model, utilising effective precipitation and evaporation estimates, followed by a demand driven routine to account for the anthropogenic stresses on the system. The GWAVA model is highly adaptable to the data availability of the region and allows for additional processes and features to be represented (Meigh, et al., 1999). The use of the GWAVA model in the Cauvery Basin provides the opportunity to investigate the effect of interventions on basin scale hydrology by introducing check dams, farm bunds and tanks into the model structure.

To investigate the effect of the interventions on the hydrology of the Cauvery Basin, a bespoke version of the GWAVA model (GWAVA-GW) was developed. In GWAVA-GW, the groundwater module was modified to better capture groundwater levels. The interventions were conceptualised within the model structure using local knowledge, observed data and adaptations of existing reservoir representations. The effect of interventions on the hydrological regime and water balance of the entire Cauvery Basin were studied, as well as a more in-depth analysis of two relatively small sub-catchments contained within the basin.

2. Materials and Methods

The GWAVA model was used to understand the hydrological functioning and impacts of interventions on the water balance of the Cauvery Basin.

2.1 Site Description

The Cauvery River basin is the fourth-largest basin in Peninsular India: it drains an area of 81 155 km^2 (Jain, et al., 2007). The Cauvery originates in the Western Ghats at Talakaveri in the Kodagu district of Karnataka and the head waters of the basin form in the Nilgiri and Anaimalai mountains. The main river channel flows south-easterly through the states of Karnataka and Tamil Nadu to outflow at the Bay of Bengal (Chidambaram, et al., 2018).

The Cauvery Basin is subjected to a large degree of heterogeneity not only in topography and land use but also in climate and economic development (Madhusoodhanan, et al., 2016). The landscape is semi-arid with the majority of the basin's water coming from the south-western monsoon in the summer months. The basin experiences distinct intra-annual seasons namely, South-Western (SW) monsoon in AMJ, the North-Eastern (NE) monsoon in OND and post-monsoon conditions from JFM. The upper catchment receives rainfall from both the SW and NE monsoons, whereas the lower catchment only receives rainfall from the NE monsoon. The mean annual rainfall varies from 6000 mm in the upper reaches to 300 mm on the eastern boundary (Meunier, et al., 2015). The mean daily temperatures vary between 9°C and 25°C throughout the catchment (Sreelash, et al., 2020). The Western Ghats form a rain-shadow along the western coastline decreasing the precipitation gradient during the SW monsoon (Gunnell, 1997).

The basin is highly anthropogenically influenced. The land use of the basin comprises of 48% agriculture, 22% non-arable land, 19% forest and 9% urban (Sreelash, et al., 2020). Natural forests are under great stress due to increasing demand for the forest products and competition over land use. Across the basin, approximately 60% of the total population rely on agriculture (Sreelash, et al., 2020). The most common crops grown in the catchment are sugarcane, finger millet, sorghum, groundnut and paddy (rice). Paddy and sugarcane are found predominantly in the canal command areas and delta regions and have high dependence on the Cauvery flow. The urban areas within the basin have expanded by over 35% over the last decade, and, are expected to continue to increase with the expanse of industry (Lannerstad, 2008). Currently, there are over a hundred impounding reservoirs and approximately twenty major water transfer schemes within the basin (Water Resource Information System- India). There are millions of small-scale interventions throughout the rural and urban regions of the basin.

Model-simulated streamflow, total evaporation, water table level and baseflow were investigated at two sub-catchment outlets and the basin outlet (Figure 1) to determine the effects of the interventions on the availability of streamflow and the catchment water balance. The two sub-catchments were selected based on similar density of interventions but differing underlying geology. The baseflow component (groundwater flowing into the river channel from the aquifer) between the two sub-catchments differed. (Table 1). One sub-catchment is located in Karnataka and the other in Tamil Nadu (Figure 1).

[Table 1 here]

[Figure 1 here]

2.2 Model Application

For this application of the GWAVA model in the Cauvery Basin, a grid cell resolution of 0.125° was chosen based on data availability for the region. Hargreaves and Samani (1985) equation was utilised in the estimation of potential evaporation as the temperature data required were available and the method is recommended by (Panchal, et al., 2016) for use in Southern India. Initially, the model was calibrated and validated with all the demands, interventions and the improved groundwater module included. However, to determine the explicit effects of the interventions on the hydrological functioning and the water balance, the model was subsequently run without the inclusion of anthropogenic demands. Five scenarios were considered to analyse the effects of the interventions (Table 2).

[Table 2 here]

2.3 Conceptualisation of Interventions

The typical characteristics and functioning of each small-scale structure were determined to conceptually represent them in the GWAVA model. Due to the abundance of these small structures throughout the basin, the lack of spatially explicit data and the grid resolution of GWAVA, it was deemed impossible to simulate the effect of each single structure. Instead, each type of intervention was aggregated for every 0.125° cell to form a single composite tank, check dam and farm bund within the cell. For this aggregation to be possible, the surface area of each intervention in a cell was required to estimate the total storage capacity for each type of intervention in that cell .The check dams utilised trapezoidal scaling whilst the tanks and farm bunds utilised cuboidal scaling to determine the storage capacity.

As a result of the structures, the increased open water surface area increases evaporation losses within a grid cell. A constant open water evaporation (OWE) factor was applied to all the interventions. The monthly average OWE was estimated from the evaporation-control-in-reservoirs documentation (Central Water Commission, 1987).

2.3.1 Urban and Rural Tanks

Tanks are small-medium (<34 ha) decentralised means of harvesting runoff, particularly during the monsoon season (Gunnell & Krishnamurthy, 2003). These typically are constructed using a shallow dam across a river channel and are unlined (Penny, et al., 2018). Tanks provide small-scale storage of rainfall and streamflow, control flood waters and increase recharge to groundwater in the immediate area (Bhattacharya, 2010). Rural tank storage is seasonal (Gowda, et al., 2014) and in many semi-arid regions, tanks provide the only means to store rainwater and streamflow for irrigation (Anbumozhi, et al., 2001). Urban tanks are fundamental to city drainage systems (Penny, et al., 2018) used for the collection and recycling of wastewater.

For their conceptualisation within GWAVA, both urban and rural tanks were assumed to have an inflow component comprising of daily rainfall, wastewater and streamflow within the cell, with spill contributing to the outflow (Figure 2a). Furthermore, these tanks generally are unlined in order to help groundwater recharge locally. Thus, a leakage rate of 13 mm d-1 (Dashora, et al., 2019) and 6 mm d-1 (Lal & Stewart, 2012) was added for the rural and urban tanks respectively. The recharge from tanks is relatively low as these structures tend to be highly silted and infiltration is limited through the fine particles lining the bottom. The recharge from rural tanks was higher than from urban tanks under the assumption that tanks in rural areas were constructed more recently and, if they are dredged, they are dredged more regularly. In the absence of detailed tank bathymetry data, it was assumed that all tanks are cuboid in shape with a maximum depth of 3 m deep at full capacity, based on work in Eastern India (Pant & Verma, 2010).

2.3.2 Check Dams

Check dams are small water conservation structures (<0.5 ha) built across a stream using concrete, sandbags or logs (Dashora, et al., 2018). These are designed to reduce the velocity of streamflow through the catchment and to retain the floodwaters (monsoonal rainfall in the case of India) (Xu, et al., 2013). The process of impounding water at a local scale is thought to increase the groundwater recharge and soil water potential in the adjoining areas (Adhikari, et al., 2015).

For the model representation of check dams, it was assumed that daily rainfall, local runoff and streamflow of the cell contribute to the inflow (Figure 2b). The leakage from the bottom of the structure is assumed to be 100 mm d-1 across all the check dams in the catchment (Wable, et al., 2019). The outflows of the check dams comprise of spill. For the purpose of this study and to simplify data collection of thousands of structures, all check dams in the basin are assumed to have the same dimensions and, thus, capacity. The depth is assumed to be 1.5 m (Dashora, et al., 2019), the top width of the structure equal to 10 m and the channel slope to be 1%. In the absence of data quantifying the number and spatial repartition of check dams in the Cauvery Basin, a surrogate methodology to estimate these alongside with their storage capacity was established. Based on discussions with stakeholders and cited literature (Heede, 1966; Agoramoorthy & Hsu, 2008; Djuma, et al., 2017), it was assumed that an average check dam in the Cauvery Basin is a 3D trapezoid with a profile that is 10 m in width at a distance of 70 m upstream of the structure.

Thus the surface area of a check dam was assumed to be fixed at 350 m2 for every check dams included in the model. The assumed average surface area was used solely in the determination of the total surface area of check dams within a grid cell: the number of check dams (See Section 2.2.2) within a cell was multiplied by 350 m2 to determine the surface area of check dams in each cell. Within the model conceptualisation, the length of the conceptual aggregated check dam was dependent on the surface area. The width and depth remained at 10 m and 1.5 m, but the length was variable.

2.3.3 Farm Bunds

Farm bunding is a traditional in-situ method for soil and water conservation (Pathak, et al., 2011). Bunds are small barriers at the footslope of agricultural fields, constructed of soil or stone, to increase the time of concentration of precipitation, where it falls, allowing rainwater to percolate into the soil (Hudson, 1987). Bunds are constructed to retard the movement of overland flow and encourage infiltration within the field (Alexandrov, et al., 2007).
Farm bunds are assumed to be filled from daily rainfall and local runoff within the cell. The saturated hydraulic conductivity of the soils (Allen, et al., 2010) in the basin and the high diurnal temperatures resulted in the water within the farm bunds to infiltrate or evaporate completely within a day. The open water evaporation constant was applied to the surface area of the bunds whilst the infiltration rate differed with regards to soil type. To simulate groundwater recharge from these structures, a rate relative to the saturated hydraulic conductivity of the soil (Allen, et al., 2010) of the area is selected. Once the water held in the bund is equal to full capacity, excess water can flow over the structure and into the stream. It was assumed that all bunds are a maximum of 0.3 m deep (Critchley & Graham, 1991; Verma & Singh, 2017) (Figure 2c). The surface area of the farm bunds area derived in Section 2.2.2.

[Figure 2 here]

2.4 Data Acquisition

Input data were collected from several sources and extracted from global and regional datasets (Table A1 in Appendix A). Data regarding the number and distribution of interventions in the Cauvery Basin are sparse. Extrapolation and estimation methods described in this section were used to provide the necessary surface area data for input into GWAVA.

The surface area of the rural and urban tanks were estimated by isolating the ‘tanks’ from the Cauvery Water Bodies dataset (Figure 3). This dataset consists of a shapefile containing all the medium to large waterbodies (rivers, lakes, reservoirs, tanks, wetlands, etc), in the Cauvery Basin in 2019, derived using remote sensing techniques. The urban tanks were identified as tanks that fell within urban centre boundaries (supplied by the Indian Decadal Census 2011). The tanks outside of these boundaries were assumed to be rural. Check dams and field bunds are too small to be detected by this methodology.

[Figure 3 here]

Data for the farm bunds and check dams (Table 3) were derived from district-wise Structural Investment Report available for Karnataka from 2006 to 2012 (Figure 4 and Figure 5). For each district in Karnataka, the area covered by farm bunds and the number of check dams was calculated from this financial data by dividing the total expenditure for each type of intervention by the expenditure per hectare of bunding and of a check dam.

In the absence of data for the state of Tamil Nadu, the data from Karnataka were extrapolated. Plausible relationships between the number of check dams and the area of bunding with soil type, rainfall, slope, population, land type, irrigation type and geology in a district were all investigated. None of these yielded any significance. Meaningful relationships, however, were drawn between the number of check dams and the stream density and the area of bunding and the area of rainfed agriculture. These are described below.

Within the districts of Karnataka, a relationship was drawn between the area of farm bunds and the area of rainfed cropland within each district (r^2= 0.91, Figure 4). It was assumed that this relationship holds true into the districts of Tamil Nadu because there are no data or evidence to invalidate this assumption.

The regression (Eq1) was utilised to estimate the area of farm bunds within each district of Tamil Nadu:

$$\boldsymbol{A_b = 3.87A_c - 212.44} \qquad \text{Eq1}$$

where A_b is the area covered by bunding (m^2) and A_c is the area of rainfed cropland (m^2).

[Figure 4 here]

Additionally, a relationship was drawn between the log function of the stream density of each district in Karnataka and the number of check dams (r^2= 0.93, Figure 5). The stream density is characterised by Eq2 (Gnanaprakkasam & Ganapathy, 2019).

$$\boldsymbol{Stream\ Density\ (SD) = \sum \frac{Length\ of\ streams\ of\ all\ orders}{Area\ of\ district}} \qquad \text{Eq2}$$

As with the farm bunds, it is assumed that this relationship holds true into the districts of Tamil Nadu.

A regression function (Eq3) was used to estimate the number of check dams within each district in Tamil Nadu:

$$\boldsymbol{Log\ (SD) = 0.0017N_{cd} - 4.33} \qquad \text{Eq3}$$

where SD is the stream density and Ncd is the number of check dams.

[Figure 5 here]

The district-wise data was applied to the modelling grid using a weighing function of the grid-wise stream density (Figure 6a) and crop area respectively (Figure 6b). Across the catchment, the surface area of the interventions within each grid cell ranged between 0.02 and 53 km^2.

[Figure 6 here]

3. Results

3.1 Model Performance

The model was automatically calibrated for 14 sub-catchments using daily streamflow data downloaded from India Water Resources Information System (India- WRIS, Figure 1). The model performed well in the sub-catchments of the upper reaches but struggled to reliably simulate the flows downstream of the Mettur Dam (Figure 1, Figure 8 and Figure 9). Across the basin, the model underestimates the total volume of streamflow (Table A1 in Appendix A). As suggested in the work by (Wable, et al., 2019), the gridded precipitation data (Pai , et al., 2014) produced by the Indian Meteorological department (IMD) is underestimating the point measured rainfall in the region across the Western Ghats by an excess of 50%. This could be the fundamental explanation for the consistent underestimation of streamflow by GWAVA. Within the model, the reservoir outflow parameters were adjusted within the full range of possible values and combinations to provide the best possible fit to the daily observed outflow data. The temporal signal of the Mettur Dam outflow is noticeable through all the downstream gauges (Urachikottai and Kodumodi) to the catchment outlet (Musiri). Figure 7a illustrates the ability of the model to capture the temporal trend of the streamflow upstream of Mettur. However, the model was unable to capture the intra- and inter-annual reservoir operations from the Mettur Dam, and thus could not fully represent the timing of the observed streamflow at Urachikottai downstream of the dam (Figure 7b). However, the estimated annual release volume was still within 3% of the annual observed values (Table 5 in Appendix A).

[Figure 7 here]

The inclusion of the interventions improves the model performance (Nash-Sutcliffe Efficiency) in all the sub-catchments across the calibration period (Figure 8) and improves the model performance in nine of the sub-catchment across the validation (Table A1 in Appendix A). The poor validation results highlight that the better fitting calibration results could have been obtained for the wrong reasons and the model is not capturing the catchment processes correctly. Additionally, the automatic calibration and conceptual nature of the model could have led to the existing model parameterisation indirectly taking into account processes that are not included in the model structure. Following calibration and validation of the model, streamflow, quick overland flow, sub-surface flow (water flowing to the stream through the soil profile), baseflow (water flowing to the stream from the aquifer), groundwater levels, reservoir storage levels at Mettur Dam and evaporation for five scenarios (Table 2) were simulated.

[Figure 8 here]

3.2 Effect of Interventions

In this section, all observations are drawn from model simulations (i.e. simulated streamflow, baseflow, evaporation and groundwater level). The effect of interventions on streamflow across the modelling period (1986-2005) were evaluated using the mean flow ($\bar{Q}$), the flow exceeded 90% of the time (Q90, quantification of low flows) and the flow exceeded 10% of the time (Q10, representation of high flows). Additionally, the effects of the interventions on the simulated streamflow and evaporation, in a wet (2005), normal year (1998) and dry (2002) year at the catchment outlet of S1 and S2 and the basin outlet, were investigated. These years were chosen by considering the lowest, highest and mean total annual precipitation across the catchments (Table 3)

[Table 3 here]

In the Granite type geology catchment (S1, Table 1 and Figure 1), the stream is non-perennial and the surface flow is the dominant component of streamflow (Figure 10). The streamflow (Q10, $\bar{Q}$ and Q90) is reduced with the inclusion of interventions. However, it is the high flows, Q10, that are more significantly reduced (Figure 9). The interventions have a greater impact on the streamflow in S1 than S2. The streamflow is reduced to the largest extent in the normal year (~10%, Figure 9a). The stormflow is intercepted by the intervention and, thus, reduces the streamflow in the wet season (Q10, Figure 9b). The dry season flows (Q90, Figure 9b) are reduced as any subsurface lateral flow (from the soil store) entering the stream is impounded by the intervention. The stormflow component is larger than the subsurface lateral flow and baseflow components in this catchment and, thus, the streamflow is affected to a greater extent in the wet season. The non-perennial streams dry out earlier with the inclusions of interventions (Figure 11). The total evaporation across the sub-catchment is increased with the inclusion of interventions with the greatest increase occurring in the wet year (Figure 9a) as water is present in the interventions for a greater length of time. In this catchment, the water table is increased in the wet season with the inclusion of interventions (Figure 12). Despite the increase in simulated recharge, the water table does not reach a level where the water in the groundwater will contribute to simulated baseflow.

In the Mignatite type geology catchment (S2, Table 1 and Figure 1), the stream is perennial, and the stormflow is dominant in the wet season but the subsurface flow and baseflow is dominant in the dry season (Figure 10). The streamflow (Q10, $\bar{Q}$ and Q90) is reduced, and the Q90 is more significantly reduced with the inclusion of all interventions (Figure 9b). The interventions have a similar effect on streamflow in the dry and wet years (~5%, Figure 9a). In the wet season, the streamflow is reduced due to the in-situ impoundment and the low flows are maintained but reduced in the dry season. In the dry season, streamflow is reduced because the baseflow and any subsurface lateral flow (from the soil store) entering the stream are impounded by the intervention. The impounded water is subject to both evaporation and recharge. The total evaporation across the sub-catchment is increased with the inclusion of interventions with the greatest increase occurring in the wet and normal years (Figure 9a) as there is water in the interventions for a greater length of time. In this catchment, the groundwater level is minimally affected by the inclusion of the interventions (Figure 12). The water table is above the level at which the groundwater will flow as baseflow. Baseflow will continue to occur but streamflow will be reduced in the dry season as any streamflow produced by the baseflow above the intervention will be impounded.

At the basin outlet, the streamflow is dominated by the Mettur Dam releases (O, Figure 1). The interventions do not have an effect on the simulated Mettur Dam release flows. The minimal reduction in mean streamflow (~3%) seen at the outlet can be considered as the consequence of the interventions in the tributaries that join the main Cauvery channel downstream of Mettur Dam. However, on analysis of the effect of interventions on the inflow into Mettur Dam, it was found that the interventions reduced the mean streamflow ($\bar{Q}$) by ~6% and the streamflow in the wet season (Q10) was reduced by ~26%. This demonstrates that the large reservoir has the ability to nullify the impact of the interventions, however, their effect can be seen in the reduction of streamflow entering the reservoir. In this unique case, the effect of the interventions on the Mettur Dam inflow is more representative of the effects of interventions at a basin- scale opposed to those shown at the basin outlet and corresponds more correctly with the increase in total evaporation across the basin with the inclusion of interventions of ~10% (Figure 9a).

Majority of the flow into the Cauvery Basin is contributed by five humid sub-catchments *(Arulbalaji, et al., 2019)* along the western boundary (Figure B1 in Appendix B), however, most of the interventions are constructed in semi- arid regions. The simulated Q90 flow in these humid catchments is affected more by the interventions than in the semi-arid sub-catchments on the eastern boundary (Figure B1 and Figure B2 in Appendix B). Conversely, there is a greater effect of the interventions on the simulated Q10 flow in the semi-arid sub-catchments (Figure B3 in Appendix B). The effect on the Q10 flows is greater in the semi-arid sub-catchments because the monsoonal streamflow is required to fill these structures before they begin to spill. In the humid catchments the interventions do not have a great effect on the Q10 flow as it is likely to be the presence of water within these structures before the monsoon and the intervention immediately spills. Although the percent change in Q10 flows in the semi-arid sub-catchments is higher, the volume of water impeded in these structures may be greater in the humid sub-catchments. The Q90 flow is impacted more severely in the humid catchments as these streams are fed during the dry season through baseflow, whereas in the semi-arid sub- catchments the streams frequently run dry with or without interventions. The implementation of interventions in these sub-catchments, stores water further up in the basin and essentially impedes the downstream flow and restricts water from entering the ocean unused. Although these structures allow available water to be utilised throughout the basin, there are subsequent implications for users and environmental flows downstream.

[Figure 9 here]

[Figure 10 here]

[Figure 11 here]

[Figure 12 here]

4. Discussion

The model calibration was good in the upper reaches of the basin, but the model fit was poor downstream of the Mettur Dam (Figure 1). The inclusion of interventions improves the model bias. It provides a better account of the surface storage within the basin and better estimation of the time of concentration in the sub-catchments without major reservoirs. The farm bunds were found to have little effect on the streamflow, as the high water demands of the rainfed crops cause the infiltrated water from the bunds to be transpired quickly and there to be little difference in the water is converted to baseflow or groundwater recharge with or without the bunds. Assuming the relationship between the area of bunds and the area of rainfed cropland determined for Karnataka holds into Tamil Nadu, the majority of the bunds were located within the lower regions of the basin where there is a greater area of rainfed cropland. It is difficult to distinguish the exact effects of the farm bunds in these regions as the river system is heavily dominated by the Mettur Dam outflows. Conceptually, the model fills the farm bunds followed by the tanks and then the check dams. In the simulations with all the interventions included, the bunds are filled first thus limiting the water available for filling the tanks and check dams. Although individually the bunds have little effect on the streamflow, when cumulatively simulated, with the tanks and check dams, the reduction in water available to fill tanks and check dams reflects in the lower impact on the streamflow. Individually, the tanks and check dams have a similar effect on the streamflow (Figure 9b).

A significant challenge, in large-scale hydrological modelling, is quantifying and managing the uncertainty in climate forcing and evaluation data. Uncertainty can arise from observation gauge density, spatial and temporal interpolation methods and general measurement errors. The Western Ghats region in the NE of the basin is a known area of concern with the IMD precipitation data (Pai , et al., 2014). Each 0.5-degree grid cell contains numerous terrain and gradient increments and the grid cells fall over the basin boundary. This results in an inaccurate representation of the distribution and total rainfall, as well as the distribution of minimum and maximum temperature, in this region of the basin. This is a significant source of uncertainty as this region acts as the headwaters for the larger Cauvery Basin. At some gauging points in the basin, there is low confidence in the observed streamflow data. Eye-witness accounts, (Srinivasan, et al., 2015) report the drying out of streams in the dry season which is not reflected in the observed data. Additionally, in reality rivers downstream of significant urban areas (Arkavathy downstream of Bangalore and Eluthunimangalam downstream of Coimbatore and Tiruppur) are fed by a perennial stream of sewage. The model does represent return flows from domestic demand, but this may be underestimated compared to the volume of effluent being actually released into these rivers. The analysis of the precipitation and the observed streamflow, used within this study, showed temporal discrepancies. The temporal difference between rainfall events and the hydrograph peak did not show a systematic error or a consistent lag time.

The scale of this study (0.125 degree) required the aggregation of the surface area of each type of intervention in each cell. The simplification in the conceptualisation of the interventions is a cause of uncertainty in this study. The aggregation of the interventions into one composite tank, check dam and farm bund within the cell, skews the surface area to capacity ratio. As intervention data were limited to surface area, if one calculates the intervention capacity from the combined surface area, the capacity is greater than calculating the capacity of each individual interventions and aggregating the capacity. This causes the holding capacity of the conceptual interventions in each cell to be greater than in reality. Subsequently, the larger conceptual intervention will not fill or spill as frequently as many smaller interventions and thus the estimation of the effect on streamflow of all the interventions is uncertain. Additionally, the evaporation could be underestimated as a larger waterbody requires increased energy for evaporation and has a larger lag time (due to heat storage) than a smaller one. This may also lead to the individual smaller interventions being subjected to more evaporative losses than these estimated in the model using the larger conceptual intervention. Conversely, the model structure allocates water to the evaporative component first, and thus, the evaporative processes are favoured in times of water stress. This could additionally be one of the fundamental reasons for the systematic underestimation of streamflow across the basin. The aggregation of the cascading tank systems into one large tank, and, numerous check dams into one large check dam results in the true effects of the cascading system not being represented within the model. Numerous tanks and check dams on a river network can cause the streamflow in the river, and the subsurface and baseflow emerging into the stream to be obstructed by the downstream check dams. Due to time constraints, various conceptualisations of the interventions could not be implemented into the model. Although, doubling the surface area and reducing the recharge from the interventions to 2 mm.day-1 did not reflect significantly in the simulated streamflow, this is not to say that varying the structural characteristics of the interventions would not have improved the results.

Due to lack of data, the process of quantifying the distribution of the interventions across the basin relies upon many assumptions and, thus, generates significant uncertainty. The accuracy of the Structural Investment Report is unknown and the assumption of a fixed cost per structure/ hectare across Karnataka is unlikely to be accurate. Similarly, assuming that the systems and behavioural patterns (agricultural practices, usage of infrastructure, etc) in the state of Karnataka and Tamil Nadu are identical is also unlikely. However, due to data scarcity and lack of evidence to validate these assumptions, a pragmatic approach was used to allow the inclusion of small-scale interventions in a large-scale hydrological model.

Despite the uncertainty and pilot nature of this study, the trends identified within the Cauvery Basin are in line with the findings from Garg et al. (2012). A number of parameters were altered (surface runoff, water holding capacity, available soil water, groundwater recharge and curve number) to reflect the potential influence of the check dams and farm bunds in the basin. The interventions have a slightly greater effect on the streamflow in wetter years. Additionally, in agreement with Garg et al. (2012), it was found that majority of the water balance comprised of the evaporation component and the evaporative losses increased with the inclusion of the interventions (Figure 9b). It was found that check dams reduced the annual streamflow at the basin outlet of the Kothapally catchment by 9%. This corresponds with the GWAVA simulation which estimated ~9% reduction in streamflow (Figure 9a) in

S1 of similar MAP, soil type and land use. In contrast, the groundwater recharge from the individual interventions was significant in the Garg et al. (2012) study.

There is also agreement between the results of S2 and the work of Xu et al. (2013) in which they concluded that check dams reduce the total runoff in the rainy season (15%, Figure 12). Xu et al. (2013) did not specifically include the characteristics of the interventions but rather attributed the difference between a period of observed and simulated streamflow as the effect of the interventions. The decrease in mean annual streamflow (14%) estimated by Xu et al. (2013) and attributed to the effect of check dams does correlate to the decrease in mean annual streamflow of S2 as a result of check dams (15%, Figure 9). Sub-catchment S2 has a similar MAP and type of vegetation as the catchment studied by Xu et al. (2013).

The decrease in simulated streamflow by GWAVA in S1 and S2 due to tanks was 4% and 5%, respectively. These results differed significantly from those of Van Meter et al. (2015) where the streamflow was found to decrease by 75% from a single cascading tank system in a catchment with an MAP of 850 mm in Tamil Nadu. GWAVA conceptualises the tank systems within a cell into one large hypothetical tank and thus does not capture the cascading characteristics of the tank systems. This, along with a large upscaling effort, could explain the difference in the observed streamflow reduction; alternatively, the tank system investigated by Van Meter et al. (2015) could be atypical.

GWAVA may not capture the sensitivity of hydrological fluxes at a local-scale as a well as a catchment-scale model would. However, yielding similar results to published small-scale studies provides a good starting point for further refinement of the conceptualisation within large-scale hydrological models.

5. Conclusion

The bespoke version of GWAVA provided a valuable tool to investigate the effects of interventions at a sub-catchment and basin scale. It was found that interventions play an important part in the allocation and better representation of surface water within the basin. The results of this study corresponded well with existing literature from small-scale studies. However, at the sub-catchment and basin scale, groundwater levels appear less effected than in the cited literature or indigenous knowledge surrounding the use of interventions for water security at a local scale, suggesting further investigation to explore this is required.

The effect of interventions is dependent on the hydrogeology of the sub-catchment as well as the groundwater level. The influence is greater on the streamflow in the wet years and on evaporation in the dry years. This study incorporated stakeholder and expert knowledge, as well as, published literature information in the conceptualisation of the interventions within the model. New and creative approaches had to be utilised where data gaps existed to model the effects of interventions at the basin scale. The approach outlined in this study can be applied in different model applications in regions where interventions are prominent, if the source code is available for adaption. Although this study had to rely on a pragmatic approach and as a consequence many assumptions were made, it provides a step forward in the conceptualisation, quantification and implication of small-scale storage interventions at the basin scale.

Data Availability Statement: Datasets utilised for this research are available in these in-text data citation references: Pai et al. (2014), Central Water Commission (1987), Wable, et al. (2019), Jpl (2013), Fischer et al. (2008), Roy et al. (2008) and Robinson et al. (2014). The archiving of data produced by this study is underway in the Environmental Information Data Centre (EIDC). The EIDC is a NERC Data Centre hosted by the UK Centre for Ecology & Hydrology (UKCEH).

Appendix A

[Table 4 here]

[Table 5 here]

[Figure 13 here]

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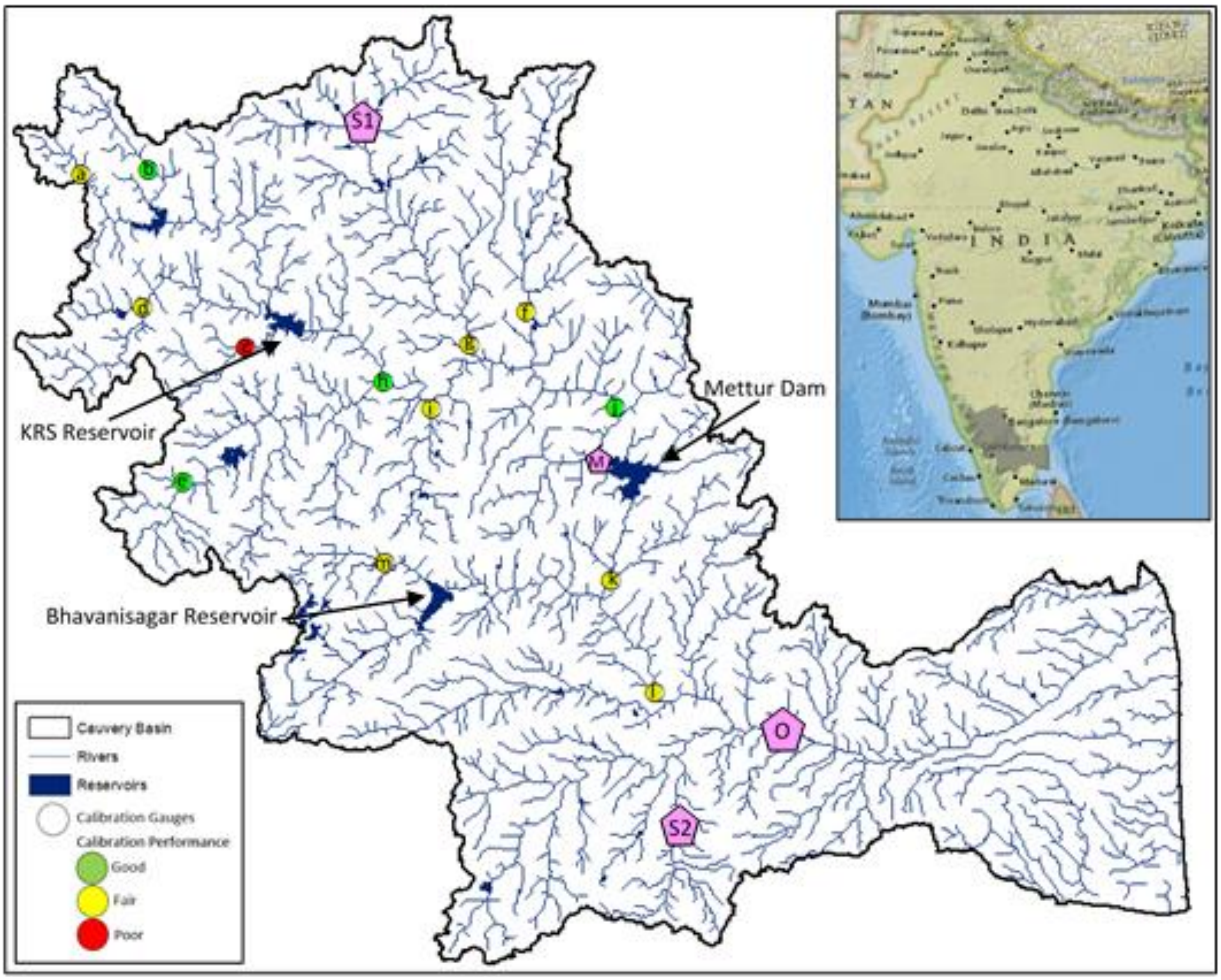


Figure 1. Inset: the location of the Cauvery Catchment within India; main map shows locations of the 14 calibration gauges (a- m and O) with the calibration performance (KGE), the outlets of the two selected sub-catchments (S1 and S2), inflow to Mettur Dam (M) and basin outlet (O) used in the quantification of the effects of interventions.

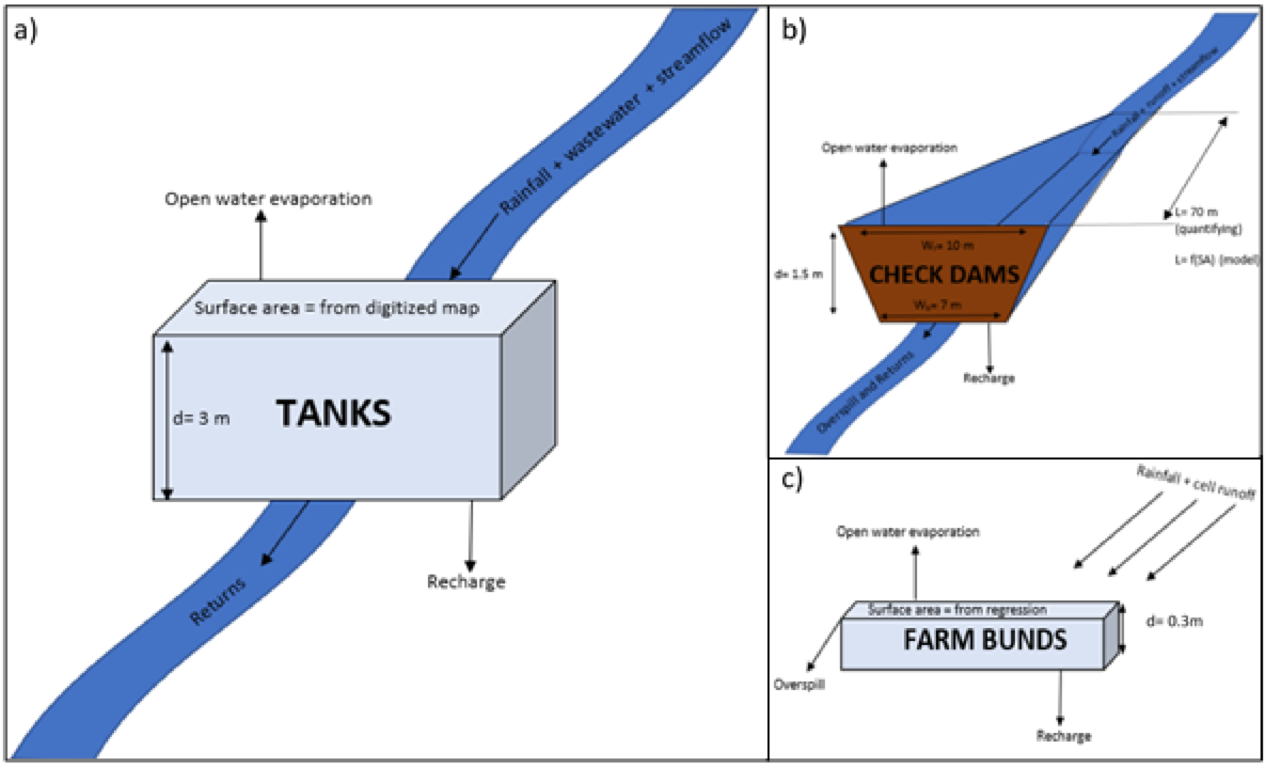


Figure 2. Conceptual diagram of **a)** tank, **b)** check dam and **c)** farm bund adopted in the GWAVA model.

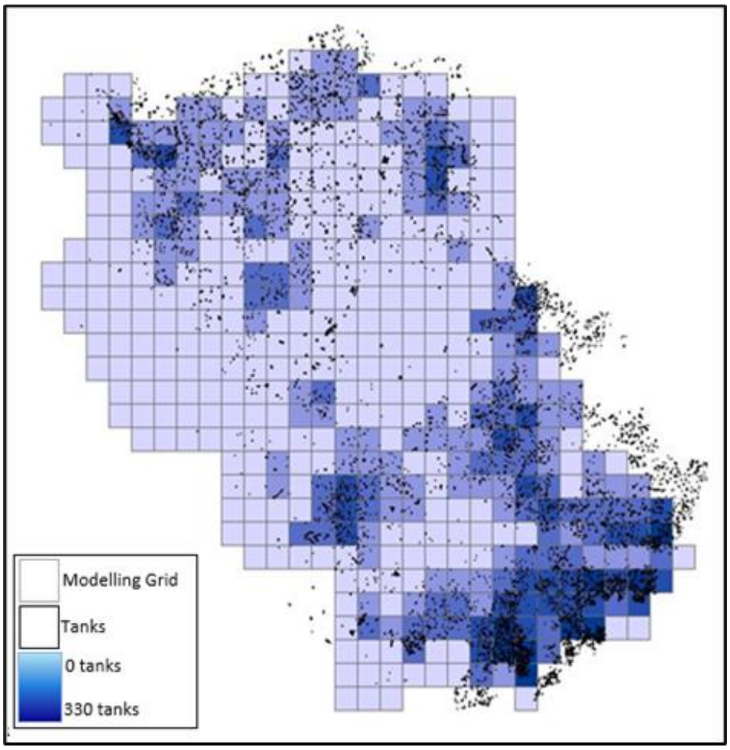


Figure 3. The distribution of tanks (Waterbodies dataset, 2019) in the Cauvery Basin and the quantity of tanks in the modelling grid.

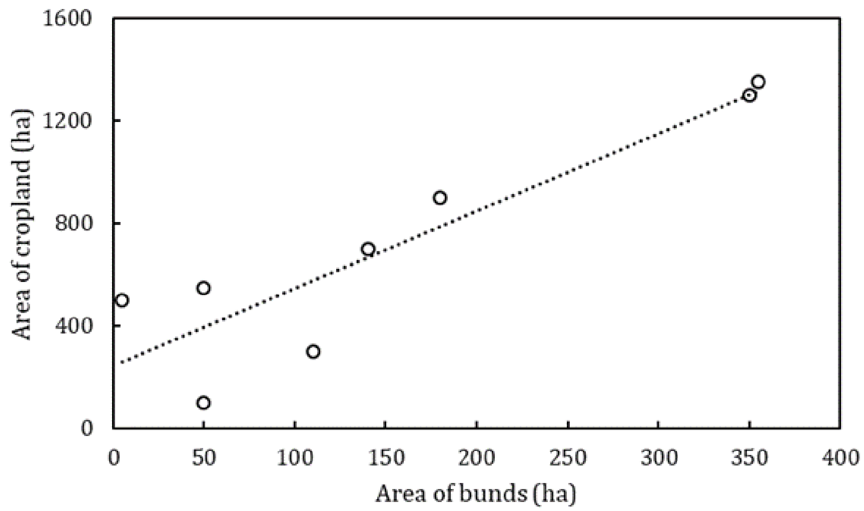


Figure 4. Graphical correlation between area of farm bunds (hectares) and area of cropland (hectares) in each district in Karnataka.

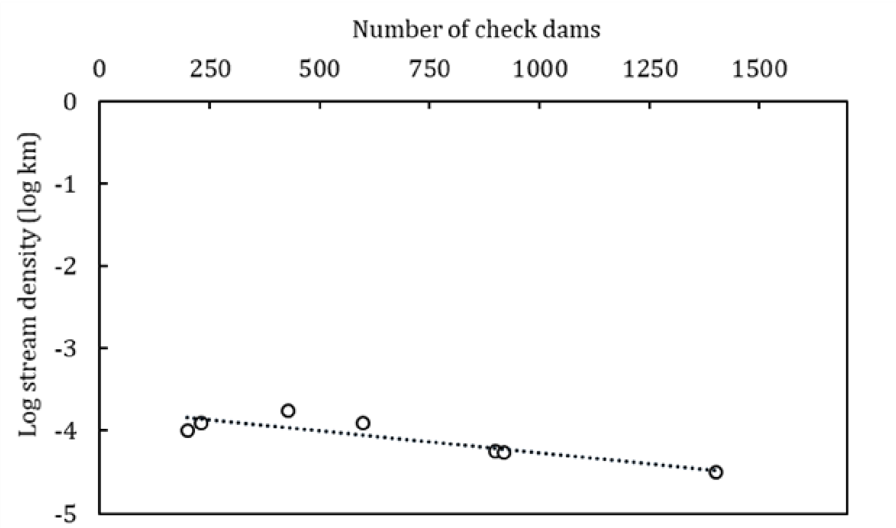


Figure 5. Graphical correlation between number of check dams and stream density in each district in Karnataka.

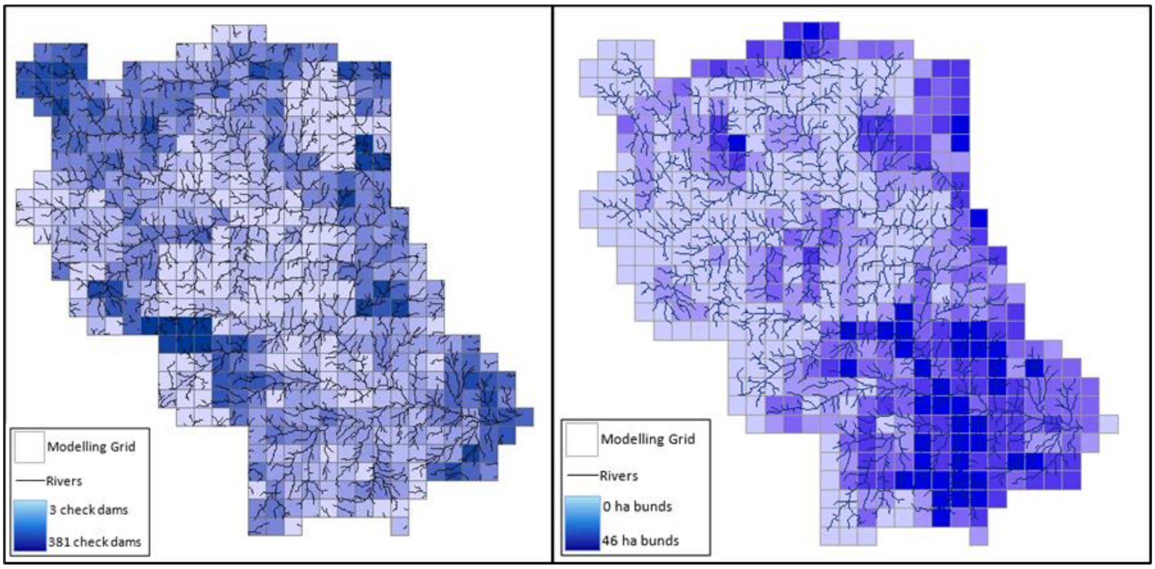


Figure 6. The distribution of **a)** check dams and **b)** farm bunds in the Cauvery Catchment**3.**

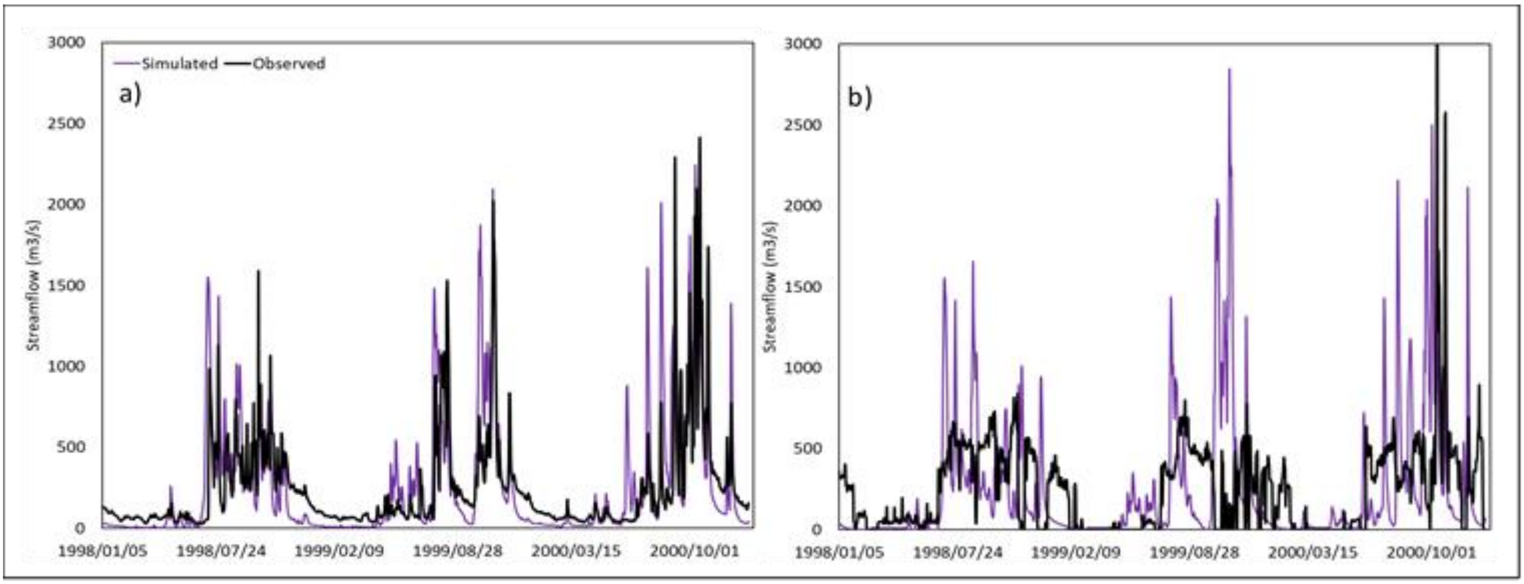


Figure 7. The model simulated and observed streamflow **a)** at Bilingudulu gauging station (Figure 1- j), upstream of the Mettur Dam and **b)** Urachikottai gauging station (Figure 1- k), downstream of the Mettur Dam

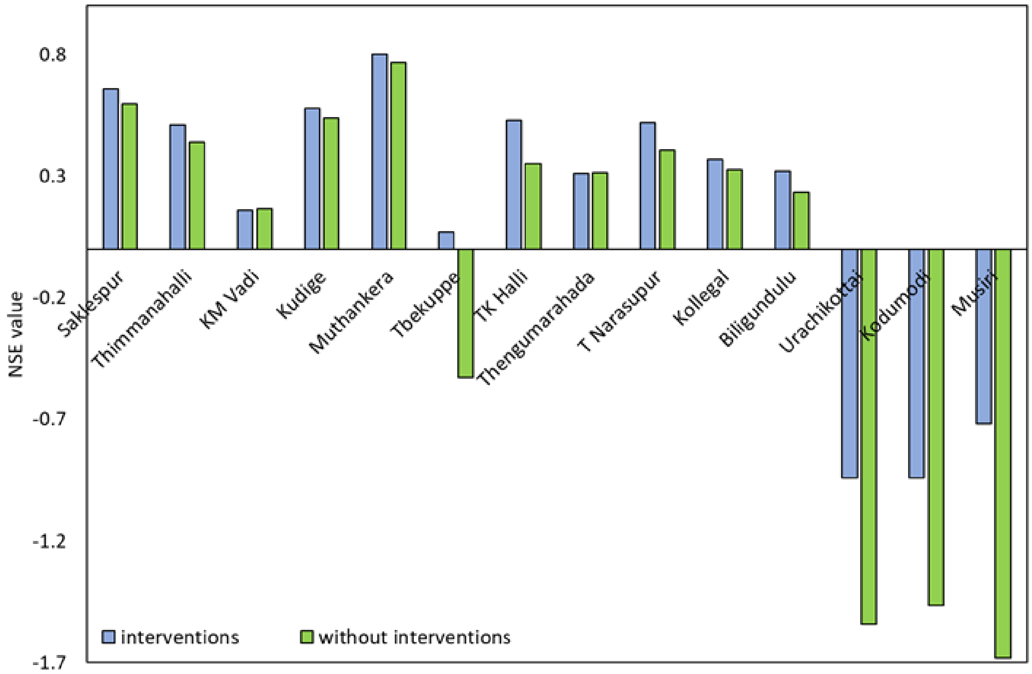


Figure 8. The NSE values obtained for each gauged sub-catchment across the calibration period.

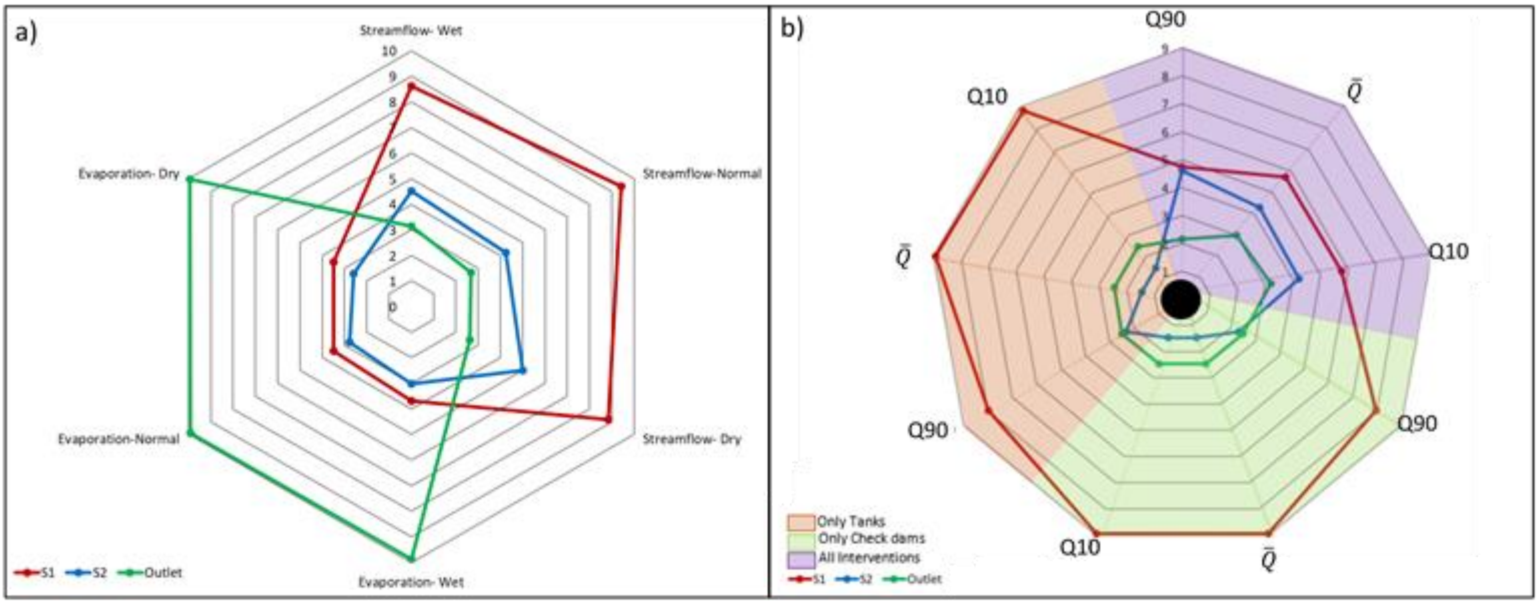
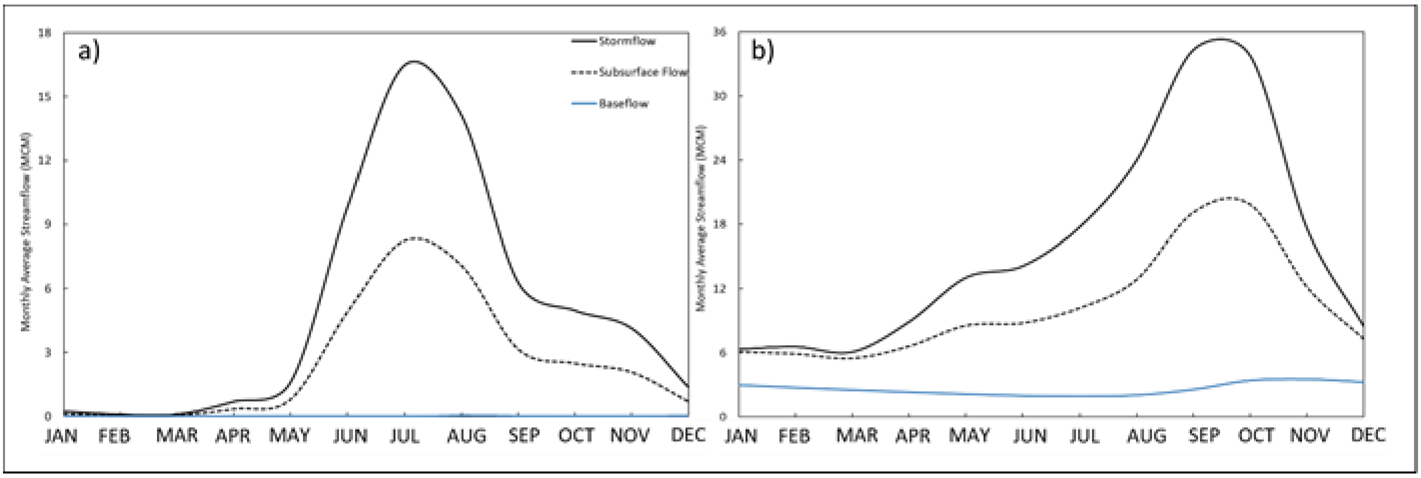


Figure 9. a) The percent reduction in total annual streamflow and increase in total annual evaporation (%) with the inclusion of interventions for S1, S2 and the basin outlet in wet (2005), normal (1998) and dry (2002) years. **b)** The effect of all the interventions (tanks, check dams and bunds), check dams only and tanks only on high flows (Q10), low flows (Q90) and mean flows ($\bar{Q}$) flows across S1, S2 and the basin outlet (Table 1, Figure 1).



899 **Figure 10.** The average monthly simulated separation hydrograph for **a)** S1 and **b)** S2 (Table
900 1 and Figure 1) from 1998 until 2000.

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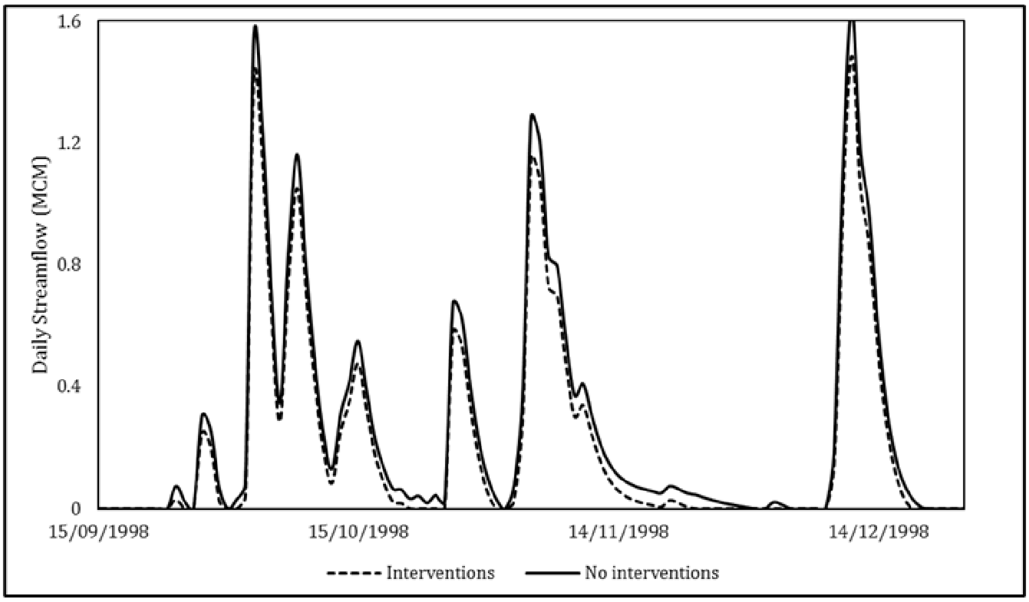

Figure 11. Simulated streamflow in sub-catchment S1 (Table1, Figure 1) with interventions and without interventions through the period of September 1998 until December 1998 (Normal year).

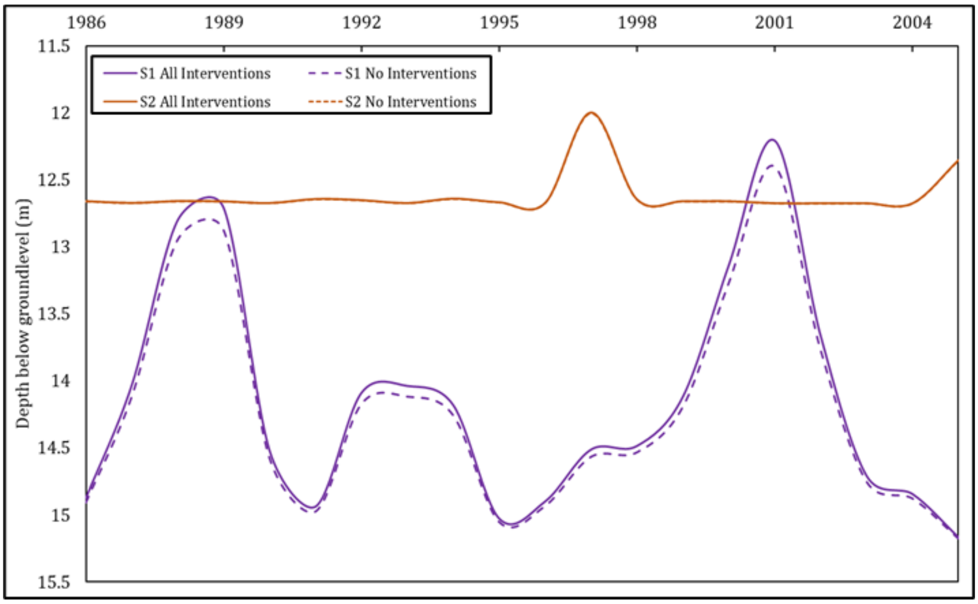

Figure 12. Monthly average groundwater level below ground surface for S1 and S2 (Table 1 and Figure 1) with and without the inclusion of interventions.

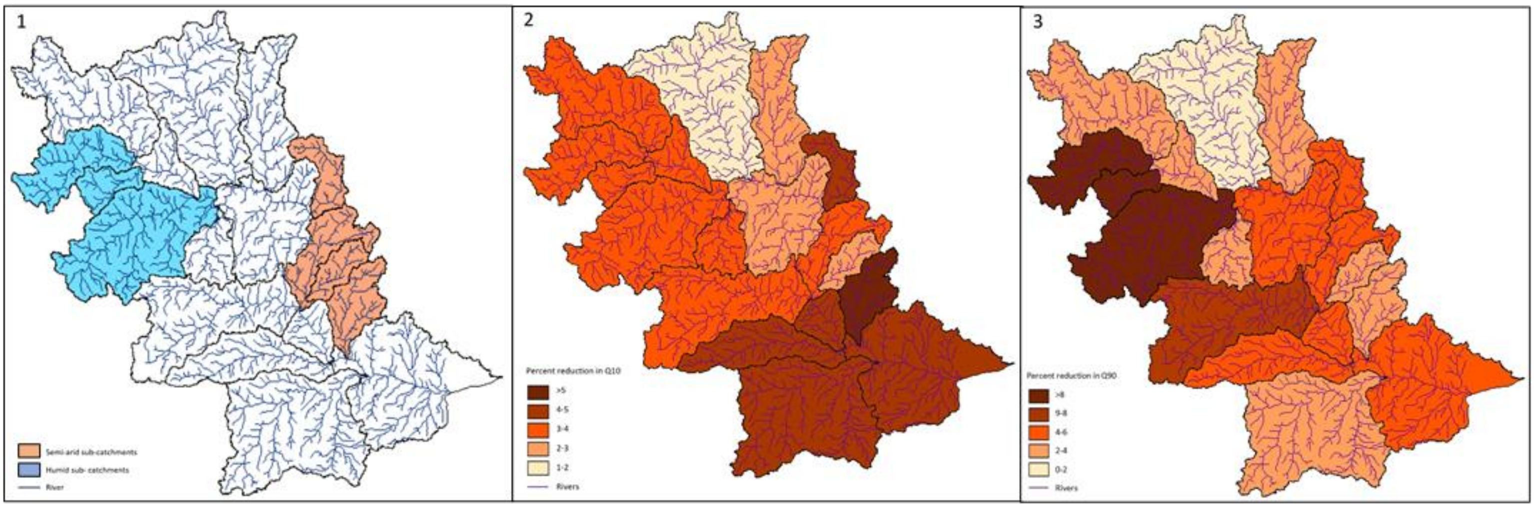

Figure 13 1) The sub-catchments identified as humid and semi-arid, **2)** the percentage reduction on Q10 flow and **3)** the percentage reduction on Q90 flow across the Cauvery Basin.

Table 1. The mean annual precipitation (MAP), catchment area (Area), the flow characteristics, the period of no streamflow in main channel (T_{noflow}-days of no streamflow) and underlying geology of two sub-catchments used in this study

Sub-catchment number	**MAP (mm)**	**Area (km^2)**	**Rainfall period**	**Flow characteristics**	**Period of no streamflow in main channel (per year)**	**Underlying geology**
S1	864	2660	March – January	Non- Perennial	30 days < T_{noflow} < 60 days	Granite
S2	867	3120	March- January	Perennial	0 days < T_{noflow} < 3 days	Mignatite [1]

Table 2. List of scenarios simulated by the GWAVA model.

Scenario	**Description**
1	All interventions included
2	No interventions included
3	Only tanks* included
4	Only check dams included
5	Only farm bunds included

*ancient, restored and new tanks in both urban and rural areas

Table 3. The total annual precipitation for the selected cucatchments S1, S2 (Figure 1) and the basin outlet (Figure 1) for wet, dry and normal year.

Sub- catchment	**Total Annual Precipitation (mm)**		
	Normal year (1998)	**Dry year (2002)**	**Wet year (2005)**
S1	507	382	668
S2	1874	656	2085
Basin	1341	685	1413

Table: 4 Input data utilised in the GWAVA model setup

Input Data	**Spatial Resolution**	**Temporal Resolution**	**Time Period**	**Source**
		Climate Forcing Data		
Precipitation	0.25 degree	Daily	1951-2017	Indian Meteorological Department (Pai et al., 2014)
Maximum Temperature	0.25 degree	Daily	1951-2016	Indian Meteorological Department (Pai et al., 2014)
Minimum Temperature	0.25 degree	Daily	1951-2016	Indian Meteorological Department (Pai et al., 2014)
Open Water Evaporation	India	Monthly	1959-1968	Central Water Commission, Basin Planning and Management Organisation (Central Water Commission, 1987)
		Hydrological Data		
Streamflow gauged data	Cauvery Basin (14 gauging stations)	Daily	1971-2014	India-WRIS
Reservoir inflow and outflow data	Cauvery Basin (6 reservoirs)	Monthly	1974-2017	India-WRIS
Water transfers	Cauvery Basin			Ashoka Trust for Research in Ecology and the Environment (ATREE)
Tanks	Cauvery Basin		2019	Waterbodies dataset (ATREE)
Check dams	Karnataka (District)		2006-2012	Structural Investment Report, Watershed Development Department, Karnataka (Wable, et al., 2019)
Farm bunds	Karnataka (District)		2006-2012	Structural Investment Report, Watershed Development Department, Karnataka (Wable, et al., 2019)
		Land Surface Data		
Elevation	0.003 degree		2000	NASA Shuttle Radar Mission Global 1 arc second V003 (Jpl, 2013)

Soil type	0.008 degree	1971-1981	Harmonized World Soil Database v1.2 (Fischer et al., 2008)
Land Cover Land Use	0.001 degree	2005	Decadal land use and land cover across India 2005 (Roy et al., 2008)
Crops	Cauvery Basin (Taluk*)	2000	National Remote Sensing Centre (NRSC)
Demand Data			
Total Population	Cauvery Basin (Village)	2011	Indian Decadal Census
Rural Population	Cauvery Basin (Village)	2011	Indian Decadal Census
Livestock	0.05 degree	2005	CGIR Livestock of the World v2 (Robinson et al., 2014)

*Taluk-a subdivision of a district consisting of a group of several villages organized for revenue purposes

Table: 5. Calibration and Validation Statistics with and without interventions

	Catchment	**Calibration**					**Validation**				
		Without Interventions		**With Interventions**		**Calibration Period**	**Without Interventions**		**With Interventions**		**Validation Period**
		NSE	**Bias**	**NSE**	**Bias**		**NSE**	**Bias**	**NSE**	**Bias**	
a	Saklesphur	0.60	-46.45	0.66	-45.80	2006-2010	0.30	57.10	0.34	-56.00	2010-2013
b	Thimmanahali	0.44	-3.66	0.51	-18.40	2005-2009	0.31	-15.52	0.43	9.40	2010-2013
c	KMVadi	0.17	-50.33	0.16	-54.80	1991-2000	-0.18	-13.78	-0.14	-27.30	2001-2011
d	Kudige	0.54	-50.79	0.58	-48.50	1990-2000	0.57	14.30	0.58	-8.00	2012-2014
e	Munthankera	0.77	-25.46	0.80	-41.50	1990-2000	0.76	26.82	0.83	-22.30	2001-2011
f	Tbekuppe	-0.53	-5.49	0.07	-31.70	1980-1990	-3.26	-1.96	-1.84	5.30	2001-2003
g	TKHali	0.35	7.34	0.53	-10.80	1990-2000	0.61	7.74	0.72	-12.30	2001-2008
h	T Narasupiar	0.41	-12.01	0.52	-14.70	1988-1998	-0.57	36.89	-0.60	-27.00	1999-2002
i	Kollegal	0.32	-16.99	0.37	-18.60	2008-2011	-0.66	15.34	-0.19	-8.60	2012-2013
j	Bilingudulu	0.23	-2.24	0.32	-7.30	1990-2000	-0.87	-16.84	-0.38	-13.40	2001-2011
k	Urachikottai	-1.54	-11.56	-0.94	13.10	1990-2000	-1.67	5.93	-1.70	-2.70	2001-2008
l	Kodumodi	-1.47	-22.80	-0.94	-1.70	1990-2000	-1.83	18.64	-1.95	-14.40	2005-2010
o	Musiri	-1.68	-6.85	-0.72	14.20	1990-2000	-1.41	8.29	-1.28	-3.90	2006-2010
m	Thengumarahada	0.32	-22.33	0.31	-13.80	1990-2000	0.60	19.33	-0.09	-11.00	2001-2008

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