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How economically and environmentally viable are multiple dams in the upper Cauvery Basin, India? A hydro-economic analysis using a landscape-based hydrological model

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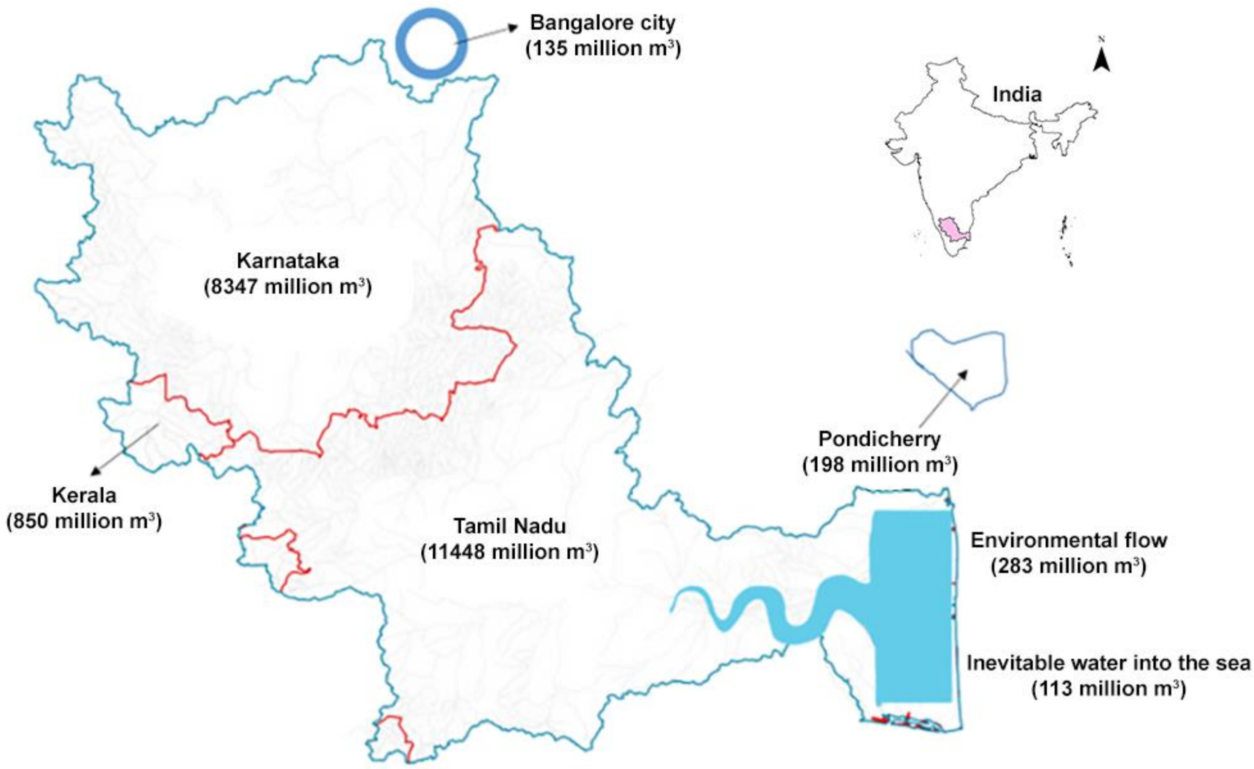

Figure S.1. Overview of water allocation (million m^3/year) in the Cauvery basin among different states/union territories as per the supreme court Verdict in 2018.

Supplementary materials

1. The model structures

The FLEX-Topo model employs a graphical representation (Figure S.2) and a set of variables (Table S.1) to simulate hydrological processes in different landscape units known as hydrological response units (HRUs). These HRUs are classified based on elevation (DEM), slope, and Height Above Nearest Drainage (HAND). The model starts by dividing the landscape into Hillslope, Plateau, and Wetland regions, taking into account the land use patterns identified from maps.

Rainfall (P) is partitioned into interception evaporation (Ei) and effective rainfall (Pe) based on a threshold value (Si max). The effective rainfall is further divided between soil water retention and yield runoff (R) using the root zone storage capacity (Su, max) and a shape parameter (β). Plant transpiration (Et) is calculated considering potential evaporation (E0), a soil moisture threshold parameter (Ce), and the relative soil moisture (Su/Su, max). The generated runoff is then separated into fast (Rf) and slow (Rs) components using a separator (D). A lag function is applied to represent the lag time (T) between peak flow and the storm event. The fast and slow runoff components are modeled using two linear reservoirs with different time constants (Kf and Ks). The total runoff (Qm) is the sum of these fast and slow components (Qf and Qs).

The landscape classification affects the parameters of the unsaturated root zone reservoir (Su, max) due to variations in rooting depth caused by topography and hydrology. The Su, max values for hillslope forest and plateau forest are comparatively larger than those for hillslope crops and plateau crops. In wetlands, the root zone storage capacity (Su, max, W) is relatively low due to the shallow groundwater table.

Five HRUs are determined based on the percentage of landscape classes for the upstream and downstream areas of the reservoir for each sub-basin (Figure 5). These HRUs are connected to a common groundwater reservoir, recharged by different sources depending on the landscape unit (e.g., hillslope forest, hillslope crop, plateau forest, plateau crop, and capillary rise from wetlands).

During the calibration of the model, parameter ranges (Table S.1) are set by optimization to ensure accurate representation of the hydrological processes in the studied area, particularly the Cauvery basin, which is predominantly covered by field crops, plantation crops, and evergreen forests. However, the land use pattern has been significantly influenced by agricultural activities.

Table S.1. Model parameters prior ranges. These define the feasible range within which parameters are calibrated.

Parameters	Parameter Range				
	Plateaucrop	**Plateau forest**	**Hillslope crop**	**Hillslope forest**	**Wetlands**
I_{max} [mm/day] (Storage capacity of the Interception reservoir)	1-8	6-10	1-8	6-10	1-5
C_e [-] (Fraction of $S_{u, max}$)	0.1-1	0.1-1	0.1-1	0.1-1	0.1-1
Su_{max} [mm] (Maximum soil moisture capacity in the root zone)	100-500	100-1000	100-500	100-1000	10-100
β [-] (Spatial heterogeneity in the catchment/shape parameter)	0.1-5	0.1-5	0.1-5	0.1-5	0.1-5
Pmax [-] (Maximum percolation rate)	0.1-5	0.1-5	-	-	-
D [-] (The splitter)	-	-	0-0.5	0-0.5	-
$C_R$max [mm/day] (Capillary rise)	-	-	-	-	0.01-1
K_f [d] (Recession coefficient of the fast reservoir)	0.005 -1	0.005 -1	0.005-1	0.005-1	0.005-1
Catchment parameters					
K_s [d] (Recession coefficient of the slow reservoir)	0.0001-0.01				
T_{lag} [d] (Time lag between the storm and peak flow)	0.1 – 30				
Frac 1 [-] (Fraction of forests cover)	The value is fixed (0 -1) based on the percentage of forest area in the sub-basin				
Frac 2 [-] (Fraction of Irrigation)	The value is fixed (0 -1) based on the percentage of Irrigated area in the sub-basin				

Source Ekka et al., 2022

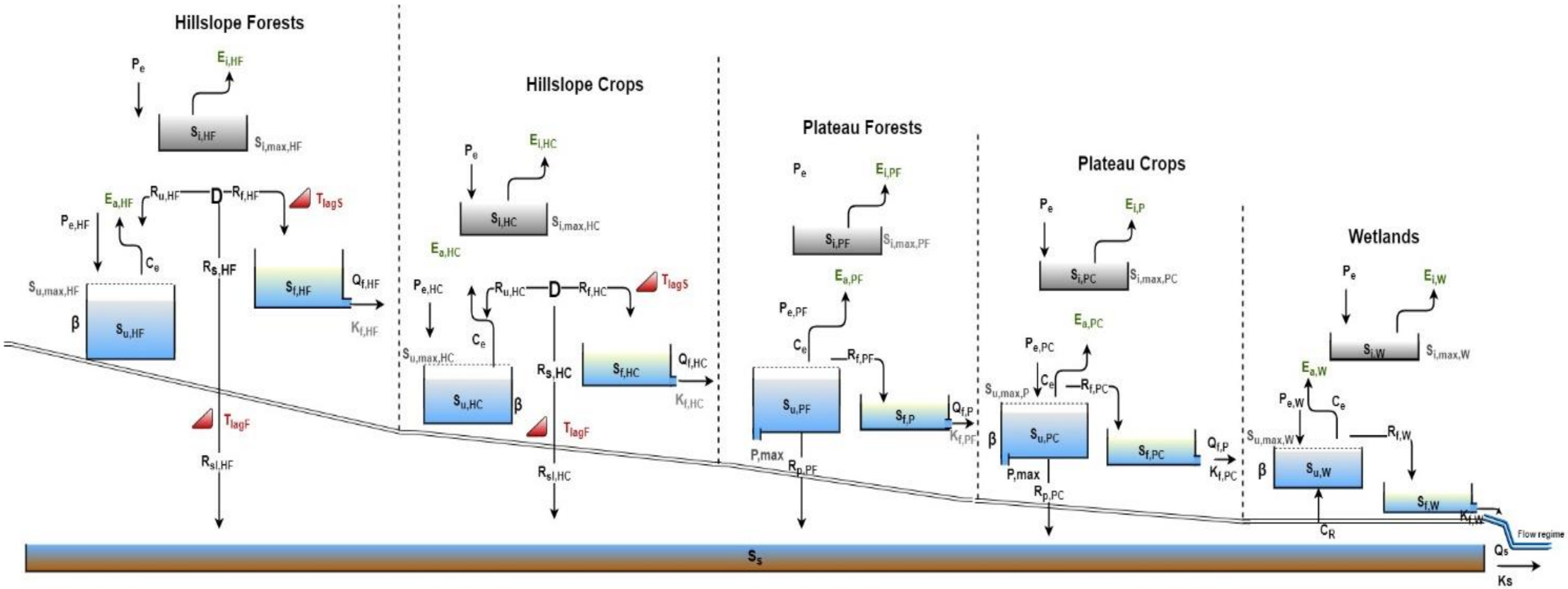

Figure S.2 The model structure; Source: Ekka et al., 2022

2. Calibration and validation of the integrated model

The Elitist Non-Dominated Sorting Genetic (NSGA-II) algorithm is used to calibrate the model parameters (Deb et al., 2000). NSGA-II is a multi-objective optimization algorithm. It simultaneously optimizes multiple objectives by identifying parameters that yield model performances that are not dominated by any other feasible parameters in the multi-objective space (Efstratiadis & Koutsoyiannis, 2010). In total 25 parameters were calibrated and are indicated in Table S. 1 The population size, number of generations, crossover and mutation probability were indicated in Table S.2.

The NSGA-II parameter setting may have different impacts on computational effectiveness. The population size, number of generations were indicated in Table 3. The population crossing over and population mutation play critical roles during optimization higher fraction of the population crossing over (0.9) and a lower value of mutation value are preferred for better convergence and to prevent the population from getting trapped in local optima (Wang et al., 2019). The population size depends on the number of the decision variables calibrated in the model and keeping the population size five times the number of decision variables is considered ideal for the simulation (Gutierrez et al., 2019). Since for Flex-Topo, there are 20 parameters, the population size is kept at 100. Similarly, for the reservoir model, the number of parameters is five, which translates into a population size of 25. Higher population sizes were also attempted but not used and reported for later analysis because the performance achieved was similar to the reported population sizes. The number of iterations is first tested using 50, 100, 250 and 500 iteration runs and 250 was finally chosen based on the best optimization results.

Table S.2. Parameter setting for NSGA II optimization of the model

NSGA parameters	Reservoir calibration	Integrated FLEX-Topo Calibration
No. of Iterations	250	300
No. of decision variables	5-8	25
No. of population size	25-40	125
Population Crossover	0.7	0.7
Mutation probabilities	0.2	0.2
New generation selection	Elitist selection	Elitist selection
Ordering criteria	Crowding distance	Crowding distance

Source: Ekka et al., 2022

The reservoir calibration was conducted on a daily time scale, using all available years of data due to limited reservoir data. Negative NSE values are reported instead of positive NSE (due to its use to maximize as an objective in NSGA II). NSE values are greater than 0.5 and sometimes even around 0.7, which indicates reasonably good performance of a model at daily scale that also incorporated reservoir operations. In the current model, the negative reverse of NSE value is used to calibrate and validate the model parameters.

The calibration results, presented in Table S.3, were obtained using the NSGA II algorithm, and the Pareto front ranges for both -NSE and MAE are shown within parentheses. The MAE values, which indicate the accuracy of predictions, range from 0.71 to 2.92 (106 m^3 day^{-1}), falling within an acceptable range. Lower MAE values indicate better predictions. Similarly, the NSE values, which assess the model's goodness of fit, range from 0.51

to 0.73, all above the acceptable threshold of 0.50. It is important to note that the calibration and validation of the reservoir models did not include validation against observed streamflow at the reservoir outlets. Despite this limitation, the overall MAE and NSE values indicate acceptable performance for the reservoir models, given the available data and operational considerations

Table S.3. The model performance metrics for the calibration of the four reservoirs and the calibration and validation of the Flex-Topo models (i.e., the integration of calibrated reservoirs with upstream and downstream FLEX-Topo models) for the corresponding four sub-basins.

	Reservoir Calibration (2011-2016)					
Reservoirs	**-NSE [range]**			**MAE [range]** 5 fff		
Harangi(kudige)	-0.64 [-0.65 - (-0.63)]			2.92 [2.92 -3.01]		
Hemavathi (M.H. Halli)	-0.51 [-0.52 - (-0.51)]			1.15 [1.15 -1.16]		
Kabini (T. Narasipur)	-0.73 [-0.73 - (-0.72)]			1.24 [1.24-1.24]		
KRS(Kollegal)	-0.68 [-0.67 - (-0.69)]			0.71 [0.70 - 0.72]		
Flex-Topo model calibration and validation						
Sub-basins	**Calibration (1991-2010)**			**Validation (2011-2016)**		
	-NSE [range]	**MAE [range]** (mm day^{-1})	**PBIAS** (%)	**-NSE**	**MAE** (mm day^{-1})	**PBIAS** (%)
Kudige	-0.80 [-0.81 - (-0.80)]	1.36 [1.33 -1.39]	8.54	-0.65	2.05	16.27
M.H. Halli	-0.57 [-0.57 - (-0.56)]	0.37 [0.40 -0.41]	3.24	-0.52	0.48	17.66
T.Narasipur	-0.53 [-0.53 - (-0.50)]	0.67 [0.67- 0.69]	11.62	-0.52	0.66	-42.80
Kollegal	-0.53 [-0.54 - (-0.52)]	0.92 [0.92 -0.97]	-6.23	-0.50	0.86	-57.54

Note - The value indicates the best-performing parameters following the minimum Euclidean distance. The figures in parenthesis indicate the pareto-optimal range of all solutions considered feasible. $\text{PBIAS} = 100\sum_{i=1}^{n}(Q_i^o - Q_i^m) / \sum_{i=1}^{n} Q_i^o$ is provided only for the Flex-Topo model to evaluate its performance for the four sub-basins.

Source Ekka et al., 2022

Table S.3 presents the performance evaluation of the calibrated Flex-Topo model compared to observed data for the four sub-basins. During the calibration phase, the Nash-Sutcliffe Efficiency (NSE) values ranged from 0.53 to 0.80, and during the validation phase, they were between 0.50 to 0.65 for all sub-basins. NSE values above 0.50 are considered acceptable, indicating a satisfactory level of model performance. Additionally, the Mean Absolute Error (MAE) values during calibration ranged from 0.92 to 1.36 mm day-1, and during validation, they fell between 0.86 to 2.05 mm day-1, also deemed acceptable.

The Percentage Bias (PBIAS) values for both calibration and validation periods are provided in Table 5. For Kuidge and M.H. Halli sub-basins, the PBIAS values are within the acceptable range of ±25 percent. However, for T. Narasipur and Kollegal sub-basins, the PBIAS values during the validation period exceed the acceptable limits.

The positive PBIAS values indicate that the model performs better in simulating low flows compared to high flows. This observation is supported by Figure 8, where high flows are often underpredicted, particularly for Harangi, Hemavathi, and Kabini reservoirs. The parameter sets chosen for the simulations are from the Pareto front and may not represent the best possible performances in either of the two objective functions (NSE and

MAE). While NSE is sensitive to high flows as it is a quadratic function of residuals, MAE is more robust to outliers. This robustness of MAE might explain why high flows are not as well simulated as low flows in the model. (Pande, 2013 a, b) discusses these characteristics of the model's performance evaluation metrics.

Table S.4 Definitions of major Indicators of hydrological alterations

Flow characteristics	Indicators of Hydrologic Alteration (IHA)	Definitions (for non-parametric)
Magnitude/ timing	The median value for each calendar month	Median (m3s-1) of daily flow condition from January to December
Magnitude/ duration	Annual minima, 1-day median	Minimum flow value (m^3s^{-1}) occurred in a year
	Annual minima, 3-day median	Minimum flow value (m^3s^{-1}) for the mean daily flow of 3 consecutive days of the year
	Annual minima, 7-day median	Minimum flow value (m^3s^{-1}) for the mean daily flow of 7 consecutive days of the year
	Annual minima, 30-day median	Minimum flow value (m^3s^{-1}) for the mean daily flow of 30 consecutive days of the year
	Annual minima, 90-day median	Minimum flow value (m^3s^{-1}) for the mean daily flow of 90 consecutive days of the year
	Annual maxima, 1-day median	Maximum flow value (m^3s^{-1}) occurred in a year
	Annual maxima, 3-day median	Maximum flow value (m^3s^{-1}) for the mean daily flow of 3 consecutive days of the year
	Annual maxima, 7-day median	Maximum flow value (m^3s^{-1}) for the mean daily flow of 7 consecutive days of the year
	Annual maxima, 30-day median	Maximum flow value (m^3s^{-1}) for the mean daily flow of 30 consecutive days of the year
	Annual maxima, 90-day median	Maximum flow value (m^3s^{-1}) for the mean daily flow of 90 consecutive days of the year
Duration	Low pulse count (days)	No of times in a year when the flow is lower than the 25 % percentile of the flow period
	High pulse count (days)	No. of times in a year when the flow is higher than the 75 % percentile of the flow period in analysis
	Low pulse duration (days):	The median duration of the low pulses (days)
	High pulse duration (days):	The median duration of the high pulses (days)
Environmental flow components	Extreme low peak	Minimum flow event during each water year or season
	Extreme low frequency	Frequency of extreme low flows during each water year or season

References: compiled from The Nature Conservancy (TMC), 2009

Table S.4. The residence time of the reservoirs

Reservoir	Year of construction	Sub-basin based on gauge location	Catchment area (10^6 m^2)	Gross Storage (10^6 m^3)	Residence time (months)
Harangi	1982	Kudige	419.58	240.69	7.23
Hemavathi	1979	M.H. Halli	2810	1050.63	22.63
Krishna Raja Sagara (KRS)	1938	Kollegal	10619	1400.31	8.68
Kabini	1974	T. Narasipur	2141.90	552.74	3.57

Supplementary materials

Table S.5 The Crop coefficient (Kc) and yield response factor (Ky) used to calculate the yield

	Crops	Kc	Ky
1	**CEREAL CROPS**		
	Bajra	0.67	0.92
	Jowar	0.69	0.92
	Maize	1.06	1.25
	Paddy	1.14	1.20
	Ragi	0.69	0.90
2	**PULSES CROPS**		
	Avare	0.74	0.85
	Bengal gram (Gram)	0.90	0.90
	Black gram	0.65	0.85
	Cowpea	1.19	0.98
	Green gram	0.89	0.80
	Horse gram	0.74	0.90
	Navane	0.74	0.70
	Tur (Red gram)	0.74	0.90
3	**OIL SEEDS CROPS**		
	Linseed	0.78	0.70
	Castor	0.7	0.70
	Groundnut	0.78	0.70
	Niger seed	0.7	0.80
	Rape & Mustard	0.75	0.80
	Safflower	0.75	0.80
	Sesamum	0.75	0.95
	Soyabean	0.70	0.85
	Sunflower	0.75	0.95
4	**COMMERCIAL / FIBRE CROPS**		
	Cotton	0.88	0.85
	Sugarcane	1.58	1.20
	Tobacco	0.9	1.10
	Crops	**Kc**	**Ky**
5	**PLANTATION & HORTICULTURAL CROPS**		
	Lemon	0.7	1.10
	Onion	1.19	1.10
	Tomato	1.19	1.05
	Banana	1.12	1.20
	Beans	0.93	1.15
	Brinjal	0.93	0.85
	Cabbage	1.19	0.85
	Cashewnut (Raw&Processed Nuts)	0.8	0.90
	Coconut	0.8	0.90
	Grapes	0.85	1.10
	Guava	0.69	1.10
	Mango	0.69	1.10
	Papaya	0.93	0.90
	Pomogranate	0.5	0.90
	Potato	1.09	1.10
	Sapota	0.7	0.90
	Sweetpotato	1.09	1.00
	Tapioca	1.09	0.80
	Coffee (Arabica)		
	Coffee (Robusta)		
6	**CONDIMENTS & SPICES CROPS**		
	Coriandar	1.19	1.20
	Arecanut (Raw & Processed Nuts)	0.8	0.90
	Black pepper	1.19	1.10
	Cardamom	1.19	1.10
	Dry Chillies	0.95	1.10
	Dry Ginger	0.93	1.10
	Garlic	1.19	0.90
	Turmeric	1.01	0.85

Source: Compiled from Allen et al., 1998; Mohan & Arumugam.,1994

Table S.6 An overview of the irrigated and non-irrigated areas for each district under respective reservoirs

Reservoirs	Kodagu (ha)			Mysore (ha)			Hassan (ha)			Chikmagalur (ha)		
	Irrigated (with in basin)	Irrigated (Outside basin)	Unirrigated	Irrigated (with in basin)	Irrigated (Outside basin)	Unirrigated	Irrigated (with in basin)	Irrigated (Outside the basin)	Unirrigated	Irrigated (with in basin)	Irrigated (Outside basin)	Unirrigated
Harangi	2,792	0.00	79,808	14,482	27,329	0.00	0.00	8,935	0.00	0.00	0.00	0.00
Hemavathi	1,060	0.00	17,661	0.00	2,267	0.00	69,223	0.00	82,028	0.00	0.00	75,937
Kabini	0.00	0.00	15,461	23,028	0.00	133,799	0.00	0.00	0.00	0.00	0.00	0.00
KRS	0.00	0.00	55,919	34,673	0.00	124,432	0.00	0.00	268,041	0.00	0.00	0.00

Reservoirs	Chamrajanagar (ha)			Mandya (ha)			Tumkur (ha)			Wayanad (ha)		
	Irrigated (with in sub-basin)	Irrigated (Outside sub-basin)	Unirrigated	Irrigated (with in basin)	Irrigated (Outside the basin)	Unirrigated	Irrigated (with in basin)	Irrigated (Outside basin)	Unirrigated	Irrigated (with in sub-basin)	Irrigated (Outside sub-basin)	Unirrigated
Harangi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hemavathi	0.00	0.00	0.00	0.00	92,239	0.00	0.00	127,076	0.00	0.00	0.00	0.00
Kabini	22,702	0.00	103,389	0.00	0.00	226	0.00	0.00	0.00	0.00	0.00	98,641
KRS	73,409	0.00	72,243	0.00	0.00	207,379	0.00	0.00	0.00	0.00	0.00	0.00

Reservoirs	Erode (ha)			The Nilgiris (ha)		
	Irrigated (with in basin)	Irrigated (Outside the basin)	Unirrigated	Irrigated (with in basin)	Irrigated (Outside the basin)	Unirrigated
Harangi	0.00	0.00	0.00	0.00	0.00	0.00
Hemavathi	0.00	0.00	0.00	0.00	0.00	0.00
Kabini	0.00	0.00	0.00	0.00	0.00	22,711
KRS	0.00	0.00	54,349	0.00	0.00	0.00

Supplementary materials

Table S.7 Average yearly price of crops used to calculate the economic value of the agricultural production. (2011 to 2016)

	CROPS	District									
1	**CEREAL CROPS**	**Chikamagalur**	**Chamrajanagar**	**Hassan**	**Kodagu**	**Mandya**	**Mysore**	**Wayanad**	**Erode**	**Nilgiris**	**Tumkur**
	Bajra	-	886	-	-	-	-	-	-	-	-
	Jowar	938	887	938		943	834	-	-	-	-
	Maize	900	875	900	893	926	822	-	926	-	-
	Minor Millets	1,560	-	1,560	-	-	-	-	-	-	-
	Paddy	946	979	946	988	984	953	983	984	984	946
	Ragi	939	948	939	951	989	903	-	989	-	-
2	**PULSES CROPS**										
	Avare	2,550	2,235	2,550	-	2,457	2,433	-	-	2,457	2,550
	Bengal gram (Gram)	2,626	4,394	2,626	-	3,533	3,238	-	3,533	-	2,626
	Black gram	4,985	3,874	4,985	-	5,473	4,420	-	5,473	5,473	4,985
	Cowpea	2,337	2,252	2,337	2,689	2,607	3,536	-	2,607	2,607	2,337
	Green gram	3,486	3,967	3,486	-	4,129	4,239	-	4,129	4,129	3,486
	Horse gram	1,601	1,667	1,601	-	1,560	1,665	-	1,560	1,560	1,601
	Tur (Red gram)	4,496	4,387	4,496	-	3,974		-	-	3,974	4,496
3	**OIL SEEDS CROPS**										
	Linseed	2,570	-	-	-	-	-	-	-	-	-
	Castor	2,564	2,521	2,570		3,974	2,605	-	-	-	-

	Groundnut	3,336	1,497	2,564	2,717	2,131	2,352	-	2,131	-	2,564
	Niger seed	4,466	3,432	3,336	-	3,094	2,854	-	-	-	-
	Rape & Mustard	2,703	4,466	4,466	-	-	-	-	-	-	-
	Safflower	3,994	3,384	2,703	-	-	-	-	-	-	-
	Sesamum	3,994	2,368	3,994	-	4,466	4,258	-	-	-	-
	Soyabean	-	-	-	-	-	-	-	-	-	-
	Sunflower	2,429	-	2,429	-	2,476	2,676	-	-	-	-
4	**COMMERCIAL / FIBRE CROPS**										
	Cotton	3,691	2,806	3,691	-	-	2,980	-	-	-	3,691
	Sugarcane	930	930	930	-	-	920	-	-	-	930
	Tobacco	2,684	2,684	2,684	2,684	-	2,557	-	-	-	2,684
5	**PLANTATION & HORTICULTURAL CROPS**										
	Lemon	3,017	3,017	3,017	-	3,017	2,884	-	-	-	3,017
	Onion	870	923	923	-	890	928	-	-	890	870
	Tomato	677	614	939	561	561	545	-	-	561	677
	Banana	1,691	1,691	1,691	1,691	1,691	1,510	1,646	-	-	1,691
	Beans	1,391	1,391	1,309	1,310	1,310	1,534	-	-	1,310	1,391
	Brinjal	740	748	747	748	748	638	-	-	748	740
	Cabbage	406	406	406	406	408	375	-	-	-	406

Cashewnut (Raw &Processed Nuts)	4,668	4,668	4,668	4,668	4,348	4,098	4,098	-	-	4,668
Coconut	4,466	4,466	4,466	4,466	4,466	4,352	4,352	-	-	4,466
Grapes	1,739	1,739	1,739	-	-	1,619	-	-	-	1,739
Guava	585	585	585	585	585	552	-	-	-	585
Mango	671	671	671	671	671	634	-	671	-	671
Papaya	726	726	726	726	726	714	-	-	-	726
Pomogranate	7,443	7,443	7,443		7,443	7,224	-	-	-	7,443
Potato	883	639	799	800	800	955	-	-	-	883
Sapota	1,493	1,493	1,493	1,493	1,493	1,409	-	-	-	1,493
Sweet potato	451	568	568	568	275	552	-	-	-	451
Tapioca	807	807	-	807	-	777	721	-	-	807
Coffee (Arabica)	11,997	-	14,250	14,304	-	-	14,304	-	-	-
Coffee (Robusta)	8,209	-	9,982	6,772	-	-	6,772	-	-	-
CONDIMENTS & SPICES CROPS										
Coriandar	4,558	4,558	4,558	-	4,558	4,351	-	-	-	4,558
Arecanut (Raw & Processed Nuts)	13,331	9,344	9,344	9,344	9,344	13,877	12,942	-	-	13,331
Black Pepper	21,846	20,785	20,785	19,542	-	18,152	23,284	-	-	21,846
Cardamom	73,692	73,692	73,692	73,692	-	73,548	73,548	-	-	73,692
Dry Chillies	4,388	4,339	4,339	4,339	5,395	4,938		-	-	4,388

Supplementary materials

Dry Ginger	3,525	1,669	3,525	3,525	3,525	3,275	7,294	-	-	3,525
Garlic		3,311	3,311			3,146		-	-	4,460
Turmeric	4,460	4,765	4,460	4,460	4,460	3,803	3,803	-	-	-

Source: Extracted and compiled from https://agmarknet.gov.in/.