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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Supplementary materials

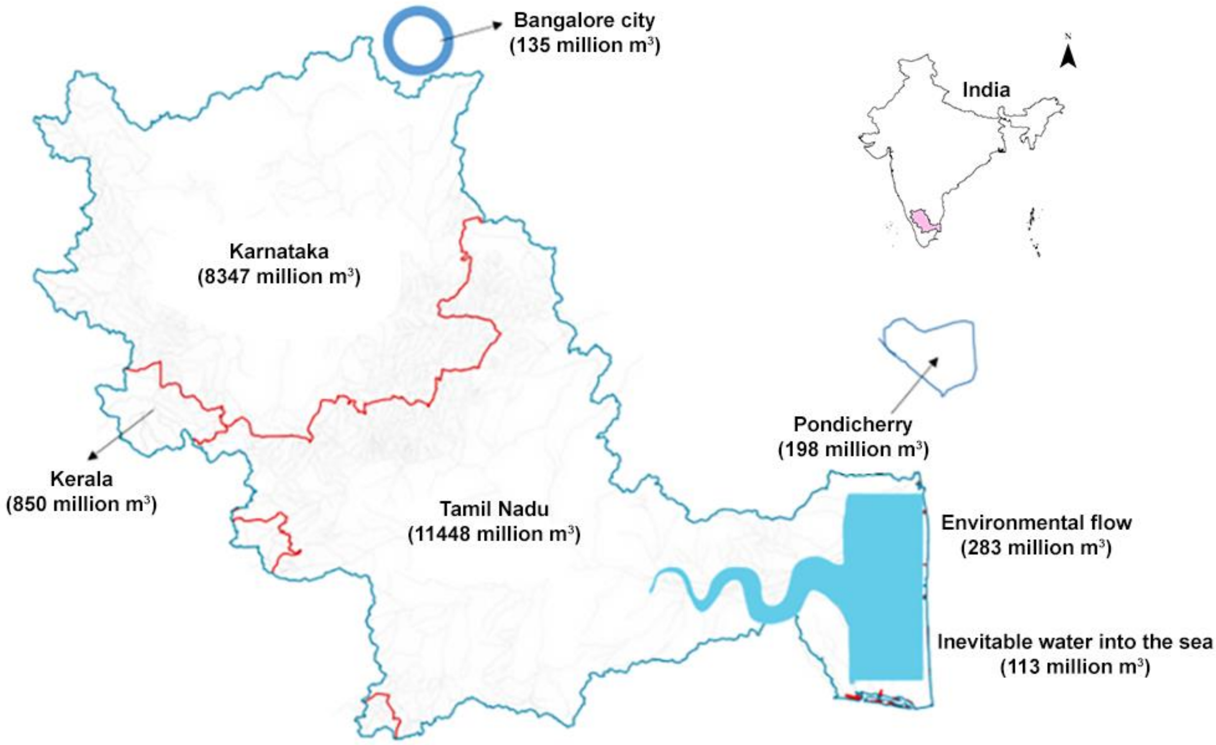

Figure S.1. Water allocation in the Cauvery basin (million m^3/year) across the several states and union territories in accordance with the Supreme Court's 2018 Judgment.

Supplementary materials

1. The FLEX-Topo model

The FLEX-Topo model simulates dominant hydrological processes in various landscape units known as hydrological response units (HRUs). Figure S.2 illustrates such HRU specific processes modeled by FLEX-Topo, which are calibrated based on the parameters shown in Table S.1. Height Above Nearest Drainage (HAND), slope, elevation (DEM) and land use maps are used to categorize these HRUs.

Rainfall (P) is partitioned into interception evaporation (Ei) and effective rainfall (Pe) based on a threshold value (Si max). The effective rainfall is retained by the soil and excess results in runoff, R, which is a function of root zone storage capacity parameter (Su, max) and a shape parameter (β). Plant transpiration (E) is calculated considering potential evaporation (Eo), a soil moisture threshold parameter (Ce), and 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 land use. The Su, max values for hillslope forest and plateau forest are assumed to be 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 S.2). These HRUs are connected to a common groundwater reservoir, recharged by different sources depending on the landscape class (e.g., hillslope forest, hillslope crop, plateau forest, plateau crop, and capillary rise from wetlands).

After calibrating the reservoir operations model and integrating it with the FLEX-Topo models for the areas upstream and downstream of a reservoir within the corresponding sub-basin, the FLEX-Topo parameters (within the ranges shown in Table S.1) are optimized to ensure the representation of the hydrological processes for various sub-basins (four sub-basins, one for each of the four reservoirs) in the Upper Cauvery basin, which is predominantly covered by field crops, plantation crops, and evergreen forests. For more details readers are referred to Ekka et al. (2022).

Table S.1. FLEX-Topo model parameters ranges. These define the feasible range within which parameters are calibrated and are discussed in detail in Ekka et al. (2022).

Parameters	HRU specific parameter ranges				
	Plateau crop	**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 scale parameter ranges					
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)

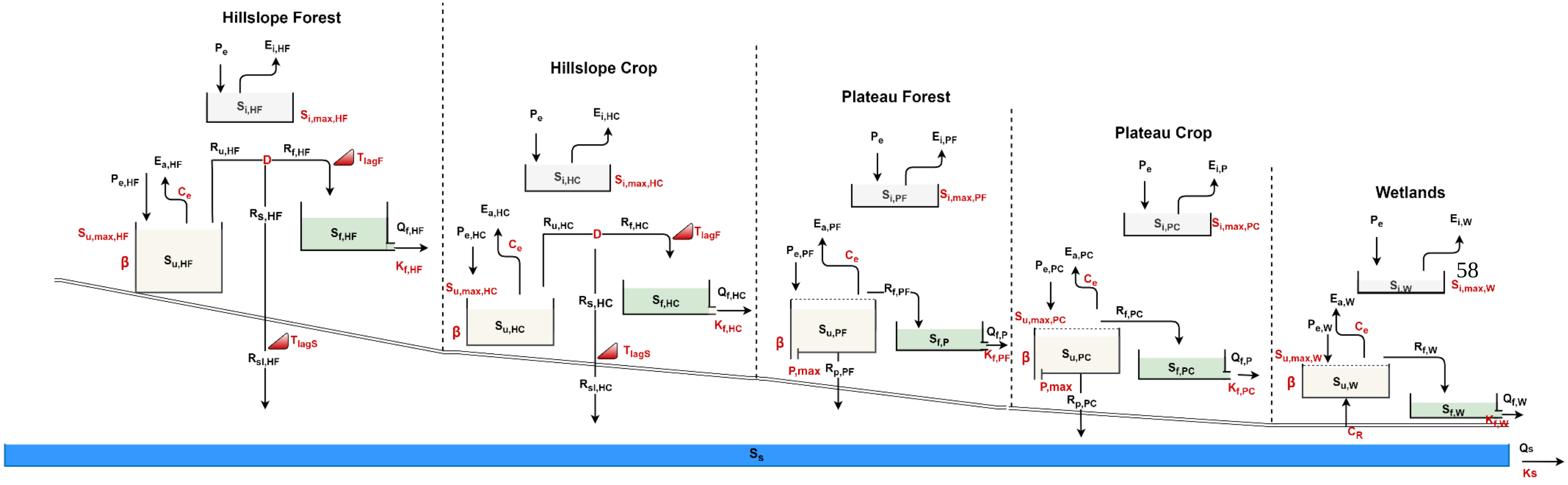

Figure S.2 The dominant processes of different HRUs of the FLEX-Topo model used in this study. Various landscape class specific parameters are shown in red and variables in black. Flows from various reservoirs, Q with corresponding subscripts, are added to obtained total flow and the regime. Source: Ekka et al. (2022).

2. Calibration and validation of the integrated model

The model parameters are calibrated using the Elitist Non-Dominated Sorting Genetic (NSGA-II) algorithm (Deb et al., 2000). NSGA-II is a multi-objective optimization algorithm, which can optimize multiple objectives and provides a collection of parameter values (Pareto optimal) that are not dominated by any other feasible parameters in terms of performance in the multi-objective space.

Table S.2 provides the parameter setting of the NSGA-II algorithm. Population crossing over and population mutation play crucial roles in optimization. For better convergence and to prevent the population from becoming trapped in local optima, a higher fraction of population crossing over and a lower value of mutation value are preferred (Wang et al., 2019). The population size depends on the number of decision variables calibrated in the model, and it is recommended for the simulation to maintain a population size that is five times the number of decision variables (Gutierrez et al., 2019). The reservoir operations model has five parameters and therefore NSGA-II has a population size of 25 when calibrating its parameters. Since there are 20 parameters that are calibrated for FLEX-Topo, the population size is maintained at 100 when calibrating its parameters after the calibrated reservoir operations model has been integrated. Higher population sizes were also tested but not used due to similar performance. 250 iterations were ultimately selected based on the best optimization from amongst 50, 100, 250, and 500 iterations.

NSGA II 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

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

Source: Ekka et al., 2022

Table S.3 presents the calibration results of both reservoir operations models and FLEX-Topo parameters after integrating the reservoir operations models for each of the sub-basins, obtained using the NSGA II algorithm. Negative Nash-Sutcliffe Efficiency (NSE) values are reported instead of positive NSE (due to its use to maximize as an objective in NSGA-II), and the Pareto front ranges for both -NSE (note the negative sign in front of NSE) and Mean Absolute Error (MAE) are shown within the parentheses. The MAE values range from 0.71 to 2.92 (10^6 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.

Note that the calibration and validation of the reservoir operations 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 operations 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.

Reservoirs	Reservoir Calibration (2011-2016) -NSE [range]		MAE [range] (10^6 m^3 day^{-1})	
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})	**-NSE**	**MAE** (mm day^{-1})
Kudige	-0.80 [-0.81 - (-0.80)]	1.36 [1.33 -1.39]	-0.65	2.05
M.H. Halli	-0.57 [-0.57 - (-0.56)]	0.37 [0.40 -0.41]	-0.52	0.48
T.Narasipur	-0.53 [-0.53 - (-0.50)]	0.67 [0.67- 0.69]	-0.52	0.66
Kollegal	-0.53 [-0.54 - (-0.52)]	0.92 [0.92 -0.97]	-0.50	0.86

Note: The reported value in front of the parenthesis represents the parameter value on the Pareto front this is closed to the origin using Euclidean distance. The range in the parenthesis represent the range of possible solutions lying on the Pareto front. Source: Ekka et al. (2022).

The calibrated reservoir model is integrated with the FLEX-Topo model, the FLEX-Topo model parameters are calibrated and Table S.3 reports the performance of the resulting integrated model. The NSE values for all sub-basins ranged from 0.53 to 0.80 during the calibration phase and from 0.50 to 0.65 during the validation phase. NSE scores over 0.50 are regarded as acceptable and denote the integrated model's performance at acceptable levels for all the four sub-basins. Further, the Mean Absolute Error (MAE) for calibration and validation are within acceptable ranges of 0.86 to 2.05 mm day^{-1} and 0.92 to 1.36 mm day^{-1}, for calibration and validation phases respectively.

Table S.4. Definitions of major Indicators of Hydrological Alteration (IHA)

Flow characteristics	Indicators of Hydrologic Alteration (IHA)	Definitions (for non-parametric)
Magnitude/ timing	The median value for each calendar month	Median (m^3s-1) of daily flow condition from January to December
	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

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Magnitude/ duration	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.5. 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

Table S.6. The crop coefficients (Kc) and yield response factors (Ky) used to calculate crop specific yields

	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

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Table S.7. An overview of the irrigated and non-irrigated areas of the districts (columns) lying within the sub-basins of the respective reservoirs (rows)

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	2792.00	0.00	79808.30	14481.78	27329.22	0.00	0.00	8935.00	0.00	0.00	0.00	0.00
Hemavathi	1060.00	0.00	17661.12	0.00	2267.00	0.00	69223.00	0.00	82027.64	0.00	0.00	75937.08
Kabini	0.00	0.00	15461.33	23028.00	0.00	133798.82	0.00	0.00	0.00	0.00	0.00	0.00
KRS	0.00	0.00	55919.38	34673.00	0.00	124432.11	0.00	0.00	268040.72	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	92239.00	0.00	0.00	127076.00	0.00	0.00	0.00	0.00
Kabini	22702.00	0.00	103389.02	0.00	0.00	225.47	0.00	0.00	0.00	0.00	0.00	98640.87
KRS	73409.00	0.00	72242.64	0.00	0.00	207379.38	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	22711.92
KRS	0.00	0.00	54349.34	0.00	0.00	0.00

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Table S.8. Average yearly price (₹, Indian National Rupees) of crops (rows)) used to calculate the economic value of the agricultural production (2011 to 2016) for various districts shown as columns.

	CROPS	**District**									
1	**CEREAL CROPS**	**Chikamagalur**	**Chamrajanagar**	**Hassan**	**Kodagu**	**Mandya**	**Mysore**	**Wayanad**	**Erode**	**Nilgiris**	**Tumkur**
	Bajra	-	886.35	-	-	-	-	-	-	-	-
	Jowar	937.51	887.01	937.51		942.67	834.06	-	-	-	-
	Maize	900.00	874.97	900.27	893.11	925.90	821.62	-	925.90	-	-
	Minor Millets	1560.00	-	1560.00	-	-	-	-	-	-	-
	Paddy	945.54	979.32	945.54	988.40	984.06	953.27	983.36	984.00	984.00	946.00
	Ragi	939.27	947.74	939.27	950.91	988.99	902.61	-	989.00	-	-
2	**PULSES CROPS**										
	Avare	2550.23	2234.87	2550.23	-	2456.71	2432.92	-	-	2456.71	2550.23
	Bengal gram (Gram)	2626.19	4394.24	2626.19	-	3532.86	3238.28	-	3532.86	-	2626.19
	Black gram	4984.98	3874.48	4984.98	-	5473.22	4420.44	-	5473.22	5473.22	4984.98
	Cowpea	2336.74	2251.65	2336.74	2689.33	2606.98	3536.14	-	2606.98	2606.98	2336.74
	Green gram	3486.06	3967.20	3486.06	-	4128.95	4239.37	-	4128.95	4128.95	3486.06
	Horse gram	1601.18	1667.18	1601.18	-	1560.01	1665.11	-	1560.01	1560.01	1601.18
	Tur (Red gram)	4495.61	4387.40	4495.61	-	3973.62	-	-	-	3973.62	4495.61
3	**OIL SEEDS CROPS**										
	Linseed	2569.52	-	-	-	-	-	-	-	-	-
	Castor	2563.52	2520.74	2569.52		3973.62	2605.32	-	-	-	-
	Groundnut	3335.87	1496.76	2563.52	2716.52	2130.70	2351.64	-	2130.70	-	2564.00
	Niger seed	4465.82	3432.45	3335.87	-	3093.87	2853.61	-	-	-	-
	Rape & Mustard	2703.29	4465.82	4465.82	-	-	-	-	-	-	-
	Safflower	3993.88	3383.83	2703.29	-	-	-	-	-	-	-
	Sesamum	3993.88	2368.29	3993.88	-	4465.82	4258.06	-	-	-	-
	Soyabean	-	-	-	-	-	-	-	-	-	-
	Sunflower	2429.32	-	2429.32	-	2476.03	2676.09	-	-	-	-
4	**COMMERCIAL / FIBRE CROPS**										

	Cotton	3690.52	2805.66	3690.52	-	-	2980.41	-	-	-	3690.52
	Sugarcane	929.57	929.57	929.57	-	-	919.98	-	-	-	930.00
	Tobacco	2684.29	2684.29	2684.29	2684.29	-	2556.56	-	-	-	2684.29
5	**PLANTATION & HORTICULTURAL CROPS**										
	Lemon	3016.56	3016.56	3016.56	-	3016.56	2883.71	-	-	-	3016.56
	Onion	869.96	922.69	922.69	-	890.30	927.60	-	-	890.00	870.00
	Tomato	677.08	613.56	939.20	561.42	561.42	544.90	-	-	561.00	677.00
	Banana	1690.69	1690.69	1690.69	1690.69	1690.69	1510.27	1646.28	-	-	1690.69
	Beans	1390.81	1391.21	1309.42	1309.67	1309.67	1533.91	-	-	1310.00	1391.00
	Brinjal	740.28	748.49	747.26	748.49	748.49	637.83	-	-	748.00	740.00
	Cabbage	405.93	405.93	405.93	405.93	407.94	374.99	-	-	-	406.00
	Cashewnut (Raw &Processed Nuts)	4667.80	4667.80	4667.80	4667.80	4348.33	4098.33	4098.33	-	-	4667.80
	Coconut	4466.02	4466.02	4466.02	4466.02	4466.02	4351.66	4351.66	-	-	4466.02
	Grapes	1738.93	1738.93	1738.93	-	-	1619.04	-	-	-	1738.93
	Guava	584.71	584.71	584.71	584.71	584.71	552.13	-	-	-	584.71
	Mango	670.58	670.58	670.58	670.58	670.58	633.50	-	671.00	-	670.58
	Papaya	726.04	726.04	726.04	726.04	726.04	714.00	-	-	-	726.04
	Pomogranate	7443.38	7443.38	7443.38		7443.38	7224.00	-	-	-	7443.38
	Potato	883.49	639.43	799.11	800.00	800.00	954.64	-	-	-	883.49
	Sapota	1493.10	1493.10	1493.10	1493.10	1493.00	1408.63	-	-	-	1493.10
	Sweet potato	450.96	568.27	568.27	568.27	275.00	551.63	-	-	-	450.96
	Tapioca	806.59	806.59	-	806.59	-	776.76	721.29	-	-	806.59
	Coffee (Arabica)	11997.13	-	14250.18	14304.36	-	-	14304.36	-	-	-
	Coffee (Robusta)	8208.75	-	9981.82	6772.36	-	-	6772.36	-	-	-
6	**CONDIMENTS & SPICES CROPS**										
	Coriandar	4558.09	4558.09	4558.09	-	4558.09	4350.82	-	-	-	4558.09
	Arecanut (Raw & Processed Nuts)	13331.14	9343.66	9343.66	9343.66	9343.66	13876.97	12942.44	-	-	13331.14
	Black Pepper	21845.87	20784.95	20784.95	19541.56	-	18152.31	23283.95	-	-	21845.87

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Cardamom	73691.80	73691.80	73691.80	73691.80	-	73547.61	73547.61	-	-	73691.80
Dry Chillies	4388.39	4338.89	4338.89	4338.89	5394.66	4937.84		-	-	4388.39
Dry Ginger	3525.27	1668.86	3525.27	3525.27	3525.27	3275.26	7293.97	-	-	3525.27
Garlic	-	3310.75	3310.75	-	-	3145.66	-	-	-	4459.60
Turmeric	4459.60	4765.48	4459.60	4459.60	4459.60	3802.76	3802.76	-	-	-

Source: Extracted and compiled fro**m https://agmarknet.gov.in/.**

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