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APPLICATION OF CROP WATER MODELLING IN SUSTAINABILITY OF GROUNDWATER AGRICULTURE

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ABSTRACT

The sustainability of agriculture depends upon sustainable use of water, especially groundwater which is available throughout the year, even in summer. Over the past decades, in India, the area irrigated through groundwater has gained momentum. This led to increase in the number of over-exploited and critical firkas. The same trend is also witnessed in the western agroclimatic zone of Tamil Nadu and hence, Erode district of this region is purposively selected to calculate groundwater availability and requirement for agriculture in the study area. The study found that there is an imbalance between groundwater availability for agriculture and requirement for agriculture in the study area and so recommends for optimization of cropping area. Hence, Sen's Multiple Objective Programming is used to optimize the cropping area which will ensure sustainability groundwater resources of the study area leading to sustainable agriculture in future. The study also recommends points for sustainability of agriculture and groundwater use.
***Keywords* :** Groundwater irrigation, sustainability, agriculture, over-exploitation.

Introduction

Water is the most important elixir of human life. Not only humans, all living organisms require water for their daily external activities, physiological and metabolic process. Also, it is one of the most essential inputs for agriculture. Now-a-days several latest measures and technologies has been introduced for increasing productivity in crop cultivation. Even technology advancement had gone to very long extent by introducing cultivation without soil, but with water alone called hydroponics had been developed on one hand. On the other hand, land less cultivation, cultivation in pots called vertical gardening. But the technology to cultivate crops without water has not been developed till now and it is impossible. This shows the importance of water in agriculture. Hence, inorder to sustain agriculture, sustainable use of water is also required, as without water agriculture is not possible.

Total water available on earth was estimated to be a volume of 1386 million kilometer cube. It includes water from oceans, glaciers, surface water sources like tanks, rivers and groundwater source. Oceans and glaciers cannot be consumed or used because of their salty and crystalline nature respectively. Surface water sources will be available in plenty during the rainy period whereas groundwater sources are found to be used throughout the year. Also, groundwater is the only source, where the surface water sources like rivers, dams, tanks are unavailable or limited. Ground water is the very good source for drinking and irrigation, because of the purification properties of the soil. In arid and dry zones, ground water becomes the major source of water (Fried, 1975). Over the past half century, groundwater has boosted agricultural production in large parts of Asia, North Africa and the Middle East.

In India, the groundwater irrigation has gained momentum after independence, that too especially after

1960s (Zaveri *et al*., 2016). This is due to the introduction of tube well technology in India. The contribution of area irrigated by groundwater was only 29 per cent in 1951 and it has increased to 63 per cent in the year 2014 (Jain *et al*., 2019; Jain *et al*., 2021). This clearly shows that without groundwater, agriculture in India would have become critical but, now the groundwater level in India is becoming critical.

There are several reasons quoted by researchers for increase in groundwater consumption. Green revolution is one of the important factors responsible for the increase in groundwater consumption (Devinini, 2022). Feeding the entire population of the country is the motive of green revolution (Singh *et al*., 2020). Thus, introduction of tubewell technology and green revolution helped to increase the area under cultivation of crops and thus helped to meet the food requirements of the country. In addition to this several state governments in India provide free electricity for farmers inorder to operate pumps for irrigation. However, on the other side this paves the way for depletion of groundwater and decrease in groundwater levels in India. It is acceptable that surface water irrigation alone is not sufficient to meet the food demand of the nation, groundwater is also essential to satisfy the growing population need (Dhawan 2017), but Patle *et al*. (2015) described that in several places in India the groundwater level shows a declining trend over the years from 1970 to 2010.

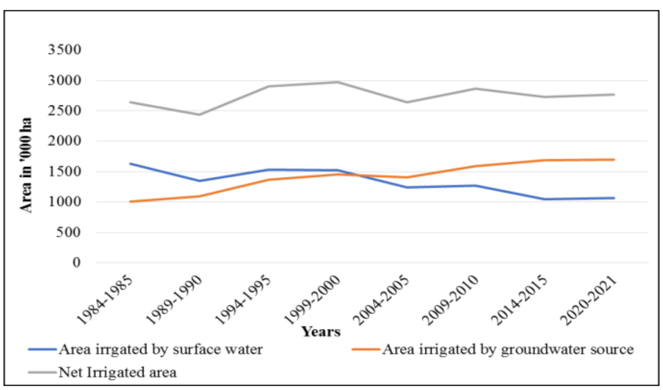

Fig. 1 : Net area irrigated by source in Tamil Nadu (1974 – 2021)

The same trend was also found in Tamil Nadu. The area irrigated by surface water resources had declined but the area irrigated through groundwater resources had increased. In addition, the net area irrigated also slowly increasing over years. So, it is evident that, the area irrigated by groundwater has to saturate the decreasing area irrigated by surface water and then to increase the net irrigated area. From this, it is clear that this continuous increase in the area irrigated by groundwater resources, leading to continuous exploitation of groundwater resources.

Since agriculture is the top most exploiter of groundwater in India, modifications are required in case of crop water modelling, irrigation systems etc., especially in the areas of predominant groundwater irrigation.

Statement of problem

According to Public Works Department of Tamil Nadu, in the year 2016, the total number of firkas in Tamil Nadu was 1129 and the number of over-exploited and critical firkas in Tamil Nadu was 374 firkas and 48 firkas respectively. In the year 2019, the total number of firkas was 1166 and the number of over-exploited and critical firkas has increased to 462 and 79 respectively. If the trend continues, then in future, majority of the firkas will fall under over-exploited and critical category. According to several studies, groundwater exploitation is highest for agriculture and hence a study was carried out to focus towards sustainability of groundwater resources which will lead to sustain agriculture in future with the following objectives:

Objectives

- To estimate the crop water requirement of crops and water availability for agriculture (Groundwater and surface water) in the study area.
- To optimise cropping area of the existing cropping for profit maximisation, water use minimization and both.

Materials and Methods

Design of the study

Tamil Nadu is one of the leading states of groundwater exploitation in India. Western Agroclimatic zone of Tamil Nadu is purposively selected based on the status of groundwater exploitation. The western Agro-climatic zone comprises of Coimbatore, Tiruppur and Erode districts. These three districts together have a total of 105 firkas. In this, 68 firkas comes under over-exploited category, 13 firkas under critical category, 15 firkas as semi-critical and only 9 firkas are safe. In other words, more than 50 per cent (64.76 per cent) of the firkas are over-exploited in the Western Agro-climatic zone (Groundwater resource Assessment report - 2020). Hence this zone is purposively selected.

Two stage purposive sampling is followed and in the next stage based upon the quantity of groundwater extraction, the district is selected. Annual groundwater extraction of Tiruppur, Coimbatore and Erode districts were 55988.43, 49635.60 and 64481.82 ha.m respectively. Quantity of annual water extraction is highest in Erode district and hence the district is purposively selected.

Crop water

Crop water requirement for each crop in the study area was calculated by CROPWAT 8.0 software developed by FAO by which the total water demand in the study area can be calculated. The FAO CROPWAT program includes reference evapotranspiration and crop water requirement calculations under various soil, crop and climatic characteristics.

Reference evapotranspiration (ET_0), was calculated by using Penman–Monteith method by using maximum and minimum temperature, relative humidity, windspeed, sunshine hour of the available meteorological station in the study area. Crop evapotranspiration (ET_C) of a particular crop was calculated by the formula

$$ET_C = K_C * ET_0$$

where, K_C is the crop coefficient of the crop.

K_C values for initial, mid and late growth stages are used for annual and seasonal crops, same K_C is used for the whole year in case of perennial crops, same K_C is used for the whole year (Surendran *et al*., 2015). The calculation also includes soil characteristics, effective rainfall and crop details for calculation of crop evapotranspiration. Thus, crop water requirement (mm) is calculated by subtracting crop evapotranspiration from effective rainfall.

Thus, water requirement (ha.mm) of a particular crop is calculated by multiplying crop water requirement (calculated by CROPWAT) with total cultivated area (ha) of that crop in the study area. The total cultivated area of Erode district in the year 2020-21 was taken into account. In this way water requirement is calculated for different crops cultivated in the study area. By summing, the water requirement of all the crops in the study area, the total water requirement (ha.m) of the study area for agriculture can be obtained.

Water availability

Data of groundwater availability for agriculture in the study area was taken from the report on Dynamic Ground Water Resources Assessment of Tamil Nadu–2020. Annual extractable groundwater is taken as total groundwater available. Water use for industry and house hold are detected from the total and 10 percent may be left for sustaining future use. Quantity of water left after meeting those demands are meant for irrigation purpose. Surface water availability was calculated from Irrigation profile of Erode district. It is the sum of total capacity of dams and tanks used for irrigation. Data on surface water available for agriculture is calculated as the balance water available after deducting the demands of households and industry. Transmission loss and other losses of water in canal were taken into account as 20 percent (Mohammadi *et al*., 2019; Clemente *et al*., 2013).

Linear Programming

Linear programming is a method for determining the profit maximizing combination of farm enterprises that is feasible with respect to a set of fixed farm constraints. In this study Linear Programming is used for sustaining groundwater use by maximizing profits (Z_1) and minimizing water use (Z_2).

Objective function 1 - Maximization of Profit (Z_1)

$$\text{Maximize } Z_1 = \sum_{i=1}^{n} P_i * A_i, \text{ (i = 1,2,….. n)}$$

where P is the profit from ith crop (in Rs./ ha), A is the Area of the ith crop (in ha) and n is the number of crops. (Kumari *et al*., 2017; Gautam *et al*., 2020)

Objective function 2 – Minimization of water use (Z_2)

$$\text{Maximize } Z_2 = \sum_{i=1}^{n} W_i * A_i, \text{ (i = 1,2,….. n)}$$

where W is the water requirement from ith crop (in mm), A is the Area of the ith crop (in ha) and n is the number of crops.

Model constraints

i) Land area constraint

Land area constraint is one of the important constraints. The sum of land optimized under all the crops should not be greater than the total cultivable area. It is given as follows

$$\sum_{i=1}^{n} A_i \le TA$$

Where ‘A’ is the area of individual crops from 1 to n and ‘TA’ is the total cultivable area (ha)

ii) Water availability constraints

Total quantity of water required for irrigation of all the crops in the study area should be less than or equal to total available water (surface and ground water) after meeting all the demands except agriculture including households, industry, transmission losses and others in the study area. It is given as

$$\sum_{i=1}^{n} W_i * A_i \le TWA$$

Where $W_i * A_i$ is the water required for i th crop and TWA is the total water availability (in ha.m) in the study area.

iii) Crop Area constraint

To meet the local requirements and to prevent the prevailing cropping practices in the study area, Upper and lower limits was fixed by considering the area of all cultivated crops for the past ten years in the study area

$$A_i^{min} \leq A_i^{opt} \leq A_i^{max}$$

where, A_i^{min} and A_i^{max} is the minimal and maximal area respectively that the i^{th} crop can be cultivated to that extent and A_i^{opt} is the optimized area.

iv) Non negativity constraint

$$A_i \geq 0; W_i \geq 0$$

Area and water requirement of i th crop will not be negative and should be greater than 0 (Singh *et al*., 2020; Singh A 2016).

Multiple Objective Programming

The individual optimization of profit and water use have generated two different cropping patterns that have a vast differences and variation of cropping pattern were at both the extremes. To overcome this problem and to generate an optimal and appropriate farming system ty achieving both the objectives simultaneously, Sen's Multiple Objective Programming method [Sen (1983)] was used. Sen's MOP method is described as below:

$$\text{Maximize } Z^* = \frac{\sum_{i=1}^{n} P_i * A_i}{W_1} - \frac{\sum_{i=1}^{n} W_i * A_i}{W_2}$$

Where, Z* represents multiple objective function W_1 and W_2 are individual optimizations under profits and water use. The constraints that given in the individual optimizations were considered in the Multiple objective programming to draw optimized conclusions (Kumari *et al*., 2017 and Maurya *et al*., 2019).

Results and Discussion

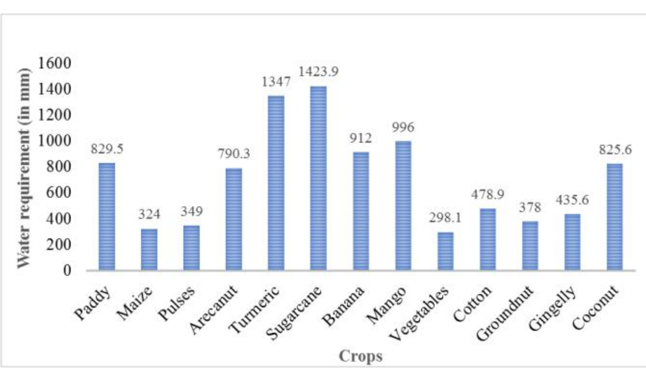

Fig. 2 : Water requirement of different crops in Erode district

Figure-1 showed the water requirements of crops in the Erode district. It is found that sugarcane requires more water for growth with 1423.9 mm followed by Turmeric with 1347 mm of water. Mango, Banana requires above 900 mm of water per year followed by coconut with 825.6 mm of water. The economic life period of crops like sugarcane, banana ranges from 10 – 12 months, coconut and mango are perennial crops, which makes these crops to require more quantity water since it has to be irrigated throughout the year. On the other hand, crops like Maize, millets, vegetables and groundnut are seasonal and has a shorter duration of 4 to 6 months, requires very low amount of water compared to other crops and their water requirement ranges from 250 mm to 450 mm. Paddy is one of the important crops in the Erode district and it requires about 829.5 mm of water for growth. Even though paddy is seasonal crop, it requires more water for its physiological growth and metabolism. Based on the water requirements of different crops in the study area, the total water requirement for agriculture in erode district was calculated and found to be 94742.05 ha. m.

Table 1 : Source wise water availability in Erode district

Source	No	Water available for irrigation (ha.m)
Dams, reservoirs and canals	10	42120.21 (46.56)
Ponds/ Tanks	698	765.22 (0.84)
Tubewell/ Borewell	9612	47595.09 (52.60)
Open well	75163	
Total		**90480.52(100.00)**

Note - Figures in the parentheses indicates the percentage share to the total.

The source wise water available for irrigation in Erode district can be traced from the table-1. It was found that quantity of water available for irrigation from surface and ground are almost equal. The quantity of water available for irrigation from groundwater source was collected from the central groundwater board district level data and that was entered in place of water available irrigation through wells together. The quantity of water available for irrigation by groundwater source is 52. 60 per cent and by surface water source is 47.40 per cent. However, 46.56 per cent of water is stored in dams and reservoirs, the capacity of tanks is too low as they store only 0.84 per cent of water for irrigation.

Table 2 : Source-wise area irrigated in Erode district, 2020 -2021

Source	Potential irrigable area (ha)	Actual area irrigated (ha)	% of actual area irrigated to potential area
Dams, reservoirs and canals	51090.49	46490.49 (37.98)	91.88
Ponds/ Tanks	1382.131	12.63 (0.01)	0.91
Tubewell/ Borewell	NA	14859.17 (12.14)	-
Open well	NA	61044.78 (49.87)	-
Total		**122407.07 (100.00)**	-

Note - Figures in the parentheses indicates the percentage share to the total.

The table–2 showed the area irrigated from different sources in Erode district. The results revealed that openwells are the predominant source of irrigation, which alone irrigates almost 50 per cent of the total irrigated area. Dams and reservoirs occupy the second place by irrigating 37.98 per cent of total irrigated area followed by tubewell and borewell with 12.14 per cent. Lastly tanks provide water only to 0.01 per cent of the irrigated area. The table also revealed that dams and reservoirs irrigates 91.88 per cent of the total area that can be irrigated by it, whereas tanks irrigates only 0.91 per cent of its total capacity. Crops like sugarcane, banana, coconut, mango and other perennial fruits occupy almost 40 per cent of the total irrigated area under cultivation in the Erode district, whose life period is either perennial or 10 -12 months and hence these crops require water for the whole year. In addition, water released by the tanks and dams are seasonal in nature, farmers cannot depend on then for the whole year. These made famers to construct wells of their own for irrigating these perennial crops, which lead to increased use of groundwater and excess depletion of groundwater.

By comparing the table–1 and 2, it was revealed that with the available water of 42120.21 ha. m, dams, reservoirs and canals could be able to irrigate 51090.49 ha area of land, but it actually irrigates only 46490.49 ha of land. On the other hand, with the annual total extractable volume of 47595.09 ha. m of groundwater, wells irrigates 75903.95 ha of land. This clearly showed that extraction of water is beyond the limit. The study found that this might be the reason for increase in the number of overexploited and critical firkas in Erode district. Also, from the above tables – 1 and 2, it can be concluded that the water requirement is higher than the water availability in Erode district. In addition, more than 60 percent area under irrigation is by groundwater in the district, and hence sustainability of groundwater resources can be achieved by crop area optimization, which is done in this study in the next section.

Table 3 : Profits and water requirements under different cropping plan in Erode district

Particulars	Existing cropping plan	Profit maximization cropping plan	Water use minimization cropping plan	MOP cropping plan
Area considered (in ha)	59459.198	59459.198	59459.198	59459.198
Profit (in crore Rs.)	294.67	445.71 (51.26)	290.72 (-1.34)	318.58 (8.11)
Water requirement (in ha. m)	50320.48	58470.99 (16.20)	41768.594 (-16.99)	43549.13 (13.46)

The table – 3 showed the profit and water requirements of different cropping plans calculated for Erode district. Out of the total irrigated area of 122407.07 ha, area considered for optimisation was 59459.198 ha, leaving perennial crops, fruit trees and vegetables, which cannot be considered for changing cropping plan. As per the existing cropping plan under the considered area for optimisation the profit was Rs. 294.67 crores using 50320.48 ha.m of water. Individual optimisation of profit maximization objective yields maximum profit of Rs. 445.71 crores using 58470.99 ha.m of water, which is 16.20 per cent excess profit than existing cropping plan and also requires 21.72 per cent excess water.

Similarly, water use minimization objective uses only 41768.594 ha.m of water by yielding Rs. 290.72 crore profit, which is 1.34 per cent less than the profit obtained in the existing cropping but with 16.99 per cent reduction in water use. Both these plans are at the extremes one with high profit with increased water use and other with reduced water use with reduced profit. Inorder to achieve high profits with reduced water use together multiple objective programming was considered. Multiple objective programming provides profit of Rs. 318.58 crores with 43549.13 ha.m of water use, which is 8.11 per cent more profitable than existing cropping plan and reduces 13.46 per cent water use. Thus, this optimised cropping plan will be helpful in reducing the water use without affecting the profit levels of farmers in Erode district.

Table 4 : Existing Vs Optimised cropping plan of Erode district

Crop	Existing area (in ha)	Optimised area (in ha)	Change in area (in ha)	Percentage change
Paddy	29143.60	22309.94	-6833.7	-23.45
Maize	7587.82	12461.72	4873.9	64.23
Cumbu	74.04	74.04	0.00	0.00
Ragi	12.56	82.56	70.00	557.36
Red gram	59.39	438.07	378.68	637.62
Black gram	436.73	595.47	158.735	36.34
Green gram	79.075	148.22	69.145	87.44
Gingelly	3520.50	7194.26	3673.77	104.35
Cotton	550.44	737.03	186.58	33.90
Sugarcane	14211.20	10742.03	-3469.20	-24.41
Groundnut	3783.81	4675.845	892.04	23.57

The differences in the existing cropping plan and the optimised cropping plan calculated by using multiple objective programming of Erode district can be seen from the table– 4 and figure- 2. A negative sign in the column- 4 and 5 of table- 5 indicates that the area under the corresponding crop has to be decreased and conversely positive sign indicating the area of these corresponding crop area has to be increased. As per the cropping plan obtained by multiple objective programming area under water intensive crops like Paddy and Sugarcane are to be reduced upto 23.44 per cent and 24.41 per cent respectively. Maize, pulses, Gingelly, Groundnut are likely to be increased inorder to obtain more profit with reduced water use as their water requirement is comparatively low. Area under maize and Gingelly cultivation has to be increased to 64.23 and 104.35 per cent respectively. In addition, crops like ragi and red gram requires more than 500 per cent changes in area, it doesn't mean the entire area has to be changes to rag and red gram. The initial area under cultivation of these crops were very low i.e. only 12 ha and 59 ha respectively. The optimised cropping plan has increased it to 82 ha and 438 ha, which is five times higher than exiting area and hence the percentage value seems to be very high.

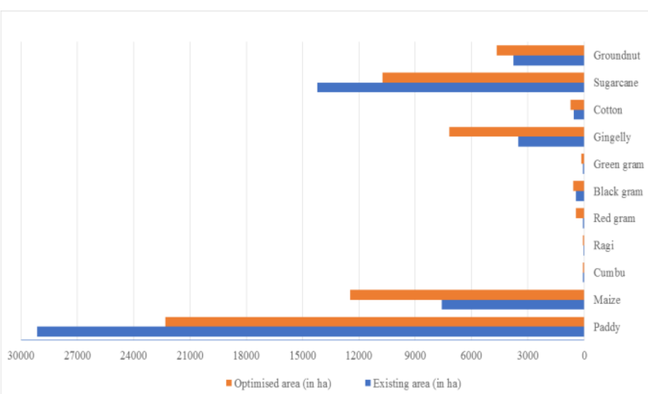

Fig. 3 : Comparison of area under optimized plan vs existing plan

Though water use can be reduced at macrolevel by adopting this cropping plan, it will not be sufficient and hence, increasing the efficiency of individual farms is required to reduce water consumption. Also, individual farms need to adopt water conservation practices for reducing water consumption in groundwater irrigated areas ensuring sustainability of groundwater.

Conclusion

The study found that there is an imbalance between water availability for agriculture and water requirement for agriculture in the study area, especially in groundwater irrigation. Hence concluded that this might be the reason for over-exploitation of groundwater in the Erode district. Crops like sugarcane, banana, coconut, mango and other perennial fruits occupy almost 40 per cent of the total irrigated area under cultivation in the Erode district, whose life period is either perennial or 10-12 months and hence these crops require water for the whole year. In addition, water released by the tanks and dams are seasonal in nature, farmers cannot depend on then for the whole year. These made famers to construct wells of their own for irrigating these perennial crops, which again lead to increased use of groundwater and excess depletion of groundwater in Erode district. Hence optimizing the cropping area is essential.

Out of the total irrigated area of 122407.07 ha, area considered for optimisation was 59459.198 ha, leaving perennial crops, fruit trees and vegetables, which cannot be considered for changing cropping plan. The results of linear programming plans are at the extremes, one with high profit coupled with increased water use and other with reduced water use coupled with reduced profit. Inorder to achieve high profits with reduced water use together multiple objective programming was considered. Multiple objective programming provides profit of Rs.318.58 crores with 43549.13 ha.m of water use, which is 8.11 per cent more profitable and reduces 13.46 per cent water use compared to existing cropping plan. As per the cropping plan obtained by multiple objective programming area under water intensive crops like paddy and sugarcane are to be reduced and crops like maize, pulses, gingelly, groundnut are likely to be increased inorder to obtain more profit with reduced water use.

The findings of the study have found the following implications on the policy issues

- The study found that the problem of over-exploitation of groundwater resources is due to reduction in area irrigated by surface water resources.
- Decrease in area irrigated through surface water resources may be due to reduction in storage capacity of surface water resources over years because of encroachments. Hence, proper desiltation of surface water resources at regular intervals may maintain the water storge in surface water resources, which may in turn increases the area irrigated by surface water resources, leads to decrease in groundwater irrigation.
- Two things are required for obtaining sustainability in groundwater resources in the study area. They are reducing the use of groundwater resources for agriculture and increasing the groundwater recharges.
- Reducing the use of groundwater resources includes following the optimised cropping plan and in crops like paddy sugarcane, coconut, mango, turmeric etc., which are either perennial in nature or require high water for growth, should adopt water conservation practices.
- Development of artificial groundwater recharge structures are to be encouraged.
- Improving rainwater harvesting, improving recharges through check dams, lakes etc., are to be encouraged.
- Also, individual farms need to adopt water conservation practices for reducing water consumption in groundwater irrigated areas ensuring sustainability of groundwater, which leads to sustainable agriculture.

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