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A Remote Sensing Approach to Map Crop Stress and Optimize Irrigation through Crop-Water Production Functions

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Abstract

Irrigated agriculture consumes over 70 % of global freshwater, intensifying competition among agricultural, urban, industrial and environmental needs. This study presents a geospatial framework that integrates remote sensing–derived evapotranspiration (ET) with crop–water production (CWP) functions to map wheat stress and optimize irrigation across Allahabad district, India. Using surface energy-balance modelling (METRIC/SEBAL) and FAO 56 reference-ET, we estimated actual (ETa) and potential (ETp) evapotranspiration for the December 2015–April 2016 season. Remote sensing–based biomass and harvest-index models yielded actual and potential grain output, enabling stage-wise yield response factor (Ky), calculation - the key coefficient in many CWP formulations via the Doorenbos–Kassam approach (FAO 33). At the district scale, wheat exhibited Ky values of 0.6, 1.5 and 1.1 for vegetative, flowering and grain-filling stages, respectively (overall Ky = 1.1), indicating high sensitivity to water deficits. Tehsil-level analyses revealed pronounced spatial variability in Ky, driven by differences in irrigation timing, volume and management practices. The Ky functions obtained using predicted yield can pinpoint "hot spots" where targeted irrigation at critical growth stages can maximize yield per drop. Embedding these spatially explicit CWP functions into an operational decision-support tool allows growers and agencies to schedule water more precisely, reallocate scarce supplies across fields, and bolster regional water security. This remote sensing–CWP fusion offers a scalable strategy for precision irrigation that enhances crop water productivity under constrained resources.

Keywords: Remote sensing, Crop–water production functions, Yield response factor (Ky), Crop stress mapping, Evapotranspiration mapping, Irrigation optimization

1. Introduction

Irrigated agriculture is by far the world's largest user of freshwater, accounting for over 70 percent of global withdrawals [1]. With rising urban and industrial demands, plus ecosystem needs, competition for that water is only going to intensify in coming decades [2]. Conserving irrigation supplies and squeezing more crop out of every drop isn't just vital for farm productivity—it underpins food security, economic development and healthy environments downstream.

At the heart of irrigation-water planning lies the crop–water production (CWP) function, which links crop yield to water consumed (through evapotranspiration, ET). By quantifying how yield falls off as ET is curtailed, CWP functions allow us to evaluate deficit-irrigation strategies—where deliberate under-irrigation in some periods boosts overall water-use efficiency without disproportionate yield loss. Classic analyses show a near-linear relationship between relative yield decline and relative ET deficit [3]. In practice, a 30 % cut in irrigation often costs only ~10 % in yield—leaving a sizable "water dividend" to reallocate or save elsewhere on the farm [5].

These CWP models come in two forms viz., Jensen's stage-wise multiplicative model treats each growth phase's water stress as compounding the next [4], while Doorenbos & Kassam's FAO Irrigation and Drainage Paper 33 framework uses single-factor yield-response curves (Ky) across either the whole season or individual stages [3]. FAO 33 was later extended into additive and multiplicative forms that cover multiple stress periods simultaneously [6].

Extensive FAO data show that water-deficit sensitivity varies sharply by crop and by phenological stage. For many cereals, a 20 % ET shortfall during heading through flowering can slash grain yield by up to 50 %, whereas similar deficits during tillering may cost only ~10 % of yield. Beyond cereals, CWP parameters shift with species, cultivar, irrigation method and management, and precisely when stress strikes in the crop cycle.

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Building on those classical frameworks, recent physiological and field studies point to new levers for boosting water productivity under stress. Under dryland conditions, the balance between reactive oxygen species (ROS) production and antioxidative systems (AOS) governs a crop's effective use of water (EUW)—defined as biomass generated per unit of available soil moisture rather than per unit of ET [7]. By modulating ROS–AOS interactions through genetic or exogenous treatments, plants can sustain growth and photosynthesis during and after drought episodes, effectively stretching limited water supplies without incurring proportional yield losses. Integrating ROS–AOS–mediated EUW gains into CWP models offers a pathway to refine Ky values, especially under transient stress, by coupling biochemical resilience metrics with stage-specific ET deficits.

In parallel, field trials in two distinct Punjab agro-climatic zones quantified how timing and amount of irrigation interact with sowing date and nitrogen management to shape wheat's water–yield response [8]. For HD-2967, optimal irrigation at crown-root initiation, jointing, flowering and grain-fill stages lifted WUE (kg grain · m^{-3} water) by up to 25 % compared to sub-optimal regimes, while delayed planting amplified sensitivity to water deficits—shifting CWP slopes toward steeper yield penalties under the same ET shortfall.

Yet all these functions hinge on point-based ET and yield measurements, so they miss the field's inherent spatial variability in soil moisture, canopy cover and crop stress. Remote sensing bridges that gap—delivering wall-to-wall maps of crop water status, evapotranspiration and stress indicators. Integrating satellite- or UAV-derived ET fields with established CWP functions opens the door to spatially optimized irrigation: allocating just the right amount of water where and when it will most boost water productivity, and flagging stress "hot spots" before yield is lost. That fusion of remote sensing and CWP modelling is exactly what this paper explores, offering a pathway to map crop stress and fine-tune irrigation for maximum yield per drop.

1. Methodology

The present study was conducted for the wheat growing regions of the Prayagraj (formerly Allahabad) district in the state of Uttar Pradesh. All the estimates in the study area were made for the crop growing season of December, 2015 - April, 2016. With respect to its total area, Allahabad is the sixth largest district in U.P. and have the largest population in the state (Census of India, 2011). The district is sub-divided into eight tehsils/administrative divisions namely Koraon, Allahabad, Soraon, Karchhana, Bara, Handia, Phulpur and Meja. As per the 2011 census, the total area of Allahabad district was 5,57,014 hectares with rural and urban areas being 5,34,729 and 22,285 hectares respectively.

The yield response factors for wheat crop grown in Allahabad district were developed in the present study using the following relationship (Doorenbos and Kassam, 1979):

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{ET_m}\right) \quad (1)$$

Where: Y_a = Actual Harvested Yield

Y_m = Maximum Harvested Yield/Potential Yield

K_y = Yield Response Factor

ET_a = Actual Evapotranspiration

ET_m = Maximum/Potential Evapotranspiration

Equation 1 was developed to relate crop water use/evapotranspiration (ET) with its relative yield. Through this equation the changes in relative yield of a crop can be modeled with respect to the changes in crop ET. In this equation, the yield response factor, K_y represents the biological, physical and chemical processes involved in the production and water used by the crop. The Ky values are crop specific and vary with the individual growth stages of the crop across its growing season. The Ky values can be greater, lesser or equal to one and following classification of the yield response factor is used to describe the impact of water deficit on yield:

- $K_y > 1$: crop is highly sensitive to water deficit and could result in proportionally larger reduction in yield.
- $K_y < 1$: crop is more tolerant to water deficit and partially recovers from water stress resulting in less than proportional reduction in the yield.
- $K_y = 1$: reduction in yield is directly proportional to water deficit.

The present study utilized equation 1 to model yield response factors for wheat grown in the Allahabad district during the 2015-16 growing season. The following procedural steps were adopted to obtain the yield response factors:

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- Actual ET (ETa) for wheat was estimated by applying surface energy balance modelling [9], [10] and [11] with remotely sensed data and ancillary ground-based weather data.
- The maximum/potential evapotranspiration for wheat in the present study was estimated following reference ET and crop coefficient approach suggested in Food and Agriculture Organization, Irrigation and Drainage Paper # 56 [12].
- The actual yield (Ya) for wheat was estimated following a remote sensing approach [13] by taking into account the photosynthetically absorbed radiation (PAR), biomass and harvest index.
- The maximum/potential yield for wheat crop was estimated following the procedure suggested in Food and Agriculture Organization, Irrigation and Drainage Paper # 33 [2].

The methodology followed in the present study for developing yield response factors for wheat is summarized in figure 1 using a flowchart.

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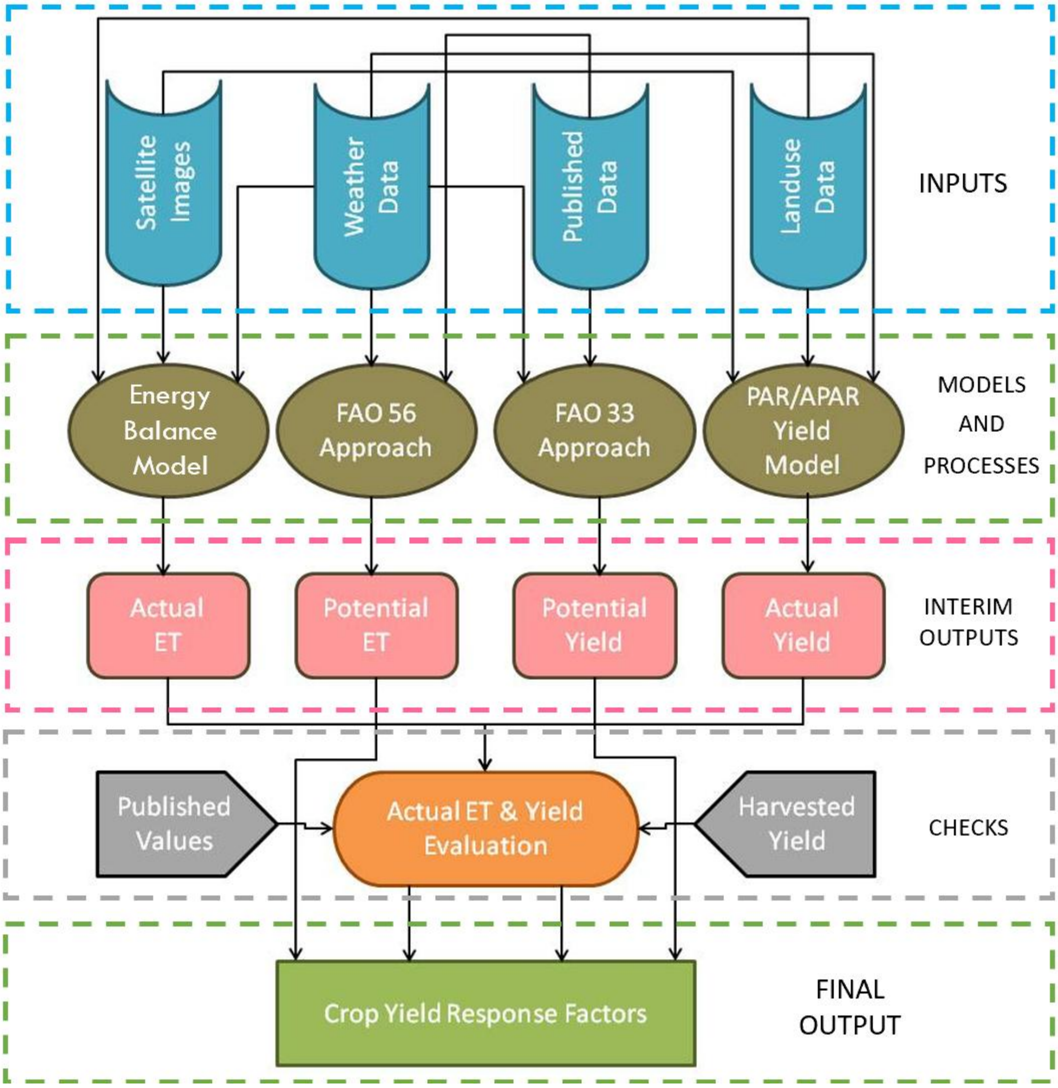

Figure 1. Methodology Flowchart for Developing Yield Response Factors for Wheat

2. Results and Discussion

The yield response functions for wheat grown in the entire Allahabad district were estimated to be 0.6, 1.5 and 1.1 for vegetative, flowering and yield formation stages respectively. The Ky value of 0.6 during vegetative stage indicates that crop is more tolerant to water deficit in this stage and partially recovers from water stress resulting in less than proportional reduction in the yield. The Ky functions for next two stages (flowering and yield formation) are greater than 1 and indicates that crop is highly sensitive to water deficit in these stages and could result in proportionally larger reduction in yield. Overall, with a Ky value of 1.1 over total growing period, the

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wheat crop at district level was found to be highly sensitive to water deficit which potentially can lead into proportionally larger reduction in yield.

The yield response functions were also estimated for the wheat grown in individual tehsils in the study area viz., Allahabad, Bara, Handia, Karchana, Koraon, Meja, Phulpur and Soraon (Table 1 and Figure 2).

The Ky function for the wheat grown in Allahabad tehsil were found to be 0.4, 1.0 and 0.7 for the vegetative, flowering and yield formation stages respectively. The Ky value of 0.4 during vegetative growth stage indicates that crop is more tolerant to water deficit in this stage and partially recovers from water stress which results in less than proportional reduction in the yield.

Table 1 Yield Response Functions Developed for the entire District

Tehsils Under Consideration	Growth Stages			Total Growing Period
	Vegetative	Flowering	Yield Formation	
Allahabad	0.4	1.0	0.7	0.7
Bara	0.2	0.7	0.5	0.5
Handia	0.1	2.1	0.2	0.3
Karchana	0.3	0.7	0.7	0.6
Koraon	0.7	0.7	0.7	0.7
Meja	0.1	2.6	0.2	0.3
Phulpur	0.1	1.5	0.3	0.4
Soraon	0.3	0.7	0.4	0.4

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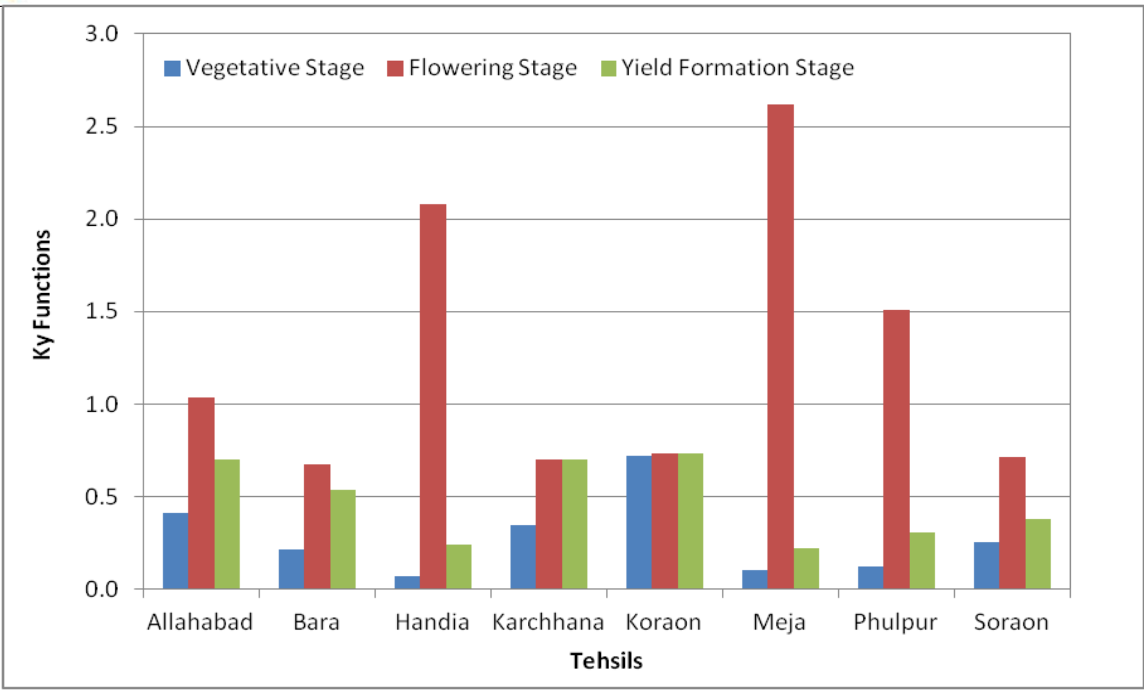

Figure 2. Crop Water Production Functions for Wheat in respective Tehsils

However, with a Ky value of 1.0 for flowering stage makes this stage highly sensitive as the reduction in yield is directly proportional to water deficit that could occur during this stage. In the yield formation stage the Ky function value for this tehsil again drops below 1.0 indicating that crop in this stage becomes more tolerant to water deficit and the reduction in yield will not proportional to the reduction in water applied. The Ky function for total growing period was also found to be less than 1.0 which leads to an overall conclusion that wheat grown in Allahabad tehsil can bear water deficit to an extent where the yield will not decrease proportionally with the decrease in water applied.

The Ky functions for wheat grown in Bara tehsil were found to be 0.2, 0.7 and 0.5 during vegetative, flowering and yield formation stages respectively. These less than 1.0 values of Ky function indicates that wheat grown in this tehsil is tolerant towards water deficit and there won't be a proportional decrease in the yield with respect to the decrease in water applied. The Ky function over total growing period was also found to be less than 1.0 indicating the same conclusion as mentioned above.

The Ky functions for the wheat grown in Handia tehsil were found to be 0.1, 2.1 and

0.2 during the vegetative, flowering and yield formation stages respectively. The less than 1.0 value of Ky function for vegetative stage indicates that the crop is more tolerant to water deficit and partially recovers from water stress resulting in less than proportional reduction in the yield. However, in the flowering stage the Ky value is apparently greater than one which makes the wheat during this stage highly sensitive to water deficit and that could result in proportionally larger reduction in yield. During the yield formation stage the Ky function is again below 1.0 which indicates that crop has certain amount of tolerance against water deficit which gives it a chance to recover partially from the deficit ultimately resulting in less than proportional decrease in the yield. The overall Ky function (total growing period) for the wheat grown in this tehsil was found to be less than 1.0 indicating more tolerance and less than proportional decrease in the yield with respect to decrease in water applied.

The Ky functions for the wheat grown in Karchana tehsil were found to be 0.3, 0.7 and 0.7 during the vegetative, flowering and yield formation stages respectively. With Ky functions being less than 1.0 in all the aforementioned growth stages, the wheat grown in this tehsil appears to be more tolerant to water deficit and partially recovers from water stress. The partial recovery from water deficit means that it will result in less than proportional reduction in the yield. The Ky function for total growing period was also found to be less than 1.0 making the wheat grown in this tehsil more tolerant to the deficit in water applied and hence comparatively less reduction in yield that would be otherwise if Ky was greater than 1.0.

The Ky functions for the wheat grown in Koraon tehsil were found to be 0.7, 0.7 and 0.7 during the vegetative, flowering and yield formation stages respectively. The Ky functions below 1.0 leads to a similar indication as in the case of Karchana tehsil that wheat grown in this tehsil has more tolerance towards water deficit and has a tendency to recover partially from the water stress in all the three aforementioned growth stages. This would ultimately will lead in less than proportional decrease in the yield. Overall, a similar conclusion stands for wheat grown in this tehsil with Ky function being less than one over the total growing period.

The Ky functions for the wheat grown in Meja tehsil were found to be 0.1, 2.6 and

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0.7 during the vegetative, flowering and yield formation stages respectively. With Ky functions being less than 1.0 during the vegetative and yield formation, the wheat grown in this tehsil appears to have more tolerance to water deficit and partially recovers from water stress. The partial recovery from water deficit means that it will result in less than proportional reduction in the yield during these stages. However, in the flowering stage the Ky value is apparently greater than one which makes the wheat during this stage highly sensitive to water deficit and that could result in proportionally larger reduction in yield. The Ky function estimated for the total growing period was also found to be less than 1.0 leading to a same conclusion in regards to reduction in yield as in the case of individual stages.

The Ky functions for the wheat grown in Phulpur tehsil were found to be 0.1, 1.5 and 0.3 during the vegetative, flowering and yield formation stages respectively. The less than 1.0 value of Ky function for vegetative and Yield formation stages indicates that the crop is more tolerant to water deficit and partially recovers from water stress resulting in less than proportional reduction in the yield during these stages. However, in the flowering stage the Ky value is apparently above 1.0 indicating that wheat during this stage is highly sensitive to water deficit and that could result in proportionally larger reduction in yield. The overall Ky function (total growing period) for the wheat grown in this tehsil was found to be less than 1.0 which indicates that crop has certain amount of tolerance against water deficit which gives it a chance to recover partially from the deficit ultimately resulting in less than proportional decrease in the yield.

The Ky functions for the wheat grown in Soraon tehsil were found to be 0.3, 0.7 and 0.4 during the vegetative, flowering and yield formation stages respectively. The less than 1.0 value of Ky function for during all the three growth stages (vegetative, flowering and yield) indicates that the crop is more tolerant to water deficit and partially recovers from water stress. This attribute of having being able to partially recovered from the stress induced by water deficit results in less than proportional reduction in the yield during these stages. The Ky function over the total growing period is also less than 1.0 leading to a similar conclusion that overall the wheat grown in this tehsil is more tolerant towards water stress.

The actual ET rates estimated for the respective growth periods (Vegetative, Flowering and Yield Formation Stages) of wheat grown in individual tehsils are presented in Figure 3. It is

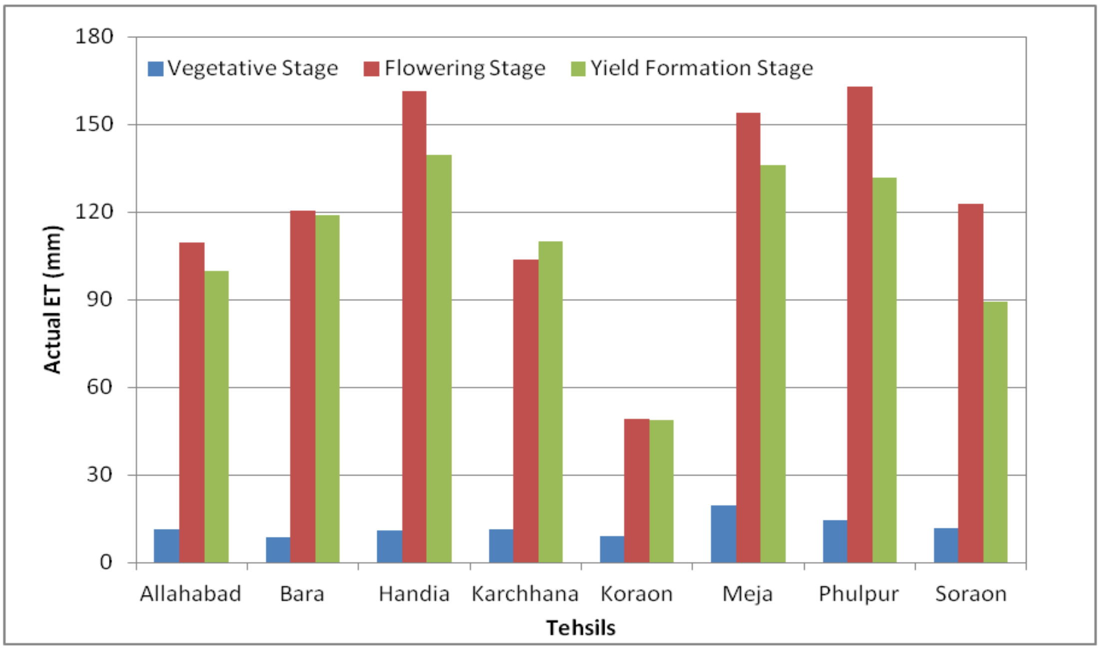

Figure 3. Actual Crop Evapotranspiration rates in Vegetative, Flowering and Yield Formation Stages of wheat grown for individual tehsils

apparent that the trend of Ky function (Figure 2) are similar to actual ET rates (Figure 3) and the variation and amount of crop ET reflects (among other factors) the impacts of timing and/or amount of irrigation applied. The crop water production functions (Ky) developed in the present study for wheat were compared with Ky functions of the same crop grown in other regions. The other sources from where the Ky functions were obtained for comparison purpose included FAO paper #33 [2], Moutonnet, P. (2002) [14] and a study conducted by Najarch et. al., 2011 [15].

The Ky function developed in the present study for vegetative period of wheat indicated that during this growth stage the crop appears to more tolerant to water deficit. The Ky functions from other sources for the same period were also below 1.0 and hence indicated that the crop is more tolerant to water deficit and partially recovers from water stress resulting in less than proportional reduction in the yield. However, the amount of reduction will differ as Ky values from all the sources are different from one another for the vegetative stage.

The Ky function developed in the present study for flowering period of wheat indicated that the crop appears to highly sensitive to water deficit and can result in proportionally large reduction in yield (Ky > 1.0). However, the Ky functions from other sources were found to be

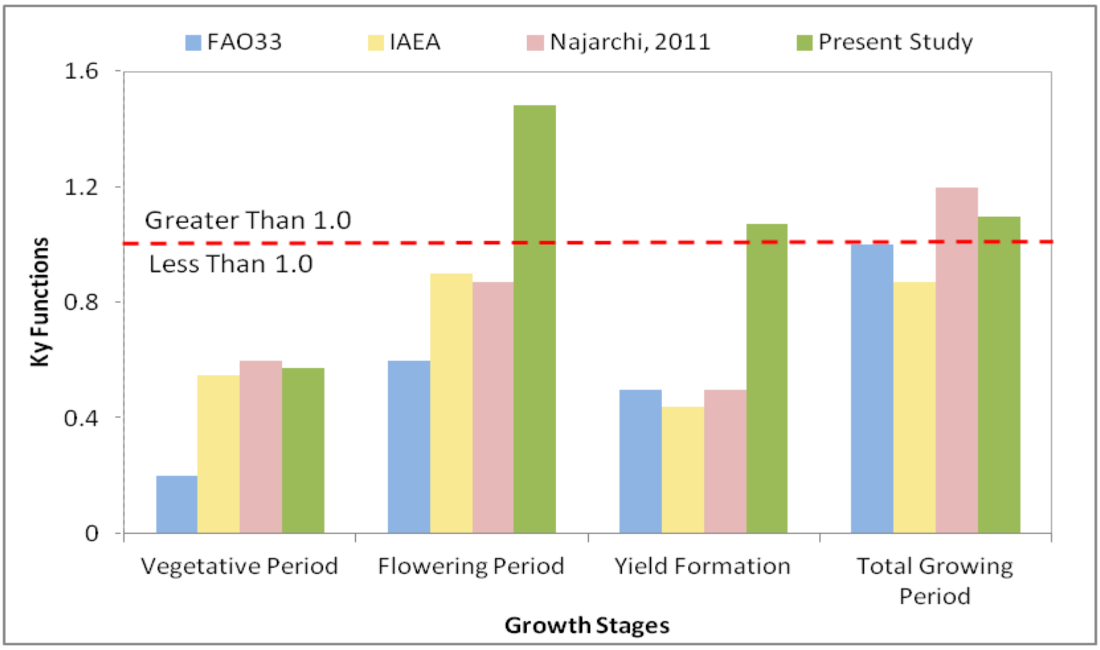

Figure 4. Comparison Of Crop Water Production Functions with Other Sources

below 1.0 indicating that in their respective areas the wheat was more tolerant to water stress with regards to it relative yield during this growth stage. However, all the Ky functions from other sources were different from one another and ranged between 0.6 - 0.9. A similar trend was apparent in Ky functions for the yield formation stage where in the Ky developed in the present study was greater than 1.0 and Ky from rest of sources were below 1.0.

The Ky function developed in the present study for the entire growing period was found to be greater than 1.0 again indicating the high sensitiveness of wheat towards the water deficit with respect to its relative yield. The Ky function from FAO 33 was 1.0 indicating proportional reduction in yield with respect to water deficit. The Ky

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function from Moutonnet, P. (2002) [14] was found to be below 1.0 which indicates that wheat was more tolerant towards water deficit in their region. However, the Ky developed for the wheat grown in Iran [15] was greater than 1.0 (but different from the Ky developed in present study) indicating that crop is highly sensitive to water deficit and could result in proportionally larger reduction in yield.

3. Conclusion

This study set out to quantify crop–water production (CWP) functions (Ky) for wheat across Allahabad district, integrating estimates of actual (ETa) and potential evapotranspiration (ETp) with yield data. The resulting district-level Ky exceeded 1.0, signaling that wheat here is exceptionally sensitive to water deficits—yield losses outpace relative reductions in ET, unlike the proportional response (Ky = 1.0) recommended by FAO 33 [2].

By deriving Ky separately for each tehsil, we demonstrated clear spatial variability in wheat's water–yield response. Differences in stage-specific Ky were traced back to both irrigation practices (timing and volume) and management factors, which drove observed disparities in ETa. This spatial heterogeneity underscores the inadequacy of one-size-fits-all irrigation guidelines and the need for field-to-field calibration of CWP functions.

Crucially, our fusion of remote sensing–derived ET with yield estimates enabled wall-to-wall mapping of crop stress and stage-wise water productivity. Such spatially explicit CWP functions offer a powerful decision-support tool: they pinpoint when and where irrigation delivers the greatest yield benefit per unit water, and highlight "hot spots" of stress before irreversible yield loss occurs.

By embedding these locally tailored CWP curves into an operational irrigation-management platform, growers and government agencies can optimize water allocation—scheduling just the right volumes at critical growth stages and rebalancing scarce supplies across fields. This remote sensing–CWP framework thus paves the way for precision irrigation that maximizes wheat yield per drop and strengthens regional water security.

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