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Review Paper

WATER -USE EFFICIENCY AS AFFECTED BY DIFFERENT FACTORS AND MANAGEMENT INTERVENTIONS - A REVIEW

B B Vashisht* and S K Jalota

Department of Soil Science
Punjab Agricultural University, Ludhiana-141004, Punjab

ABSTRACT

Measurement of water productivity/use efficiency is an important tool for the selection of soil and crop management technologies for enhancing yield as well as irrigating water savings In the present study quantitative information is synthesized from the data at hand in the literature on change in water productivity, based on irrigation water (WP_I), total water (irrigation rain) input (WP_{I+R}) and evapotranspiration (WP_{ET}), corresponding to change in yield, irrigation water, and evapotranspiration (ET) in different soil, water and crop management technologies. WP_I and WP_{ET} are more in the technology which ensures a more % increase in yield than a % reduction in irrigation water and/ or ET. WP_{ET} is increased with increasing transpiration (T) component of ET and subsequently yield by means of mulching with crop residue, deep tillage, and N application. WP_I is increased with a reduction in irrigation water via (i) growing shorter duration cultivars in the period of least potential evaporative demand in which yield potential is highest (ii) scheduling irrigation based on the demand and using proper irrigation method (iii) modifying soil surface in such a way that irrigation is applied in shorter period (with laser leveling) and applied water retained is more and for longer period by the soil (medium to finer textured soils). Amongst different crops, WP_I is more in sugarcane and less in rice while WP_{ET} is more in sugarcane and less in cotton. In a cropping system, WP_{ET} is less as ET is more due to its inclusion from intervening bare period too.

Keywords: Crops, Irrigation efficiency, Transpiration, Water productivity

Knowledge of water use efficiency is vital for the selection of yield-enhancing soil and crop management technologies. Theoretically, efficiency is a measure of the output obtainable from a given input. Engineers, plant physiologists, and agronomists define water efficiency variably depending upon the nature of the input and output of water. From the agricultural engineering viewpoint, water efficiency is percent water added to the root zone (as irrigation) of the supplied from any source. There are two types of efficiencies i.e. *conveyance efficiency and distribution efficiency,* which are expressed as percentage. The conveyance efficiency is the percent water reached at point of application (crop) of the discharged water from the source (distributaries and tube-wells) while passing through channels. In opened earthen channels conveyance efficiency is very low (ranging from 30 to 40 per cent) as lot of water is lost by seepage and evaporation due to their vulnerability to erosion, breaches, damage by rodents and weed infestation as well as high evaporative demand. The *distribution efficiency* is percent water irrigation distributed in the profile at the point of its application of the water delivered at the soil surface in the plot. Generally, two measures are used for water application efficiency viz. application efficiency (E_A) and distribution efficiency (E_D). Percent E_A and E_D are computed as

Per cent $E_A = (W_S/W_d)*100$

Per cent $E_D = (1-N/D)*100$

Where W_S is water stored in the root zone, W_d is water delivered to the field during irrigation, N is average numerical deviation in depth of water stored at different locations from the average storage depth (D) of the field following irrigation.

A more objective criterion is the agronomic one where yield is the output and irrigation water is input, and then the water efficiency is called *water productivity*, WP_I (Zwart and Bastiaanssen, 2004). Though WP_I is commonly used, but it has some limitations. (i) It not only the irrigation water is used by plants for contributing dry matter/yield, but rain water as well as water by capillary rise also. There are some reports that the efficiency of rainwater as well as capillary water is more than irrigation water (ii) while calculating irrigation water productivity of a crop or cropping system, the irrigation water applied for preparation of seed beds and sowing of the crop during the intervening periods is not accounted for computing total irrigation water applied. Such amounts are of greater importance in some crops (Jalota and Arora, 2002: Jalota and Gill, 2003; Bhatt and Kukal, 2015). For example, in transplanted rice crop seedlings are transplanted on puddle soil. Puddling

*Corresponding author : bharatpau@pau.edu
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is a necessary operation to minimize drainage during the crop period although it requires a plenty of irrigation water is required. The concept of water productivity is objectionable as it is not useful in agricultural water management (Dirk Zoebl, 2006).

When crop dry matter is output and transpired water as input, the efficiency is called *water use efficiency* WUE (Viets, 1962).

$$WUE = Y_{act}/T_{act}$$

Where Y_{act} is actual yield and T_{act} is actual transpiration by the plant. As most of the applied water (99%) is transpired and only a small fraction is retained by the plant, therefore, water use efficiency is the reciprocal of transpiration ratio, the mass of water transpires per unit mass of dry matter produced (Briggs and Shantz, 1913). But under field conditions it is very difficult to separate out transpiration from evaporation because transpiration from plant is in concert with evaporation from soil surface. Hence rather than transpiration, evapotranspiration is used to calculate WUE. The numerical value of WUE based on evapotranspiration is relatively less than based on transpiration because evaporation of soil water does not contribute to dry matter or yield of the crops. The WUE is also called crop water productivity (CWP) or water productivity based on evapotranspiration (WP_{ET}) as

$$WUE \text{ or } CWP \text{ or } WP_{ET} = Y_{act}/ET_{act}$$

Where Y_{act} is actual yield and ET_{act} is actual evapotranspiration. Since ET_{act} is based on root water uptake, it integrates all supplies from rainfall, irrigation and capillarity. Some researchers (Prihar *et al.,* 1978; Jalota *et al.,* 1985) used water expense efficiency, where water used also includes the soil profile depletion (soil moisture storage in the root zone at sowing minus at harvest of the crop) when crops are grown under limited water supplies. Sometimes efficiency of water is defined in terms of costs of output (yield) and input (water) and that is called *economic efficiency of water* (Jalota *et al*., 2011). However, the economic criterion of efficiency has the inherent problem of fluctuations in prices of inputs and outputs so it is a very dynamic. In the literature mostly two types of crop water productivities are talked about. First type is based on water input as irrigations i.e. post- sowing only or both pre-sowing + post- sowing (WP_I) and total water input comprising of irrigations + rain (WP_{I+R}). Second type is based on water depletion or evapotranspiration (WP_{ET}).

Factors affecting irrigation water -efficiency/ -productivity and water -use efficiency

A. Irrigation water efficiency

The efficiency of irrigation water is affected by conveying efficiency depending upon the structure of the channel and season. If the channels are open and susceptible to breaches, damage by rodents and weed infestation, and water is flowing season is of high evaporative demand then the conveyance efficiency is low (ranging from 30 to 40 per cent). In opened channels conveyance efficiency can be increased if are lined with concrete and bricks and stones or other sources like polyethylene, clay, bitumen etc. as these reduce seepage losses. Conveyance efficiency is further improved with underground pipeline water distribution system which is unique water conveying system at different points at the farm. The distribution efficiency is influenced by soil (surface roughness, slope and texture) and method of irrigation (flooded, sprinkler, drip etc.). It can be improved by selecting a proper method of irrigation in relation crop type.

B. Crop water productivity/use efficiency

Crop water productivity is influenced by all the factors which affect crop yield, water input irrigation water + precipitation and water depletion by evapotranspiration. The factors affecting crop water productivity are crops/cropping systems, cultivars, irrigation (amount, schedule and method), soil texture, climate change as well as management interventions (trans-/planting date, crop establishment method, mulching, tillage, fertilizer use, which are discussed individually as follows:

Crop

A range of water productivity for different crops grown and cropping system followed in northern part of India is at hand in the literature. By and large water productivity values based on irrigation (WP_I), total water input (WP_{I+R}) and evapotranspiration (WP_{ET}) presented in Table 1 revealing that the values of WP_{I+R} are less than WP_I and WP_{ET} in all the crops.

Amongst the crops, WP_I is more in sugarcane (4.26 kg m^{-3}) and least (0.40 or/0.46 kg m^{-3}) in sunflower or/ rice and follows the order sugarcane> wheat> maize> raya=chickpea>cotton> rice> sunflower. WP_{I+R} is more (2.45 kg m^{-3}) in sugarcane and least (0.17 kg m^{-3}) in cotton and follows the sugarcane> wheat> maize> raya=chickpea > rice >sunflower> cotton. WP_{ET} is more in sugarcane (2.68 kg m^{-3}) and least (0.27 km^{-3}) in cotton and follows the order sugarcane> wheat> rice > rice> maize >oil seeds >cotton. Amongst the cereals more water productivity (WP_I, WP_{I+R} and WP_{ET}) in wheat and least (WP_I and WP_{I+R}) in rice shows that in rice crop the major portion of the total water input (irrigation+ rain) goes as drainage without contributing to yield. At global level WP_{ET} for wheat, rice, maize, cotton seed and cotton lint are 1.09, 1.09, 1.80, 0.65 and 0.23 kg m^{-3}. In most of the studies, the corresponding values ranges 0.6-0.7, 0.6-1.6, 0.41-0.95, 0.14-0.33 and 1.1-1.27 kg

Table 1. Water productivity of different crops in central Punjab, India

Crop	Yield	Irrigation	Rain	ET	WPI	WPI+R	WPET
	t ha-1		mm			kg m-3	
Rice	6.5	1400	600	650	0.46	0.33	1.00
Maize	4.5	350	500	480	1.29	0.53	0.94
Wheat	4.7	350	110	350	1.34	1.02	1.34
Raya	1.5	200	120	280	0.75	0.47	0.54
Chickpea	1.5	200	110	320	0.75	0.48	0.47
Sunflower	2.2	550	100	550	0.40	0.34	0.40
Cotton	1.6	300	630	600	0.53	0.17	0.27
Sugarcane	36.2	850	630	1350	4.26	2.45	2.68

m^{-3} (Zwartz and Bastiaanssen, 2004). In general, WP_{ET} of potato, grapes, kinnow and milk are 10.0, 3.34, 1.42 and 1.0 kg m^{-3}, respectively.

Cropping system

In rice-wheat cropping system (averaged over three dates of transplanting, two irrigation regimes and four levels of nitrogen) WP_I and WP_{ET} are 0.55±0.09 and 1.09±0.15 kg $m^{-3,}$ respectively with an average yield of 10.94±1.59 t ha^{-1}, Irrigation water 1992±119 mm and ET 1006±16mm (Jalota *et al.,* 2011). Averaged over four locations in Punjab state of India WP_I, WP_{I+R} and WP_{ET} are 0.77±0.05, 0.50±0.01 and 1.03±0.04 kg m^{-3} (Jalota *et al.,* 2014). In cotton-wheat system (averaged over three soil textures and four irrigation regimes) WP_I, WP_{I+R} and WP_{ET} are 0.55±.012, 0.22 ±0.03 and 0.33±0.03 kg m^{-3} with an average yield 2.99±.0.59, irrigation water 575±175 and ET 910±.129 mm (Jalota *et al.,* 2006). In dry-land maize-wheat system (averaged over three dates of planting, two soil textures and two moisture regimes i.e. rain fed and one irrigation) WP_{ET} is 0.89±0.05 kg m^{-3} with an average yield of 3.85±0.89 t ha^{-1} and ET 475±19 mm (Jalota *et al.,* 2010). In different cropping systems WP_{ET} followed the order rice-wheat (0.94 kg m^{-3}) > cotton-wheat (0.88 kg m^{-3}) > maize wheat (0.84 kg m^{-3}). However, when ET from intervening bare period is also included the WP_{ET} is reduced to 0.78 kg m^{-3} in rice-wheat, 0.46 kg m^{-3} in cotton-wheat and 0.67 kg m^{-3} in maize-wheat cropping system, which are less by 17%, 48% and 20%, respectively than without intervening bare period (Prihar *et al.,* 2010).

Cultivars

As short duration cultivars stay for relatively shorter period in the field so these require less frequency and total amount of post sowing irrigations, and results in lesser water loss by evapo-/transpiration than long duration crops during their life cycle. Though yield potential in shorter duration varieties is generally less yet in short duration varieties yet WP_I and WP_{ET} are more which is only due to less water input (irrigation as well as rain) as well as its use by ET. For instance, in transplanted rice WP_I, WP_{I+R} and WP_{ET} of 0.40, 0.31 and 1.10 kg m^{-3} in shorter duration cultivar (HR 257, 90 days from transplanting to maturity) is more by 8%, 9% and 14% than longer duration variety (PR 118, 120 days from transplanting to maturity) due to less water input (6% rain and 5% irrigation water) though yield is more by 3% (Jalota *et al.,* 2009). Vashisht *et al.* (2015) also reports WP_I (0.64 kg m^{-3}) in HR 257 more by 6% and WP_{I+R} (0.35 kg m^{-3}) by 3% due to more yield by 5%, less irrigation water by 1% and more total water input by2% than PR 118. Amongst varieties of different durations (PR 113 of 112 days from transplanting to maturity, PR 115 of 95 days from transplanting to maturity, HR 257 of 90 days from transplanting to maturity and PAU 201 of 114 days from transplanting to maturity), the high WP_I (0.49 kg m^{-3}) is in HR 257 and least (0.39 kg m^{-3}) in PR 113 (Mahajan *et al.,* 2009). In the variety HR 257, WP_I (0.49 kg m^{-3}) is more by 27% due to less irrigation water by19% than PR 113 though yield is more by 2%. In direct seeded rice WP_I (0.56 kg m^{-3}) and WP_{I+R} (0.39 kg m^{-3}) in shorter duration variety PR115 (of 95 days from transplanting to maturity) are more by 52% and 47% than longer duration variety PR 114 of 115 days from transplanting to maturity, due to 12% less irrigation water and 34% more yield as a result of 32% more harvest index (Arora *et al.,* 2018). In two independent years of experimentation on rice WP_I, $WP_{I+R\ and}$ WP_{ET} observed was 0.72 kg m^{-3}, 0.47 kg m^{-3} and 0.96 kg m^{-3} in variety Pusa Suganda-5; and 0.90 kg m^{-3}, 0.25 kg m^{-3} and 0.81 kg m^{-3} in Pusa 1460 (Sagar *et al.,* 2017). In a field experiment during 2014-15 on wheat, WP_I, WP_{I+R} and WP_{ET} of 1.21 kg m^{-3}, 0.77 kg $m^{-3}$and 1.07 kg m^{-3} in longer duration variety (PBW 621, 160 days from seeding to harvest) increases to 1.33 kg m^{-3}, 0.84 kg m^{-3} and 1.17 kg m^{-3}, respectively in short duration cultivar (PBW550, 150 days) due to 9% more yield even with the same amount of irrigation water (Singh *et al.,* 2019). The results of 20 years simulations (1983-2013) also are show the same trends. But Vashisht *et al.,* (2019) from the field experimentation of 6 years reports 5% less WP_I and 13% more WP_{ET} in PBW 550 than PBW 343/PBW 621, due to less yield by 5%, irrigation water by 1% and ET by 22%.

Soil type

In medium and finer textured soils compared to coarser WP_I, WP_{I+R} and WP_{ET} are more as the former soils need lesser irrigation water and draw on more water as ET (Jalota *et al.,* 2021), and also provide favourable soil physical environment for higher yield. The effect of soil is reflected through its water retention and available water capacity, which is more in medium textured soils than coarser. In rice WP_I (0.95 kg m^{-3}), WP_{I+R} (0.58 kg m^{-3}) and WP_{ET} (1.47 kg m^{-3}) in silt loam soil is more by 116%, 95% and 56% than loamy sand is due to more yield by 62% and less irrigation water by 25% (Jalota *et al.,* 2013). In wheat WP_I (1.57 kg m^{-3}), WP_{I+R} (1.25 kg m^{-3}) and WP_{ET} (1.31 kg m^{-3}) is more by 50%, 45% and 0.10% in silt loam soil than loamy sand due to more yield by 25%, ET by 13% and less irrigation water by 17% (Jalota *et al.,* 2013). Even with the same amount of irrigation water WP_I, W_{PET} are more in silt loam soil than loamy sand. For example, in wheat (following cotton) with 188 mm irrigation water, the WP_I 0.88 kg m^{-3}) and WPET (0.33 kg m^{-3}) in silt loam is more by 3% and 0% than loamy sand due to more yield by 3% and ET by 18% (Jalota *et al.,* 2006) But under the situations when percent increase in ET (37%) is more than percent increase in yield (28%), WP_{ET} in silt loam is lesser by 7% than loamy sand (Singh *et al.,* 2019). The W_{PET} is not affected by soil texture when the percent increase in yield and ET are of same magnitude in different textures (Arora *et al.,* 2007). Also effect of soil texture is modified by irrigation regime i.e. more in low or no irrigation regime. In dry land wheat following maize in maize-wheat system W_{PET} (0.81 kg m^{-3}) is more by 17 % in silt loam than loamy sand due to 1% more yield and 14% less ET (Jalota *et al.,* 2010). In maize WP_{ET} (1.0 kg m^{-3}) in silt loam is 9% more than loamy sand due to more yield by 14% and ET by 5% (Jalota *et al.,* 2010). In maize-wheat system WP_{ET} (0.88 kg m^{-3}) in silt loam is 6% more than loamy sand due to more yields by 11% and ET by 5% (Jalota *et al.,* 2010). In Soybean with the same amount of irrigation (140mm) WP_I (1.65 kg m^{-3}) in sandy loam soil is more by 69% than loamy sand due to more yield by 69% (Arora *et al.,* 2011). In cotton crop during cotton-wheat system WP_I (0.60 kg m^{-3}), and WP_{I+R} (0.25 kg m^{-3}) are more by 33% each and no change in WP_{ET} (0.33 kg m^{-3}) due to 33% more yield with same amount of irrigation water (575 mm) and 794 mm rain (Jalota *et al.,* 2006).

Climate change

Presently change in climate is evident from the increased temperatures (maximum as well as minimum) and CO_2. The increased temperature and CO_2 may affect the WP_{ET} by altering photosynthesis and transpiration of plants variably depending upon their photosynthetic pathways (Jalota *et al.,* 2018). Amongst the C3 plants i.e. in rice WP_{I+R} (0.45 kg m^{-3}) and WP_{ET} (1.23 kg m^{-3}) at present would be lesser in future (at the end of century) merely by 1% though there would be reduction in yield by 26% and ET by 24% However WP_I (0.70-0.73 kg m^{-3}) at present would increase to 1.12-1.47 kg m^{-3} (i.e. 52-54%) in future (Jalota *et al.,* 2013; Kaur *et al.,* 2014) In irrigated wheat WP_I (1.33 kg m^{-3}), WP_{I+R} (1.07 kg m^{-3}) and WP_{ET} (1.27 kg m^{-3}) at present would be more by 85%, 13% and 22%, respectively at the end of century due to less yield by 13%, total water input by 22% and ET by 29%. In dry land wheat WP_{ET} (1.14 kg m^{-3}) in the past (2001-2010) would be less by 175% (0.41 kg m^{-3}) in future (2041-2050) with less yield by 154%, more ET by 8% as well as rain by 36% in future than the past (Vashisht *et al.,* 2013)

Management interventions

Date of transplanting (DOT)

Water productivity in the crops grown under high evaporative demand is low as irrigation requirement and ET are more. WP_I, WP_{I+R} and WP_{ET} in such crops can be enhanced by growing these in the period of lesser potential evaporative demand in which yield potential is highest and irrigation and ET demand is less. For example, WP based on all types of water inputs and use (WP_I, WP_{I+R} and WP_{ET}) of rice in north west India is low if the crop is transplanted during the period of higher evaporative demand accompanied by less rainfall (Julian day 120 to 161) as it required more amount of irrigation water for sustaining the yield. On contrary if rice is transplanted during period of relatively lower evaporative demand accompanied by high rainfall (Julian day 161 to 182) WP_I is high as relatively less water is required to sustain yield. For instance, in rice transplanted on Julian day 176 (June 25) WP_I (0.40 kg m^{-3}), WP_{I+R} (0.31kg m^{-3}) and WP_{ET} (1.10 kg m^{-3}) are more by 6%, 5% and 9%, respectively than transplanted on Julian day145, May 25 (Jalota *et al.,* 2009). This effect is manifested mainly through less irrigation water by 7%, rainfall by 2%, ET by 10% and yield by 2%. While shifting trans-/planting date of rice care must be taken that yield of rice is sustained with reduced ET without jeopardizing the ability to sow the next crop at the optimum time. Though study of (Jalota *et al.,* 2009) and some others (Arora, 2006; Chahal *et al.,* 2007; Hira and Khera, 2000; Khepar *et al.,* 1999) reported some yield loss for transplanting after mid-June, but WP_I and WP_{ET} increased because of greater reduction of irrigation water and ET. For example, by shifting transplanting date from May 16 to June 16 WP_I increased by 19% due to decrease in yield by 9%

and irrigation water by 23% (Singh *et al.,* 1996). The effect of DOT on WP varies with the irrigation schedule. With irrigation schedule of 2-D drainage (i.e. irrigating the crop after 2 days of cessation of the applied water) WP_I of rice transplanted on June 15 (0.45 kg m^{-3}) is more by 19% than transplanted on May 16 while in continuous flooding WP_I of transplanted rice on June 15 (0.36 kg m^{-3}) is more by 26% than transplanted on May 16. Similarly by shifting transplanting date from May 20 to July 10 WP_I is more by 49% due to less yield by 11% and irrigation water by 40% (Gill *et al.,* 1990); from June 15 to July 05 WP_I is less by 9% due to less yield by 16% and irrigation water by 8% (Mahajan *et al.,* 2009); from May16 to July 01 WP_{ET} is more by 28% due to less yield by 4% and ET by 25% (Arora, 2006); from May 01 to July 01 WP_{ET} is more by 76% due to more yield by 30% and less ET by 25% (Chahal *et al.,* 2007); from June 05 to July 05 WP_{I+R} is more by 49% due to more yield by 33% and less irrigation water +rain by 11% (Vashisht *et al.,* 2015).

In irrigated wheat sown on November 20, WP_I (1.36 kg m^{-3}), WP_{I+R} (1.03 kg m^{-3}) and WP_{ET} (1.18kg m^{-3}) is more by 18, 10 and 16% than sown on October 20 (Vashisht *et al.,* 2019). This is because of less irrigation water by 20%, ET by 18% though there is 5% decrease in yield and 14% increase in rain. In field experiment of one-year (2014-15) WP_I (1.25kg m^{-3}), and WP_{ET} (1.09 kg m^{-3}) are more by 6%, and 4% than sown on Oct 25, due to less yield by 18% and ET by 22% (Singh *et al*. (2019). But the results of a simulation study for 20years show that in wheat sown on Nov 25 WP_I (1.03 kg m^{-3}), and WP_{ET} (1.13 kg m^{-3}) is less by 5%, and 0% than sown on Oct 25, due to less yield by 5% and ET by 4%. In dry land wheat there is almost no change in WP_{ET} for change in planting time from Oct 15 to Dec 15 (Vashisht *et al.,* 2013) though there is decrease in yield (5 %) and ET (4%). In wheat following rice WP_I and WP_{ET} is also affected by the date of transplanting of rice. In wheat sown on followed by transplanting of rice on May 1 and July 1 and, WP_I and WP_{ET} in the former is more by 13% and 19% than in the later due to having sufficient bare period for creating favorable soil conditions for wheat crop (Chahal *et al.,* 2007). In dry-land wheat WP_{ET} is affected marginally by sowing wheat between Nov 15 and December 15 as the magnitude of loss in yield and reduction in ET are almost same i.e. 4-5% (Vashisht *et al.,* 2013). Thus, in north west of India up to mid-November is the best time to go for wheat sowing for having preferred WP_I, WP_{I+R} and WP_{ET} because of higher grain yield and lesser use of irrigation water; however late and earlier sowing decreases the water productivities because of lesser yields with the usage of higher irrigation water. In dry-land wheat crop sown on Nov 05 WP_{ET} of 0.72 kg m^{-3} is less by 21% due to lesser yield by 30% and ET by 12% than sown on Dec 05 (Jalota *et al.,* 2010) In dry-land maize crop sown on July 1 WP_{ET} of 1.03 kg m^{-3} is less by 15% due to less yield by 48% and more ET by 8%) when sown on July 30. The change in WP because of trans-/planting date is also observed cropping systems. In dry land maize-wheat system WP_{ET} of maize sown on July30 and wheat on Dec 05) is less by 47% due to less yield by 48% and ET by1% than maize sown July 11 and wheat on Nov 05 (Jalota *et al.,* 2010). WP_I in rice wheat system at trans-/planting date of (rice on July 05 and wheat on November 20) is more by 18% and WP_{ET} by 2% with yield more by 7, less irrigation by 9% and more ET by 18% than the date of (June 05 and wheat on October 22) (Jalota *et al.,* 2011).

Crop establishment method

Water productivity varies in different methods of crop establishment. For instance, in rice crop conventional puddle rice (CPR), direct seeded rice (DSR) and system rice intensification (SRI) are normally used. In CPR, WP_I WP_{I+R} and WP_{ET} (averaged over 2 years of experimentation) are 0.64 kg m^{-3}, 0.32 kg m^{-3} and 0.88 kg m^{-3}, respectively. In DSR compared to CPR WP_I is more by 27%, and WP_{ET} is less by 18% due to less yield by 29%, irrigation water by 44% and ET by 13% (Sagar *et al.,* 2017). In SRI WP_I, WP_{I+R} and WP_{ET} are more by 37%, 21% and 21%, respectively than that in CPR due to more yield by 8% and less irrigation water by 21% and ET 11%. Yadav *et al.* (2011) also reports 35% more WP_I and 15% less WP_{ET} in DSR compared to puddle transplanted rice (PTR) due to 4% less yield, 13% more ET. It shows that DSR in place of PTR has highest WP_I (especially in the heavy-textured soils having higher number of micro- pores which retain water at a higher suction) due to less irrigation water applied though the yield is less (due to severe iron deficiency and significantly higher weed pressure). In the DSR WP_I is changed with water availability and irrigation schedules (Yadav *et al.,* 2011a), cultivars (Sagar *et al.,* 2017), crop duration (Akhgari and Kaviani, 2011) and soil type (Bhatt and Kukal, 2015). Compared to transplanted in wet seeded rice WP_I is less by 12% due to less yield by 20% and irrigation water by 9%; in direct seeded WP_I is more by 15% rice due to less yield by 23% and irrigation water by 33%; and on raised bed WP_I is more by 17% due to less yield by 37% and 46% irrigation water (Choudhary *et al.,* 2006). Water productivity also varies for flooded and aerobic environments. In an aerobic environment WP_I (0.87 kg m^{-3}), and WP_{I+R} (0.43 kg m^{-3}) are more by 48% and 12 %, however WP_{ET} (0.96 kg m^{-3}) is less by 15% due to less yield by 27%, irrigation water by 35%, rain by 6% and ET by14% than flooded (Bouman *et al.,* 2005). Compared to TPR (WP_I =1.0 kg m^{-3}, WP_{I+R} =0.26 kg m-3 and WP_{ET} =0.62 kg m^{-3}) in DSR WP_I and WP_{I+R} are more by 48% and 8%, and WP_{ET} is less by 23% due to less yield by 14% while in WSR

WP_I and WP_{ET} are less by 38% and 13%, respectively less due to less yield by 6% (Cabangon *et al.,* 2002). The WP_I in transplanted rice and DSR also vary with the puddle or no puddle environment (Singh *et al.,* 2001). In no puddle environment WP_I in DSR (0.20 kg m^{-3}) is less by 12% than in transplanted rice due to less yield by 7% and irrigation water by 5% while in puddle environment WP_I in DSR (0.26 kg m^{-3}) is less by 17% than in transplanted rice due to less yield by 16% and more irrigation water by 2%. WP_I and WP_{I+R} in basmati rice are marginally influenced by transplanting methods i.e. mechanical or manual (Brar *et al.,* 2015). WP_{I+R} in DSR (0.42 kg m^{-3}) is less by 3% due to less yield by 16 % and irrigation water by 13% than conventional puddle method. WP_{I+R} (0.36 kg m^{-3}); on bed planted DSR s less by 15% due to less yield by35% and total water input by 23% than conventional transplanting method (Jat *et al.*, 2009). The WP_{I+R} (0.30 kg m^{-3}) on bed planted DSR is less by 14% due to less yield by 24% and total water input by 12% than non-bedded DSR. In bed transplanted rice WP_I (0.41 kg m^{-3}) and WP_{I+R} (0.28 kg m^{-3}) are more by 13% and 8% than flat due to less yield by 4% and irrigation water by 16% (Sandhu *et al.,* 2012). In row crops other than rice permanent beds are considered to increase WP_I by applying less water as irrigation is applied to lesser area (in furrows only) keeping the raised bed un-irrigated (Singh *et al.,* 2010; Brar *et al.,* 2011). In bed planted wheat WP_I (1.31 kg m^{-3}) is 25% more due to less irrigation water by 20% and almost same yield than flat planted (Butter *et al.,* 2006).). In wheat with zero tillage WP_{I+R} (1.45 kg m^{-3}) is more by 13 % due to more yield by 5% and less irrigation water by 6% than conventional tillage (Jat *et al.,* 2009). In ridge planted potato WP_I (11.76 kg m^{-3}), WP_{I+R} (9.85 kg m^{-3}) and WP_{ET} (11.0 kg m^{-3}) is less by 18%, 17% and 7%, respectively due to less yield by 7%, more irrigation water by 13% and less ET by 1% than bed planting (Brar *et al.,* 2019). However, change in WP_I, WP_{I+R} and WP_{ET} is more no mulched environment than mulched. In sugarcane WP_I in single trend (0.57 kg m^{-3}) and paired trench (0.59 kg m^{-3}) are more by 12% and 16%, respectively than conventional method due more yield by 7% and 5%, and less irrigation water by 5% and 9%, respectively (Singh *et al.,* 2015).

Irrigation scheduling

Different schedules are being practiced in different crops to have higher water productivity. For instance, in rice with alternate wetting and drying (i.e. based on irrigation 2 days drainage interval) WP_I (0.44kg m^{-3}) and WPI_{+R} (0.33 kg m^{-3}) are more by 53%, 39% and 0% than continuous flooding due to 34% less irrigation water though yield remained unaffected (Sandhu *et al.,* 1980). WP_{ET} (1.08 kg m^{-3}) remains unaffected. With increasing drainage interval to 5 days, WP_I and WP_{I+R} are further increased by 34% and 18% due to further lesser yield by 6% and irrigation water by 15%. WP_{ET} is less by 6%. In alternate wetting and drying scheduling with further increasing irrigation interval to 4 or 5 days especially during reproductive phase caused additional increase in WP_I (Aujla et al., 1984; Uppal et.al., 1991). In TPR irrigation scheduling based on soil water suction (16 kPa) WP_I (0.45 kg m^{-3}) and WP_{I+R} (0.34 kg m^{-3}) are more by 38% and 27%, and WP_{ET} (1.00 kg m^{-3}) is less by 4% due to less yield by 5%, total water input by 31% and ET by 1% than the irrigation scheduled based on 2-days drainage interval (Jalota *et al.,* 2009). Similarly, In DSR, WP_I (0.45 kg m^{-3}) is more by 47% and WP_{I+R} (0.30 kg m^{-3}) by 31% in irrigation scheduled at soil water suction (SWS) of 15 kPa than 1 drainage interval due less irrigation water by 33% and yield by 2% (Sandhu *et al.,* 2012). In Basmati rice WP_I (0.25 kg m^{-3}) with irrigation scheduling at 5 days drainage interval is more by 17% than irrigation scheduling at 2 days drainage interval although both yield and irrigation water are less (Brar *et al.,* 2015); yield is less by 20% and irrigation water by 32%. In direct seeded rice with partial irrigation WP_I (0.49 kg m^{-3}) and WP_{I+R} (0.33 kg m^{-3}) is more by 15% and 6% than full irrigation, due to less yield by 13% and irrigation water by 24% (Arora *et al.,* 2018). WP_{I+R} (0.34 kg m^{-3}) is less by 4% in SWS of 16 kPa than 2-days drainage interval due to less yield by 9% and total water input by 5% (Vashisht *et al.*, 2015).For upland crops the approach of scheduling irrigation based on irrigation water depth (IW) to cumulative open pan evaporation (PAN-E) ratio results in more water productivity compared to irrigation applied at fixed growth stages (Prihar and Sandhu, 1981; Prihar *et al.,* 1974, Jalota *et al.,* 1985; Cheema and Kaul, 1974). In wheat WP_I (1.82 kg m^{-3}) based in IW/Pan E =0.90 is more by 48% than irrigations at growth stages due to less irrigation water by36% and yield by 5% (Prihar *et al.,* 1976). From a field study of six seasons WP_I (1.61 kg m^{-3}), WP_{I+R} (1.19 kg m^{-3}) and WP_{ET} (1.34 kg m^{-3}) is more by 40%, 33% and 11%, respectively with IW/(PAN–E) ratio-based irrigation than crop stage based irrigation, due to less irrigation water by 76%, total water input water by 56%, ET by 17% and yield by 5% (Vashisht *et al.,* 2019). Likewise, WPI (2.45 kg m^{-3}), $_{WPI+R}$ (1.50 kg m^{-3}) and WP_{ET} (1.49 kg m^{-3}) is more by 69, 43 and 22%, respectively with IW/(PAN–E) ratio-based irrigation than crop stage based irrigation, due to less irrigation water by 40% and ET by 17 % though there is more yield by 1% (Jalota *et al.,* 1985). In dry land wheat WP_{ET} with one irrigation of 70mm is more by 3% due to more yield by 20 % and ET by 16% than un irrigated (Jalota *et al.,* 2010). In wheat following cotton with four irrigations of 75 mm irrigation (total water 300 mm), WP_I (1.48 kg m^{-3}) is less by 51% due to more yield by 95% and irrigation water 300% than with one irrigation (Jalota *et al.,* 2006). However, WP_{ET} (1.27 kg m^{-3}) is more by 51%. But Arora *et al.* (2007)

observed WP_{ET} (1.05 kg m^{-3}) with full irrigation which is less by 22% than no irrigation due more yield by 22% and ET 55%. In addition to scheduling of post sowing irrigations, heavy pre-sowing irrigation also improves WP_I by enhancing root growth (Jalota *et al.,* 1980) and last irrigation by exploiting the profile water (Prihar *et al.,* 1978; Cheema *et al.,* 1978). In maize with irrigation scheduling based on IW/Pan E =1.2, WP_I (0.73kg m^{-3}) is less by 8% and WP_{ET} (1.43 kg m^{-3}) is more by 25% due to more yield by 38%, irrigation water by 50% and ET by 11% than the IW/Pan E = 0.6 (Singh *et al.,* 2015). In spring maize WP_{ET} (0.85kg m^{-3}) with irrigation scheduling based on IW/Pan E =1.0 is more by 4% due to more yield by 16% and ET by 22% than the IW/ Pan E = 0.5 (Kaur and Arora, 2019). In dry land maize with only one irrigation WP_{ET} (0.94kg m^{-3}) is more by 2% due to more yield by 5% and ET by 2% rain-fed (Jalota *et al.,* 2010). In chickpeas with irrigation scheduled at IW/ Pan E = 0.4, WP_I (1.87 kg m^{-3}) is less by 51% due to less yield by 3% and more irrigation water by 100% than Pan E = 0.8; with shifting irrigation on 4 week after sowing from 12 week, WP_I (1.47 kg m^{-3}) is more by 47% due to less yield by 2% and irrigation water 33% (Sandhu *et al.,* 1978); WP_{ET} (0.72 kg m^{-3}) with two irrigations (flowering + pod filling) is less by16 % due to more yield by 57% and ET by 86% (Singh *et al.,* 1990). In Soybean WP_I (0.94 kg m^{-3}) in full irrigation (3 irrigations of 70 mm each) is less by 61% than partial irrigation (one of 70 mm) due to more irrigation water by 200 % and yield by 18% (Arora *et al.,* 2011). The effect of irrigation is also modified with tillage. WP_I in conventional tillage with full irrigation (0.90 kg m^{-3}) is less by 60% than partial irrigation due to more yields by 20% and irrigation water by 200%; and 62% in deep tillage with full irrigation than partial irrigation due to more yields by 15% and irrigation water by 200%. Irrigation schedules not only alter the water productivity in crops but in cropping system too. In cotton-wheat system with 350 mm irrigation water WP_I (0.67 kg m^{-3}), is more by 35%, WP_{I+R} (0.21 kg m^{-3}) is less by 7% and WP_{ET} (0.29 kg m^{-3}) is less by 23% than the irrigation water 800 mm due to more yield by 49%, less irrigation water by 129 % and less ET by 22% (Jalota *et al.,* 2006). In dry land maize-wheat system WP_{ET} (0.91 kg m^{-3}) in rain-fed is 1% more than with one irrigation at pollination due to more yields by 4% and ET 5% (Jalota *et al.,* 2010).

Irrigation methods

Higher irrigation water application efficiency can be achieved by reducing irrigation water through proper selection of an irrigation method in relation to crop, topography soil type and slope so that irrigation is applied as per need (time and amount). Furrow method of irrigation in wide-row crops like cotton, sunflower and maize; pressurized irrigation systems (drip and sprinkler) in orchards and vegetable are the methods to have high WP_I. Both drip and sprinkler systems of irrigation are quite efficient and increase WP_I because irrigation water and fertilizers are applied as per needs by (i) reducing irrigation water after cutting off conveyance losses (ii) increasing yield by improving nutrient efficiency, minimizing the spread of diseases from one plant to another mainly in orchards. Sprinkler irrigation system increases WP_I by irrigating the field crops at rate lesser than infiltration rate of the soil for having maximum water as wells nutrient use efficiency. In wheat with bed planting WP_I (1.31 kg m^{-3}) is more by 25% than flat due to 20% less irrigation water (Buttar *et al.,* 2006). WP_I (0.82 kg m^{-3}) and WP_{I+R} (0.33 kg m^{-3}) with irrigation to alternate furrow in cotton are more by 68%and 26%, respectively than flood method due to less irrigation water by 42% and yield by3% (Aujla *et al.,* 1991). With the introduction of micro irrigation systems drip is becoming more popular. In cotton WP_I (0.49 kg m^{-3}) in drip system is more by 51% due to more yield by 40% and less irrigation water by 8% than the conventional method (Radin *et al.,* 1991). Compared to furrow method WP_I (0.46 kg m^{-3}) in drip system is more by 63% due to more yield by 11% and less irrigation water by 32%; WP_I (0.27kg m^{-3}) in sprinkler system is more by 5% due to less yield by 22 % and less irrigation water by 17% (Cein *et al.,* 1991). In potato WP_I (16.4 kg m^{-3}), WP_{I+R} (1.3 kg m^{-3}) and WP_{ET} (12.6 kg m^{-3}) in drip system is more by 61%, 55% and 24% than furrow method due to more yield by 21% and less irrigation water by 19% and ET 5%, respectively (Brar *et al.,* 2019). Likewise, WP_I (11.5 kg m^{-3}), WP_{I+R} (11.3 m^{-3}) and WP_{ET} (9.7 kg m^{-3}) in drip is more by 46%, 45% and 41% than furrow method due to more yield by 7% and less irrigation water by 27% and ET 24%, respectively (Ati *et al.,* 2012). Also, in drip system WP_I (12.9 kg m^{-3}) is more by 83% than furrow method due to more yield by 10% and less irrigation water by 40% (Jha *et al.,* 2017). In sugarcane WP_I with drip irrigation (0.65 kg m^{-3}) is more by 35% than conventional method due to more yield by 3% and less irrigation water by 24% (Singh *et al.,* 2015). In drip irrigated wheat WP_I (2.73 kg m^{-3}) and WP_{I+R} (1.50 kg m^{-3}) are more by 89% and 47%, but WP_{ET} (1.47 kg m^{-3}) is less by 11% than conventional method due to less yield by 5% and less irrigation water by 50% and more ET by 7% (Dar *et al.,* 2017).

Laser leveling

Unlevel topography of land is considered as one of the factors responsible for low $WP_{I,}$ which is due to (i) more amount of irrigation water applied and (ii) lower yield (caused by uneven distribution of water and fertilizer in the plot i.e. under or no irrigation of the raised area and over irrigation low lying area within the plot). Both these effects decrease the water productivity. Laser land leveler alleviates both these unfavorable effects as it reduces irrigation water (due to increased conveyance and distribution efficiencies by leveling all the dukes and dikes that helps in uniform distribution of irrigation water on a large area within shorter period of time) and augments crop yield due to improved soil water status (reduced water logging and/or reduced water deficit stress due to removal of low and high spots), higher T and less evaporation due to reduced duration of free water at the surface (due to faster irrigation time and removal of depressions where water would pond after rain or irrigation) and ultimately increases water productivity. With same land configuration and fertility level, WP_I of rice and wheat crops is more to the tune of 65% and 60%, respectively by reducing irrigation water (Bhatt and Sharma, 2009) coupled with augmenting crop yield (Kahlown *et al.,* 2006); Jat *et al.,* 2006; Jat *et al.,* 2009; Jat *et al.,* 2011). With laser leveling in rice WP_I (0.22kg m^{-3}) is more by 30% due to less irrigation water by 28% and yield by 6% (Jat *et al*., 2011). This change may be different in PTR and DSR. In PTR WP_{I+R} (0.43 kg m^{-3}) with laser leveling is 19% more than conventional tillage due to 5% more yield and 11% less irrigation water while in DSR WP_{I+R} (0.42 kg m^{-3}) is more by 19% due to 2% more yield and 13 % less irrigation water (Jat *et al.,* 2009). In laser level rice WP_{I+R} (0.44 kg m^{-3}) is more by 29% due to more yield by 12% and less irrigation water by 13% than the conventional method; in wheat WP_I (1.44 kg m^{-3}) is more by 33% due to more yield by 20% and less irrigation water by 10%; in rice-wheat system WP_I (0.60 kg m^{-3}) is more by 23% due to more yield by 7% and less irrigation water by 13% than the conventional method (Jat *et al.,* 2009).

Mulching

In non-flooded rice crop, with mulching @ 5 t ha^{-1} WP_I (0.1.49 kg m^{-3}), WP_{I+R} (1.28 kg m^{-3}) and WP_{ET} (2.74 kg m^{-3}) is more by 93%, 85% and 138% respectively than no mulch (Qin *et al.,* 2006). More $WP_{I,}$ WP_{I+R} and WP_{ET} with straw mulch are due to more yields by 36%, and less irrigation water by 30% and ET by 43 %. In maize WP_I (0.86 kg m^{-3}), WP_{I+R} (0.67 kg m^{-3}) and WP_{ET} (1.40 kg m^{-3}) with 6 t ha-^{1} mulching is more by 18%, 18% and 2% respectively than no mulch due to more yield by 18% and ET by 15% (Singh *et al.,* 2015). In spring maize WP_{ET} (0.90 kg m^{-3}) with mulch @ 6 t ha^{-1} is more by 15% than no mulch due to more yield by 11% and less ET by 3% (Kaur and Arora, 2019). In minimum tilled dry land maize WP_{I+R} (0.36 kg m^{-3}) and wheat WP_{I+R} (1.05 kg m^{-3}) with crop residue is more by 20% and 18% respectively due to more yields by 20% and 18%, respectively than without residue (Ghuman and Sur, 2001). In potato WP_I (14.1 kg m^{-3}), WP_{I+R} (11.7 kg m^{-3}) and WP_{ET} (12.6 kg m^{-3}) with mulching are more by 19%, 19% and 23%, respectively due to more yield by 19% and less ET by 3% (Brar *et al.,* 2019). In Soybean WP_I (1.40 kg m^{-3}) with mulch @ 6 t ha^{-1} is more by 15% than no mulch due to more yield by15% (Arora *et al.,* 2011).

Tillage

In direct seeded rice WP_I (0.52 kg m^{-3}) and WP_{I+R} (0.37 kg m^{-3}) with deep tillage are more by 32% than conventional tillage, due to more yields by 32% (Arora *et al.,* 2018). Tillage has interaction with irrigation i.e., in deep tillage with partial irrigation WP_I (0.58 kg m^{-3}) is more by 43% due to more yield by 43%; and WP_I (0.47 kg m^{-3}) in full irrigation is more by 23%, due to more yield by 23%. WP_{I+R} (0.41 kg m^{-3}) in DSR with zero tillage is more by 6% than conventional tillage due to less yield by 1% and total water input by 5% (Jat *et al.,* 2009). In wheat with zero tillage WP_{I+R} (1.45 kg m^{-3}) is more by 13% than conventional tillage due to more yield by 5% and less total water input by 6%. The WP also varies in zero tillage and conventional tillage with and without laser leveling. In case of laser level fields in wheat WP_{I+R} (1.63 kg m^{-3}) with zero tillage is more by 18% than conventional tillage because of more yield by 18% and less total water input by 10% while in case of conventional tillage the corresponding WP_{I+R} (1.26 kg m^{-3}) is more by 6% due to more yield by 3% and less total water input by 3%. Contrarily with zero tillage WP_I (0.92 kg m^{-3}) is less by 8% due to 8% less yield than conventional tillage (Singh *et al.,* 2001). In dry-land wheat with minimum tillage WP_I (0.89 kg m^{-3}) is less by 9% due to less yield by 9% (Ghuman and Sur, 2001). In spring maize with deep tillage WP_I (0.90 kg m^{-3}) is more by 15% due to more yield by 15% and less ET by1% (Kaur and Arora, 2019). The effect of tillage is modified by irrigation regime. With irrigation based on IW/Pan E = 1.0 WP_{ET} (0.87 kg m^{-3}) in deep tillage is more by 13% than conventional tillage due to more yield by 12% and less ET by 1%; and with irrigation based on IW/Pan E = 0.5 WP_{ET} (0.93 kg m^{-3}) in deep tillage is more by 17% than conventional tillage due to 17% increase in yield and no change in ET. In nut shell the effect of tillage is more in low irrigation regime. In dry land maize with minimum tillage WP_I (0.30 kg m^{-3}) is less by 7% due to less yield by 7% (Ghuman and Sur, 2001). In cotton covered with straw, tillage WP_I (0.18 kg m^{-3}) is more by 1% only (Jalota *et al.,* 2008). In Soybean WP_I (1.35 kg m^{-3}) in deep tillage is 6% more than conventional tillage due to more yield by 6% (Arora *et al.,* 2011). Tillage also shows interaction with soil texture, mulching and irrigation which has already been discussed.

Fertilizer use/ application

In transplanted rice WP_I (0.41 kg m^{-3}) and WP_{I+R} (0.29 kg m^{-3}) are more by 3% in 150 N kg ha^{-1} than 120 kg ha^{-1} N due to more yields by 3% (Sandhu *et al.,* 2012). Likewise, WP_I (0.36 kg m^{-3}) and WP_{I+R} (0.25 kg m^{-3}) in 90 kg ha^{-1} N are less by 9% than N 120 due to lesser yields by 9%. WP_{ET} with N fertilization is more due to more yields and ET. For example, in wheat WP_{ET} (1.39 kg m^{-3}) is more by 49% with applied fertilizer N@ 120 kg ha^{-1} compared to no N which is due to more yield by 65% and ET by 11% (Arora *et al.,* 2007). However, the effects vary with soil type and irrigation. In sandy loam soil at higher N level (120 kg ha^{-1}) compared to no nitrogen, WP_{ET} (1.41 kg m^{-3}) is more by 53% due to more yield by 69% and ET 10%. In loamy sand WP_{ET} (1.37 kg m^{-3}) is more by 45% due to more yields by 62% and ET by 12%. Under the same levels of N, WP_{ET} in no post sowing irrigation (1.50 kg m^{-3}), partial irrigation (1.46kg m^{-3}) and full irrigation (1.26 kg m^{-3}) are more by 35%, 56% and 57% due to more yield by 42%, 70% and 83%, and ET by 5%, 9% and 17%, respectively. The interaction of soil type and irrigation affects the WP_{ET} marginally; however, WP_{ET} is more in loamy sand at full irrigation and less at no and partial irrigation. Maximum WP_{ET} (1.56 kg m^{-3}) is with combination of no irrigation, N120 and sandy loam soil and minimum (0.79 kg m^{-3}) is in combination of full irrigation, N0 nitrogen and sandy loam soil. In spring maize WP_{ET} (1.14kg m^{-3}) with N @ 120 kg ha^{-1} is more by 57% than N @ 0 kg ha^{-1} due to more yield by 60% and ET by 2% ET (Kaur and Arora, 2019).

General discussion and conclusions

The efficiency of water for crop production is measured as water productivity, which is the marketable yield per unit of water applied as irrigation ((WP_I) or used by the plant as transpiration (WUE or WP_{ET}). Measurement of WP_I and WP_{ET} is important for selection of yield-enhancing and irrigation water saving soil and crop management technologies. WP_I is improved through reducing irrigation water and improving crop yields or both. Irrigation water can be reduced from its source to point of use by improving conveyance efficiency (by cutting down unproductive water losses such as seepage during conveyance) as well as by improving application efficiency (through decreasing drainage and evaporation losses during application) through proper method and scheduling of irrigation water at the end point (field). WP_{ET} is increased by allowing the crop to transpire freely at the climatic limit by alleviating any water shortages while at the same time avoiding environmental constraints (light distribution in canopy, CO_2 concentration, nutrients, air etc.) and genetic constraints to attain full potential of the crop. In other words, for a higher WP_I or WP_{ET} it is important to attain either the same or more production with less irrigation water resources or less water used by the plant or higher production from the same irrigation water resources or water use. Irrigation water saved from its less application to a crop is of direct benefiting other water use or users. Based on these principles a number of scientific management interventions to improve WP_I and WP_{ET}, derived from conservation tillage, crop residue management and conservation irrigation is available in the literature.

The overall view of the data at hand indicates that shifting trans-/planting date affects WP_I and WP_{ET} by means of the altering the evaporative demand and rainfall which causes change in irrigation water and ET mainly while change in yield is marginal. This corroborates the findings of Jalota *et al.* (2009); Chahal *et al.* (2007); Arora, (2006); Hira and Khera (2000); Khepar *et al.* (1999) in case of rice; and of Vashisht *et al.* (2019) and Singh *et al.* (2019) in case of wheat crop. To be precise shifting trans-/planting date of rice to mid-June; and of wheat to mid-November in North West India has been advocated to enhance water productivity. These trans-/planting dates ensure higher water productivity due to lower evaporative demand and more rainfall during the crop period. Contrarily when evaporative demand is high and rainfall is low during a crop period, WP_I and WP_{ET} are lower due to more irrigation water and ET requirement, and less rainfall. But in dry land compared to irrigated environment, the reduction in WP_{ET} is more due to drastic decrease in yield resulting from lesser ET especially when rains are scanty. As far as crop establishment is concerned different methods are practiced. For example in rice methods are conventional transplanted rice (CTR), direct seeded rice (DSR), system rice intensification (SRI) and conventional puddle rice (CPR), WP_I and WP_{ET} in DSR compared to CPR is more due to relatively higher magnitude of the % reduction in irrigation water and ET than % increase in yield; while it is more in SRI due to higher % of increase in yields than % reduction in irrigation water and ET (Yadav *et al.,* 2011a; Sagar *et al.,* 2017). Bed planted wheat compared to flat has more WP_I as irrigation water is applied to lesser area (in furrows only) keeping the raised bed un-irrigated (Butter *et al.,* 2006; Jat *et al.,* 2009; Singh *et al.,* 2010; Brar *et al.,* 2011). Reports are also there indicating that bed planting decreases WP_I as the surface area of these beds is more (about 25%) which absorbs more radiant energy and increases evaporation losses and irrigation needs. Moreover, yield is also less as total area sown is less than flat. WP_I is also affected by tillage. It is more in deep tillage than conventional due to more proliferation of roots and ensuing yield (Arora *et al.,* 2018). It is also more in zero tillage compared to conventional tillage due to less irrigation water applied and more yield (Jat *et al.,* 2009). WP_I is also affected by pre- and post- planting irrigations. Heavy pre-sowing irrigation enhances WP_I by increasing yield due to more root proliferation (Jalota *et al.,* 1980) and post sowing irrigations (based on potential evaporative demand) by reducing irrigation water in wheat (Prihar *et al.,* 1974). But reducing post sowing irrigation under the low initial soil water storage in the profile may decrease WP_I (Jalota *et al.*, 1980). The effect of irrigation water on WP_I is also modified by irrigation methods and tillage. Amongst the irrigation methods both drip and sprinkler systems of irrigation are quite efficient to increase WP_I as irrigation water and fertilizers are applied as per needs by (i) reducing irrigation water after cutting off conveyance losses (ii) increasing yield by improving nutrient efficiency, minimizing the spreading of diseases from one plant to another mainly in orchards. Sprinkler irrigation system enhances WP_I by irrigating the field crops at rate lesser than infiltration rate of the soil for having maximum water as wells nutrient use efficiency. Laser land leveler enhances the water productivity not only by reducing irrigation water but augmenting yield too (Jat *et al.,* 2009 and 2011). Irrigation water is reduced due to increased conveyance and distribution efficiencies by leveling all the dukes and dikes that helps in uniform distribution of irrigation water on a large area within shorter period of time and augmenting crop yield due to improved soil water status (reduced water logging and/or reduced water deficit stress due to removal of low and high spots) , higher T and less evaporation due to reduced duration of free water at the surface (because of faster irrigation time and removal of depressions where water would pond after rain or irrigation). Mulching of crop residue improves the WP_I and WP_{ET} by reducing irrigation water and yield augmentation (Jalota *et al.,* 2007) as it affects the hydrothermal regime of soils, enhances root and shoot growth and subsequently yield (Chawla *et al.,* 2009; Li *et al.,* 2008; Ram *et al.,* 2013). The effect of mulching on WP_{ET} is more in summer seasons, in semiarid subtropical environments as a result of better coordination of demand and supply of water that culminates in more complete extraction of soil-stored water as evapotranspiration (Singh *et al.,* 2011: Jalota and Arora, 2002). Deep tillage enhances WP_I by providing better soil physical environment for root growth which increases water and nutrient uptake and subsequently biomass and harvest index and yield ultimately (Arora *et al.,* 2018). The effect of deep tillage for increasing WP_I is more at low irrigation regimes. Addition of N fertilizers increases both yields and ET (Arora *et al.,* 2007), but increase in WP_{ET} is only when % increase in yield is more than % increase in ET. Application of N though increases ET, but reduces direct evaporation loss from soil in the irrigated treatment due to early development of canopy in the fertilized crop, which covers the soil and intercepts more radiation, and results in higher T/ET ratio, a very conducive condition to have higher WP_{ET} for the fertilized than for the unfertilized crop. The effect may vary with irrigation and soil type. High irrigation at zero nitrogen, and high nitrogen at zero irrigation gave low WP_{ET} because the crop suffers from nitrogen and water stress, respectively, under the two situations. WP_{ET} are highest at intermediate irrigation and high nitrogen levels. Higher WP_{ET} at intermediate irrigation levels suggests that, from the WP_{ET} standpoint, limited irrigation water should be used over larger areas rather than irrigating smaller areas for high yields. Soil type affects WP_I and WP_{ET} through its extractable water capacity. In medium and finer textured soils WP_I and WP_{ET} are more due to more extractable water capacity, which causes more % yield increase than % ET increase. Thus, WP_I is maximum in the combination of low irrigation regime, higher dose of N and medium textured soils; minimum in combination of high irrigation, low nitrogen and coarser textured soils.

From the critical appraisal of the data reported in the study and subsequent discussion it is clear that % change in water productivity (WPI or WPI+R or WPET) between two treatments of a given factor or management intervention is influenced by the corresponding % change in yield plus % change in water input as irrigation water or total (irrigation water+ rainfall) or used as ET as is evident in Fig.1.

To quantify the change in water productivity (WPI or WPET or WPET) and identify the overweighing variable (change in yield or change in water input/used) an additive linear function (equation 1) is fitted to the data on relative change in water productivity (RWPI or RWPI+R or RWPET) as a function of two variables (i) relative change in yield (RY) and (ii) relative change in irrigation water (RIW) or relative change in total water input (RI+R) or relative change in evapotranspiration (RET). Relative change in two treatments of a variable is computed as (X2-X1)/X1.

$$R_{WPI} = a + b\ R_y + c\ R_{IW} \quad (1A)$$

$$R_{WPI+R} = a + b\ R_y + c\ R_{IW+R} \quad (1B)$$

$$R_{WPET} = a + b\ R_y + c\ R_{ET} \quad (1C)$$

The estimated values of coefficients a, b and c, and coefficient of determination (R^2) for different types of relative water productivities is presented in Table 2.

The values of the coefficient for relative change in water input/used (c) is higher than relative change in yield (b), This indicates indicate that over- weighing factor for increasing RWPI and RWPI+R is the relative reduction in irrigation or total input while for increasing RWPET overweighing factor is relative increase in yield than relative ET as represented by higher value of b than c.

The reported results and developed empirical relations conclude that water productivity is enhanced by reducing amount of water input through proper irrigation method and schedule (micro irrigation

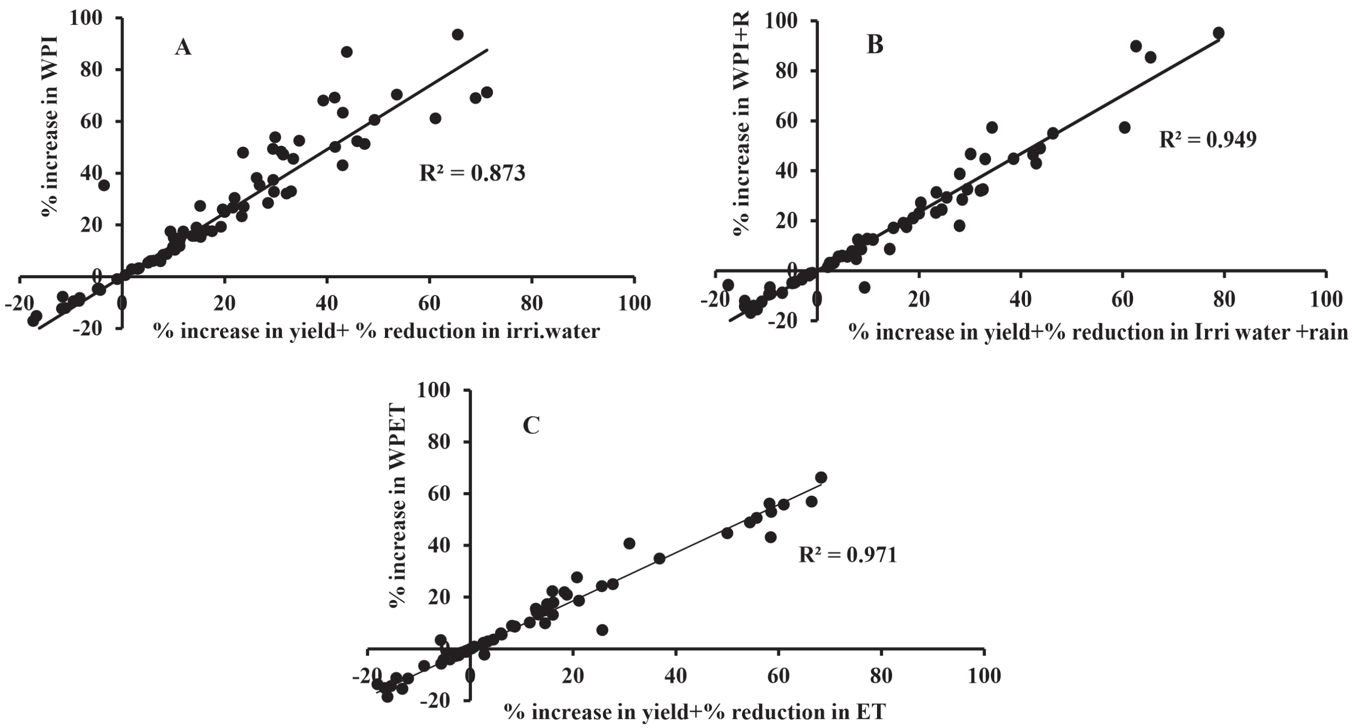

Fig. 1. Percent change in water productivity in relation to percent increase in yield and percent reduction in irrigation water (A), irrigation water +rain (B) and evapotranspiration (C)

Table 2. Estimated coefficients and coefficients of determination of the additive function for different types of water productivities

	a	b	c	R^2	n
R_{WPI}	0.017	0.036	-0.046	0.93	84
R_{WPI+R}	0.014	1.124	-1.344	0.96	68
R_{WPET}	0.016	0.871	-0.840	0.96	70

a, b and c are coefficients, R^2 is coefficient of determination and n is number of observations

system), and water use efficiency by increasing yield and decreasing evapotranspiration (but increasing transpiration) through mulching, deep tillage and use of fertilizers

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