# Assessing paddy irrigation water productivity and opportunities for improvement in Punjab

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## ABSTRACT

Predominantly due to lesser rainfall in Punjab as compared to other eastern states in India, prolonged paddy cultivation has caused ground water depletion in the region. Therefore, to optimize irrigation water usage in paddy cultivation, it is essential to intervene with the current farming and irrigation practices.

This study was undertaken to estimate an indicator of food and water security i.e. Irrigation Water Productivity (IWP) of paddy in the districts of Jalandhar and Hoshiarpur, Punjab. It also compares the results at inter-district level and with that of the best national and international irrigation water productivities. The paper also unveils that IWP in these regions can be enhanced through feasible interventions such as Alternate Wetting and Drying (AWD) system of irrigation and cultivation of short duration rice varieties.

The results of the study indicate that the average IWP was in the range of 0.20-0.29 kg/m$^3$ and 0.16-0.26 kg/m$^3$ in Jalandhar and Hoshiarpur, respectively with conventional farming practices in paddy cultivation. Upon adoption of AWD and cultivation of short duration rice varieties, the IWP can potentially increase to around 0.53-0.91 kg/m$^3$ and 0.51-0.81 kg/m$^3$ in Jalandhar and Hoshiarpur, respectively.

**Key words:** Ground water depletion, paddy cultivation, irrigation water productivity (IWP), efficient interventions, Punjab.

## INTRODUTION

Increasing water scarcity due to depletion of fresh water sources around the world has become a burning issue in the current environment scenario (Wada et al., 2011). Over the past decades, the per capita fresh water availability for all purposes has been decreasing and it is predicted that such a negative trend will remain in action for a number of upcoming years (Dinar et al., 2019). Majorly, research on increasing water scarcity is based on the long-term changes in hydro-climatic and socioeconomic conditions, of which, agriculture is one of the key drivers (Veldkamp et al., 2015). On an average, agriculture sector withdraws 70% of the freshwater for irrigation purposes (ICID, 2018).

India is amongst the top three water consumers of the world and exports approximately 4% of the world's freshwater resources (125 Bm$^3$/y) in the form of virtual water (Hoekstra & Mekonnen, 2012). India being the agriculture-nucleated country plays vital role in the global agriculture market (Brindha, 2017). With a total harvested area of 20.4*10$^2$ million hectares, India produces all kinds of crops for maintaining the required food security for the expanding population (FAO, 2017). While some crops demand lesser water supplies, others are water intensive such as paddy, sugarcane, and potato etc. (Gupta, 2008).

Paddy is grown in 119 countries and is cultivated on $11.8*10^2$ million hectares of land around the world. With a total production of $11.7*10^2$ million tonnes, total paddy produced is 9% of the overall crop production across globe (Devkota et al., 2020). It has been established that post green revolution in India (1960), the area under paddy cultivation increased in India. Due to 22% of total paddy production of the world, India is amongst the largest paddy producing countries and hence referred to as 'rice basket of the world' (Gupta & Mishra, 2018). With 43.99 million hectares of harvested area and annual production of approximately 112.91 million tonnes, paddy is amongst top three crops produced in India (Agriculture Statistics at a Glance, 2018). In India, top three paddy-producing states are West Bengal, Uttar Pradesh and Punjab. Punjab, where the total area under paddy is less than the other two states, contributes 12 percent of paddy to the focal pool of the nation (Department of Agriculture cooperation and Farmers welfare, 2017).

In India, Punjab emerges highest in context of water utilization for crop cultivation with 99.7% of paddy cultivating area under irrigation coverage (Agriculture Statistics at a Glance, 2017). This is primarily because Punjab lies in agro-climatic zone-VI, which is known as "Trans-Gangetic Plains Region". With rivers Sutlej, Beas, Ravi and Ghaggar flowing through the state and a vast network of canal system, fertile lands in the state support cultivation of paddy and high yielding varieties of crops (Dhillon et al., 2018). However, with annual availability of 3.13 Million ha-m (Mha-m) (from surface and ground water) and annual demand of 4.4 Mha-m, there is an undersupply of 1.27 Mha-m of water (Bhullar & Sidhu, 2006; Kaur et al., 2015). Moreover, categorization of 105 administrative blocks in over-exploitation of ground water category in Punjab is evident of more water consumption than that of potential supply and increasing groundwater depletion (Mohiddin, 2018).

As one of the largest water guzzler crops, paddy requires an aggregate of about 34-43 % of the total irrigation water requirement around the world (Sharma et al., 2018). Primarily, paddy is not a wetland crop; however, its cultivation in water immersed conditions (5–10 cm standing water) has been practiced as a conventional method (Manzelli & Vecchio, 2009). On an average, total water requirement for paddy cultivation is about 1300-1500 mm (Yadav et al., 2011). In the current scenario of Punjab, despite the efficient irrigation practices being experimented and recommended, paddy cultivation largely happens through flood irrigation. Due to such traditional practices, the irrigation water used is 30-35% more in paddy than other crops (Qureshi, 2019). Experimental studies conducted by Sudhir Yadav, et al. (2011) and Balwinder Singh, et al. (2015) show IWP enhancing interventions in Punjab. Amongst others, the most feasible interventions in these experimental studies are inclusive of Alternate Wetting and Drying (AWD) and cultivation of short duration paddy varieties. AWD, also known as intermittent irrigation involves an application of approximately 5 cm of water at an interval of 2-8 days after the ponded water has disappeared from soil. This method is easily adoptable by the farmers and puts no extra production cost. As compared to the conventional irrigation methods, irrigation water productivity with AWD is 0.9 kg/m$^3$ (Yadav et al., 2011). On the other hand, short duration paddy varieties are harvested in a shorter span of time (90-120 days) as compared to 140-150 days (required in traditional varieties) leading to saving of 5-7 irrigation cycles and providing more time to farmers for land preparation for the subsequent crops. IWP with cultivation of short duration paddy varieties is in the range of 0.7-1.2 kg/m$^3$ (Singh et al., 2015). Despite these water saving practices, flood irrigation is majorly practiced in Punjab due to farmers' presumptions regarding higher irrigation requirement of paddy and low awareness about water saving techniques and practices (Awan et al., 2011).

Irrigation water productivity is one of the most important evaluation indicators in the irrigation system (Brauman et al., 2013; Kazem et al., 2020). Scientifically, irrigation water productivity (kg/m$^3$) is estimated as ratio of crop produced to the amount of irrigation water used (Sharma et al., 2018). A higher crop water productivity results either in a similar yield from less water, or a higher yield from similar water consumption, hence becoming more sustainable and directly advantageous for other water consuming sectors (Zwart & Wim, 2004). Irrigation water productivity is exceptionally low for paddy in central and eastern Punjab, as the hydro-climatic conditions of the region do not support such large-scale production of paddy (Jalota et al., 2009). In central Punjab, water requirement for paddy is mainly fulfilled by irrigation water due to less rainfall in accordance with total water required for paddy cultivation. Similarly, in eastern Punjab, light density soil types such as sandy soils, lead to more water requirement in paddy cultivation as compared to the heavy density soil types such as loamy soils (Karam et al., 2019). Hence, to meet the irrigation water requirement, ground water has to be extracted.

At global level, irrigation water productivity for paddy is highly variable and is subject to different region specific cultivation practices (Monaco & Sali, 2018). Paddy irrigation water productivity ranges from 0.11-0.29 kg/$m^3$ in Iraq (Hameed et al., 2011) to 1.01 to 2.70 kg/$m^3$ in USA (Massey et al., 2014). Such difference in the water productivities is due to distinct agro-climatic conditions: such as the amount and frequency of precipitation, moisture retention capacities of different soil types as well as agriculture practices followed in paddy cultivation (Olesen et al., 2011).

The main objective of this research is to quantify irrigation water productivity in paddy cultivation in Jalandhar and Hoshiarpur districts of Punjab so as to draw a comparative picture of irrigation water productivities at inter-district level and along with that of the global benchmarks. In addition, the study also suggests feasible interventions to enhance irrigation water productivity in paddy in the region.

## STUDY AREA

The study was conducted in Jalandhar (31.21° N, 75.57° E) and Hoshiarpur district (31.53°N 75.92°E) (Districts of Punjab – Government of Punjab, India) in the state of Punjab (Fig 1). The study area has been identified based on the extent of ground water exploitation and depletion and land holding by the farmers.

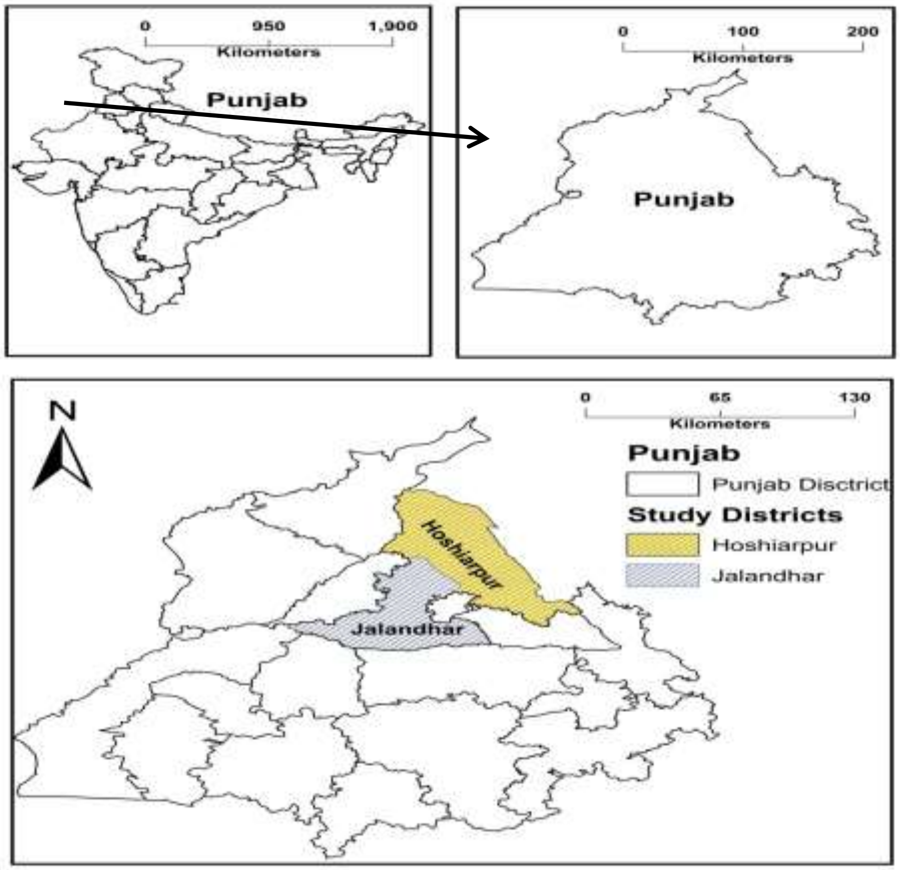



**Figure 1: Study area**

## Jalandhar

Out of the six agro climatic zones of Punjab, entire Jalandhar district lies in the central plain region situated between Sutlej and Beas rivers. The alluvial deposits of the Indus-Ganga secure the land of the district. It has sub-tropical monsoon type climate with typical precipitation of 600mm per annum (Mohiddin, 2018). The Jalandhar district in Punjab possesses 5.3 % of the total geographical region of the state, of which, 91% area is under paddy cultivation (Dhillon et al., 2019). According to the primary data collected, the farmers in the district have an average land holding of 7 acres and paddy and wheat are the major Kharif and Rabi season crop in the region.

With ground water being major source of irrigation, it irrigates almost 89% of total irrigated area (Mohiddin, 2018). Due to an overall availability of 41 canals in the district, only 11% of the net irrigated area is being irrigated by canal system. Therefore, almost all blocks in the district fall under exploited category as the ground water development, which is estimated to be 229% for Jalandhar, has exceeded the current recharge rate (CGWB, 2016). This has led to an average decline of 1m/year in the ground water level leading to increase in the ground water depth which currently is 60-65 m (WRIS, 2020).

## Hoshiarpur

Hoshiarpur lies in the eastern part of Punjab and has Sutlej and Beas rivers flowing in the region. Unlike Jalandhar, Hoshiarpur majorly consists of sand textured soil and comparatively higher rainfall of 700mm per annum. Accounting for 6.7% of the entire Punjab state, Hoshiarpur has 87% of the area under paddy cultivation (Agriculture Statistics at a Glance, 2017). As per the primary data collected, farmers in Hoshiarpur have an average land holding of 5 acres. While paddy and maize are the main Kharif crops, wheat is the major Rabi crop. Apart from these, sugarcane is a round the year crop in the district.

Ground water is used for irrigating approximately 91.36% of the total irrigated area, thus indicating that ground water is the major source of irrigation. The stage of ground water development in the district is 104%, as two blocks viz. Hoshiarpur-1 and Tanda fall in the over-exploited category while rest of the blocks are in semi-critical to exploited range (CGWB, 2016). This has led to an average decline of 0.68m/year in the ground water level. Currently, the groundwater depth is 20-30 m (WRIS, 2020).

## METHODOLOGY

The study was based on primary data collected from the farmers of these districts. For the selection of farmers, purposive sampling in which, the representative sample was assumed to be the representative of the population, was adopted along with the willingness of farmers to provide the required information.

Data collected from farmers for the assessment of irrigation water productivity included total paddy yield per acre, irrigation cycle (number of irrigations, time taken per irrigation per acre) and farmers' land holding for paddy crop. In addition to this, pump discharge for different pump capacities and bore well depth were calculated using the tank and stop watch method. In this method, the tank measurements were taken and time for filling up the tank was estimated to calculate the pump discharge (Salazar et al., 1994).

Assessment of irrigation water productivity is based on the formula (Brar et al., 2012):

***Water Productivity (kg/m$^3$) = {Crop Produced (kg/acre)} / {Water consumed (m$^3$/acre)}***

Wherein water consumption is estimated by the formula:

***Irrigation water consumed (m$^3$/acre) = No. of irrigations × Time taken per irrigation per acre (sec) × pump discharge (m$^3$/sec)***

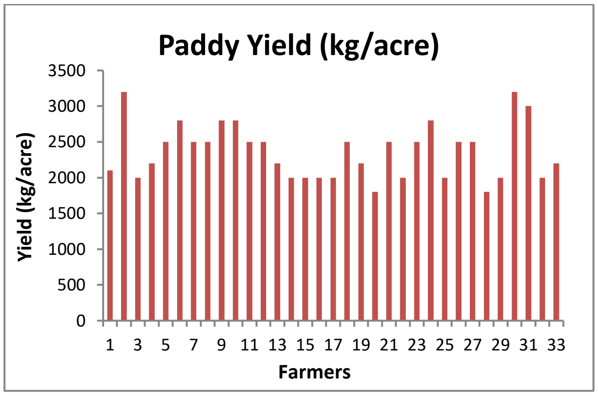
Post sensitization of farmers regarding excessive water consumption in paddy, 33 farmers in each of the two districts agreed to provide information on the above mentioned variables for estimating irrigation water productivity of paddy. The pump discharge varied with the height of the suction pipe, which in Jalandhar was in the range of 100- 180 feet and in Hoshiarpur was in the range of 25-50 feet. The height of the suction pipe approximately indicated the depth of ground water in the study area.

The calculated irrigation water productivity of the districts was compared at the inter-district level. In addition to this, the estimated paddy irrigation water productivity was compared with the best national and global paddy water productivity to ascertain areas of interventions.

## RESULTS & DISCUSSION

### Jalandhar

Varying with the variety of paddy cultivated, the yield in Jalandhar ranged from 1800 to 3200 kg per acre (Fig 2) and the applied irrigation water ranged from 3456 to 6000 litres per kilogram of paddy produced. Taking in account the above mentioned variables, average irrigation water productivity was 0.23 kg/m$^3$ with most of the farmers having irrigation water productivity in the range of 0.20-0.29 kg/m$^3$ (Fig 3).



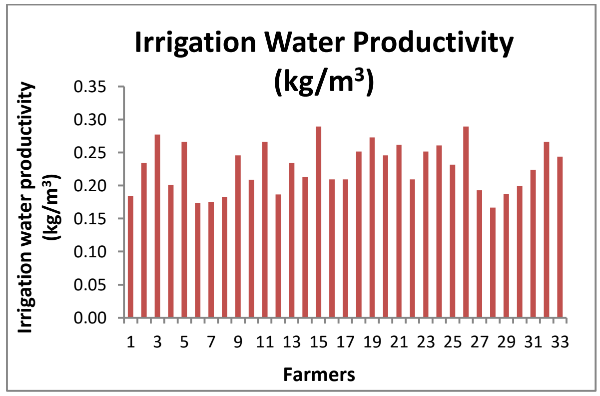



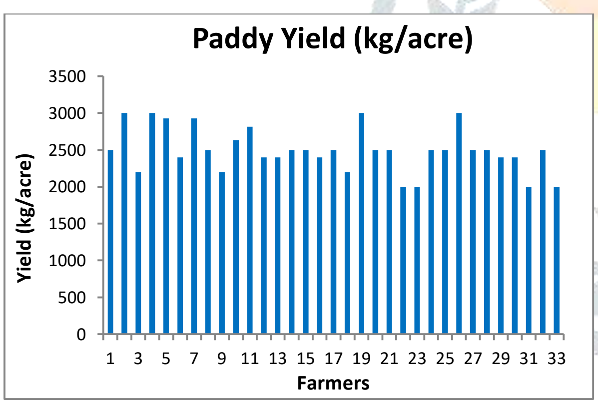

**Figure 2: Paddy Yield in Jalandhar**

**Figure 3: Irrigation water productivity in Jalandhar**

As compared to the general paddy irrigation water requirement of 4500-5700 $m^3$/acre (Kaur et al., 2010), such huge application of irrigation water i.e. 6918-16080 $m^3$/acre leads to stressed water conditions of the study area and high dependency on ground water. From the calculated irrigation water requirement and IWP, it can also be inferred that there is less crop production relative to the huge water application for irrigating the crop. Such low irrigation water productivities in Jalandhar district are due to insufficient rainfall (around 600 mm) that is unable to meet the irrigation water requirement for paddy.

## Hoshiarpur

Depending upon different varieties of paddy cultivated in the fields, yield in Hoshiarpur ranged between 2000-3000 kg per acre (Fig 4) and the irrigation water applied ranged from 3879-6142 litres per kilogram of paddy produced. Here, the average irrigation water productivity was 0.19 kg/$m^3$ with most of the farmers have irrigation water productivity in the range of 0.16-0.26 kg/$m^3$ (Fig 5),



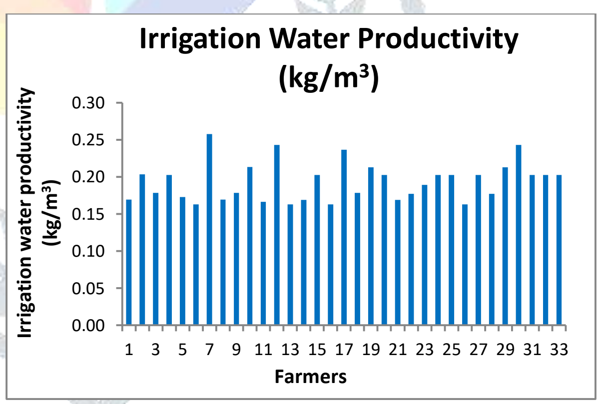




**Figure 4: Paddy Yield in Hoshiarpur**

**Figure 5: Irrigation water productivity in Hoshiarpur**

In this district also, irrigation water application of 9873-18426 $m^3$/acre is much higher than that of the general water requirement. From the calculated irrigation water productivity, it can be perceived that with more amount of irrigation water there is less production of paddy in the region. In Hoshiarpur, such less irrigation water productivity is due to the light density soils such as sandy loam (mentioned in earlier sections), which leads to more water percolation in the soil and hence there is more water requirement in the region to grow paddy.

## Comparative analysis of Irrigation water productivity

Irrigation water productivity is dependent upon two factors i.e. crop yield and irrigation water consumed for the respective crop. Since, paddy yield is comparable in both the districts; difference in irrigation water productivity is ascribed to irrigation water consumed for paddy cultivation.

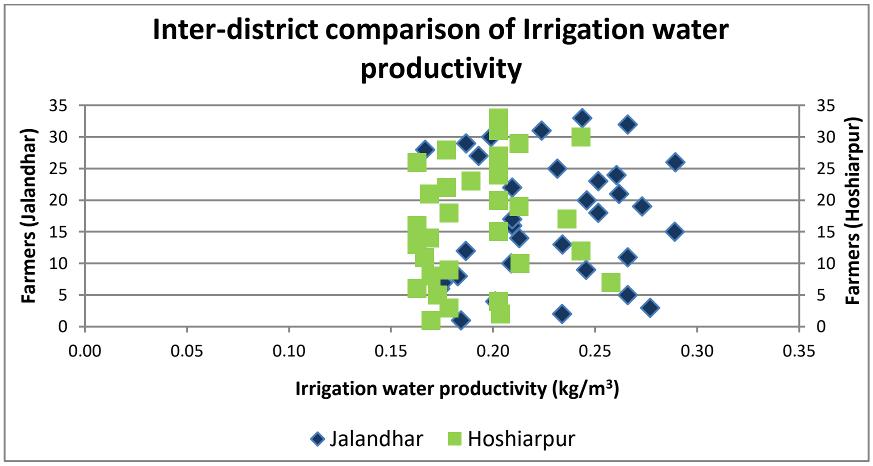



**Figure 6: Comparison of irrigation water productivity in Jalandhar and Hoshiarpur**

Despite receiving more precipitation than that of Jalandhar, 21% lower irrigation water productivity was recorded in Hoshiarpur (Fig 6). This is primarily attributed to the sandy textured soil (light density) present in the majority of the district as compared to the loamy silt textured soil (medium to heavy density) present in Jalandhar. Due to sandy soil, there is higher rate of infiltration and lesser water retention capacity that leads to higher water consumption in the region. In addition to this, shallow water depth in Hoshiarpur than that of Jalandhar also enables easy access of ground water in the region (CGWB, 2014). Therefore, it is likely for farmers in Hoshiarpur to utilize more irrigation water for paddy.

**Table 1: Comparison of Local and best national and international IWP**

| Crop | Punjab (Jalandhar) ($kg/m^3$) | Punjab (Hoshiarpur) ($kg/m^3$) | India (Jharkhand) ($kg/m^3$) | International (China) ($kg/m^3$) |
|---|---|---|---|---|
| Paddy | 0.23* | 0.19* | 0.75** | 1.03-3.31*** |

Source: *Author
** Bharat R. Sharma, U. A. (2018). *Water Productivity Mapping of Major Indian Crops.* Delhi: NABARD and ICRIER
*** Monaco, F. and Sali, G. (2018) 'How water amounts and management options drive Irrigation Water Productivity of paddy. A multivariate analysis based on field experiment data', *Agricultural Water Management*. Elsevier B.V., 195, pp.

On the other hand, Jharkhand records 0.75 $kg/m^3$ as the highest irrigation water productivity in India. This high irrigation water productivity in Jharkhand can be attributed to the fact that the state receives an annual rainfall of 1430 mm that fulfills a great portion of water demand for paddy crop in the state (IMD, 2020). Hence, given the agro-climatic conditions in the state of Jharkhand, the cultivation of paddy requires comparatively less provision of irrigation water. This rain water availability for crop cultivation makes paddy crop development reasonable in the eastern belt of India (Sharma et al., 2018). Therefore, the yield output per unit of irrigation water is generally higher in the eastern states such as Jharkhand, Chhattisgarh, Bihar, Assam, etc. Hence, along with crop shift from paddy to less water intensive crops in Punjab, eastern states such as Jharkhand must be encouraged for paddy production due to agro-climatic suitability.

On the mention of global irrigation water productivity, with a range of 1.03–3.31 $kg/m^3$ China secures a higher rank (Monaco & Sali, 2018). Primarily, this irrigation water productivity can be attributed to the high yielding paddy varieties and the associated agricultural practices. Paddy varieties in China produce 4000-5000 kg/acre paddy annually. China practices less water consuming farming techniques, especially AWD at 3-8 days intervals and direct seeded paddy (a technique that eliminates the transplantation process of paddy, thus the water required during transplantation is saved) in the fields (Jin at al., 2016). In addition to the water efficient agricultural practices, China mostly consists of loamy and clayey soil types which has high water retention capacities leading to less artificial irrigation water requirement for paddy cultivation. Therefore, despite the precipitation range of 800-1000 mm in China (Fang et al., 2005), the aforementioned factors provide the reasons for high irrigation water productivity as compared to the best one in India (Jharkhand) due to light density soil in Jharkhand (Chandra et al., 2015) as compared to that of China .

## Potential water saving in Punjab due to Recommended Practices

As estimated in the earlier sections, the water usage ranged from 3456 to 6000 $m^3$ and 3879-6142 litres per kilogram of paddy produced in the two selected districts of Punjab i.e. Jalandhar and Hoshiarpur, respectively. However, upon practicing AWD and cultivation of short duration paddy varieties, individually as well as in combination, there exists an opportunity for significant reduction in water usage and enhancement in IWP as mentioned in Table 2.

**Table 2: Potential water use and IWP due to Recommended Practices**

| District | Estimated Water use (L/kg) | Estimated IWP ($kg/m^3$) | AWD | | Short Duration Paddy Varieties | | AWD + Short Duration Paddy Varieties | |
|---|---|---|---|---|---|---|---|---|
| | | | Potential water use (L /kg) | Potential IWP ($kg/m^3$) | Potential water use (L /kg) | Potential IWP ($kg/m^3$) | Potential water use (L/kg) | Potential IWP ($kg/m^3$) |
| Jalandhar | 3456-6000 | 0.20-0.29 | 3110-5400 | 0.44-0.76 | 2938-5100 | 0.46-0.81 | 2592-4500 | 0.53-0.91 |
| Hoshiarpur | 3879-6142 | 0.16-0.26 | 3491-5528 | 0.45-0.71 | 3297-5221 | 0.48-0.76 | 2909-4607 | 0.51-0.81 |

There is a potential decrease of 10 and 15% water use in paddy cultivation due to AWD and cultivation of short duration paddy variety, respectively. Due to AWD, the IWP can potentially increase to a range of 0.44-0.76 $kg/m^3$ and 0.45- 0.71 $kg/m^3$ in Jalandhar and Hoshiarpur, respectively. Similarly, upon cultivation of short duration paddy varieties, the IWP can potentially increase to a range of 0.46- 0.81 $kg/m^3$ and 0.48-0.76 $kg/m^3$ in Jalandhar and Hoshiarpur, respectively. Moreover, adoption of both these interventions can potentially increase the IWP to a significant range of 0.53-0.91 $kg/m^3$ and 0.51-0.81 $kg/m^3$ in Jalandhar and Hoshiarpur, respectively.

Therefore, Punjab, despite having higher land productivity and about 100 percent irrigation cover under paddy has low irrigation water productivity demonstrating the requirement of better and water sustainable farming practices which will cause no or least yield penalty to the farmers.

## CONCLUSION

The results of the study presented that the irrigation water productivity of paddy in Jalandhar is in the range of 0.20-0.29 $kg/m^3$ and that in Hoshiarpur is 0.16-0.26 $kg/m^3$. On comparing the regional irrigation water productivity with the best national and international irrigation water productivity it was deciphered that low IWP in Jalandhar and Hoshiarpur is primarily attributed to lesser rainfall conditions, low density soil types and the existing agricultural practices in these districts. It was ascertained that one way to enhance the irrigation water productivity is to shift paddy cultivation from states like Punjab to those receiving more rainfall in the paddy season such as eastern states like Jharkhand.

Upon adoption of AWD and short duration paddy variety, the IWP can potentially increase to around 0.53-0.91 $kg/m^3$ and 0.51-0.81 $kg/m^3$ in Jalandhar and Hoshiarpur, respectively. However, adoption of these interventions is primarily subject to adoption by the farmers and for this, appropriate knowledge is to be disseminated to them. Therefore, an integrated approach is required for carrying out agriculture in a sustainable manner with respect to water. One of the possible ways to this approach is demonstration farms that provide handholding to farmers in terms of exposure to efficient interventions and economic benefits while adopting them.

Further, similar to schemes prevalent in the region such as micro irrigation (inclusive of providing drip irrigation system installation at farm lands), provision of subsidy under other interventions will also pave way to better irrigation water productivity. Hence, attaining significant yield with lesser water usage will lead to satisfactory water management in the region and achievement of the acclaimed motto of 'more crop per drop' under Prime Minister's national mission.

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**REFERENCES**

Awan, T. H., Ahmad, M., Ashraf, M. M., & Ali, I. (2011). Effect of different transplanting methods on paddy yield and its components at farmer's field in paddy zone of Punjab. *Journal of Animal and Plant Sciences*, *21*(3), 498–502.

Balwinder-Singh, Humphreys, E., Sudhir-Yadav, & Gaydon, D. S. (2015). Options for increasing the productivity of the paddy-wheat system of north-west India while reducing groundwater depletion. Part 1. Paddy variety duration, sowing date and inclusion of mungbean. *Field Crops Research*, *173*, 68–80. https://doi.org/10.1016/j.fcr.2014.11.018

Bharat R. Sharma, Ashok Gulati, Gayathri Mohan, Stuti Manchanda, Indo Ray, U. A. (2018). Water Productivity Mapping of Major Indian Crops. *Icrier*, *October*, 18–49.

Bhullar, A. S., & Sidhu, R. S. (2006). Integrated Land and Water Use: A Case Study of Punjab. *Economic and Political Weekly*, *41*(52), 5353–5357. http://www.jstor.org/stable/4419081

Brar, S. K., Mahal, S. S., Brar, A. S., Vashist, K. K., Sharma, N., & Buttar, G. S. (2012). Transplanting time and seedling age affect water productivity, paddy yield and quality in north-west India. *Agricultural Water Management*, *115*, 217–222. https://doi.org/10.1016/j.agwat.2012.09.001

Brauman, K. A., Siebert, S., & Foley, J. A. (2013). Improvements in crop water productivity increase water sustainability and food security - A global analysis. *Environmental Research Letters*, *8*(2). https://doi.org/10.1088/1748-9326/8/2/024030

Brindha, K. (2017). International virtual water flows from agricultural and livestock products of India. *Journal of Cleaner Production*, *161*, 922–930. https://doi.org/10.1016/j.jclepro.2017.06.005

CGWB. (2016). *Ground Water Year Book, Punjab and Chandigarh*. *September*, 186. http://www.cgwb.gov.in/Regions/GW-year-Books/GWYB-2015-16/GWYB NWR Punjab 2015-16.pdf

Central Ground Water Board, G. R. (2014). *DYNAMIC GROUND WATER Dynamic Ground Water Resources of India* (Issue March 2011).

Chandra, S., Singh, P. K., Tiwari, A. K., Panigrahy, B. P., & Kumar, A. (2015). Evaluation of hydrogeological factors and their relationship with seasonal water table fluctuation in Dhanbad district, Jharkhand, India. *ISH Journal of Hydraulic Engineering*, *21*(2), 193–206. https://doi.org/10.1080/09715010.2014.1002542

Department of Agriculture Cooperation & Farmers Welfare, Agriculture Annual Report 2018-19, New Delhi.

2019, pp. 1–224.

Department of Agriculture, Cooperation &. Farmers Welfare, 2017. Agricultural Statistics at a glance 2017, s.l.: Government of India, Ministry of Agriculture & Farmers Welfare.

Department of Agriculture, Cooperation &. Farmers Welfare, 2017. Agricultural Statistics at a glance 2018, s.l.: Government of India, Ministry of Agriculture & Farmers Welfare.

Devkota, K. P., Sudhir-Yadav, Khanda, C. M., Beebout, S. J., Mohapatra, B. K., Singleton, G. R., & Puskur, R. (2020). Assessing alternative crop establishment methods with a sustainability lens in paddy production systems of Eastern India. *Journal of Cleaner Production*, *244*, 118835. https://doi.org/10.1016/j.jclepro.2019.118835

Dhillon, M. S., Kaur, S., & Aggarwal, R. (2019). Delineation of critical regions for mitigation of carbon emissions due to groundwater pumping in central Punjab. *Groundwater for Sustainable Development*, *8*(November 2018), 302–308. https://doi.org/10.1016/j.gsd.2018.11.010

Dinar, A., Tieu, A., & Huynh, H. (2019). Water scarcity impacts on global food production. *Global Food Security*, *23*(July 2018), 212–226. https://doi.org/10.1016/j.gfs.2019.07.007

*Districts of Punjab – Government of Punjab, India*. (n.d.). Retrieved January 12, 2021, from https://punjab.gov.in/districts-of-punjab/

Fang, H., Liu, G., & Kearney, M. (2005). Georelational analysis of soil type, soil salt content, landform, and land use in the Yellow River Delta, China. *Environmental Management*, *35*(1), 72–83. https://doi.org/10.1007/s00267-004-3066-2

Gupta, K. B. (2008). Water footprint of India and its implications for international trade in food products. *South Asia Economic Journal*, *9*(2), 419–433. https://doi.org/10.1177/139156140800900208

Gupta, R., & Mishra, A. (2019). Climate change induced impact and uncertainty of paddy yield of agro-ecological zones of India. *Agricultural Systems*, *173*(October 2018), 1–11. https://doi.org/10.1016/j.agsy.2019.01.009

Hameed, K. A., Mosa, A. K. J., & Jaber, F. A. (2011). Irrigation water reduction using System of Paddy Intensification compared with conventional cultivation methods in Iraq. *Paddy and Water Environment*, *9*(1), 121–127. https://doi.org/10.1007/s10333-010-0243-1

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(9), 3232–3237. https://doi.org/10.1073/pnas.1109936109

India Meteorological Department. https://mausam.imd.gov.in/imd_latest/contents/rainfall_statistics.php. Accessed 13 Jan. 2020.

International commission on irrigation and drainage (ICID). (2018). *World Irrigated Area - 2018*. *Icid*, 1–6.

Jalota, S. K., Singh, K. B., Chahal, G. B. S., Gupta, R. K., Chakraborty, S., Sood, A., Ray, S. S., & Panigrahy, S. (2009). Integrated effect of transplanting date, cultivar and irrigation on yield, water saving and water productivity of paddy (Oryza sativa L.) in Indian Punjab: Field and simulation study. *Agricultural Water Management*, *96*(7), 1096–1104. https://doi.org/10.1016/j.agwat.2009.02.005

Jin, X., Zuo, Q., Ma, W., Li, S., Shi, J., Tao, Y., Zhang, Y., Liu, Y., Liu, X., Lin, S., & Ben-Gal, A. (2016). Water consumption and water-saving characteristics of a ground cover paddy production system. *Journal of Hydrology*, *540*, 220–231. https://doi.org/10.1016/j.jhydrol.2016.06.018

Karam, F., Mouneimne, A., Aichouche, F., Rapaport, A., & Harmand, J. (2019). Processing soil water content measurements to estimate crop water requirements and optimize irrigation supply. *IFAC-*

*PapersOnLine*, *52*(23), 49–53. https://doi.org/10.1016/j.ifacol.2019.11.008

Kaur, B., Sidhu, R. S., & Vatta, K. (2010). Optimal Crop Plans for Sustainable Water Use in Punjab. *Agricultural Economics Research Review*, *23*(December), 273–284.

Kaur, B., Vatta, K., & Sidhu, R. S. (2015). Optimising irrigation water use in punjab agriculture: Role of crop diversification and technology. *Indian Journal of Agricultural Economics*, *70*(3), 307–318.

Kazem Attar, H., Noory, H., Ebrahimian, H., & Liaghat, A. M. (2020). Efficiency and productivity of irrigation water based on water balance considering quality of return flows. *Agricultural Water Management*, *231*(January), 106025. https://doi.org/10.1016/j.agwat.2020.106025

Manzelli, M., & Vecchio, V. (2009). Aerobic paddy : crop performance and water. *Journal of Agriculture and Environment for International Development*, *103*(4), 259–270.

Massey, J. H., Walker, T. W., Anders, M. M., Smith, M. C., & Avila, L. A. (2014). Farmer adaptation of intermittent flooding using multiple-inlet paddy irrigation in Mississippi. *Agricultural Water Management*, *146*, 297–304. https://doi.org/10.1016/j.agwat.2014.08.023

Mohiddin, S. K. (2018). *Central Ground Water Board Department of Water Resources, River Development and Ganga Rejuvination Ministry of Jal Shakti Government of India Ground Water Year Book of Punjab and Chandigarh (UT).*

Monaco, F., & Sali, G. (2018). How water amounts and management options drive Irrigation Water Productivity of paddy. A multivariate analysis based on field experiment data. *Agricultural Water Management*, *195*, 47–57. https://doi.org/10.1016/j.agwat.2017.09.014

Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., & Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, *34*(2), 96–112. https://doi.org/10.1016/j.eja.2010.11.003

Qureshi, A. S. (2019). Increasing water productivity in the agricultural sector. In *Indus River Basin: Water Security and Sustainability*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-812782-7.00011-4

Salazar, LeRoy, Reith Crane, Maya ter Kuile, Jim Tolisano, David Radtke, L. W. (1994). *Planning , Design , Operation , and Management of Small-Seale Irrigation Systems Irrigation Reference Manual Peace Corps Irrigation Training Manual T0076 in the Selection , Planning , Design , Operation , and Management of Small-Scale Irrigation Systems*. 683.

Sudhir-Yadav, Humphreys, E., Kukal, S. S., Gill, G., & Rangarajan, R. (2011). Effect of water management on dry seeded and puddled transplanted paddy. Part 2: Water balance and water productivity. *Field Crops Research*, *120*(1), 123–132. https://doi.org/10.1016/j.fcr.2010.09.003

Veldkamp, T. I. E., Wada, Y., de Moel, H., Kummu, M., Eisner, S., Aerts, J. C. J. H., & Ward, P. J. (2015). Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydro-climatic variability. *Global Environmental Change*, *32*, 18–29. https://doi.org/10.1016/j.gloenvcha.2015.02.011

Wada, Y., Van Beek, L. P. H., & Bierkens, M. F. P. (2011). Modelling global water stress of the recent past: On the relative importance of trends in water demand and climate variability. *Hydrology and Earth System Sciences*, *15*(12), 3785–3808. https://doi.org/10.5194/hess-15-3785-2011

Zwart, S. J., & Bastiaanssen, W. G. M. (2004). Review of measured crop water productivity values for irrigated wheat, paddy, cotton and maize. *Agricultural Water Management*, *69*(2), 115–133. https://doi.org/10.1016/j.agwat.2004.04.007