International Journal of Irrigation and Water Management ISSN 2756-3804 Vol. 9 (1), pp. 001-011, January, 2022. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Impact Evaluation of an Operational Satellite-based Integrated Rice Advisory System in Northeastern Bangladesh

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Accepted 18 December, 2021

Abstract

During the 2021 winter season (January– May), locally known as Boro season, an *Integrated Rice Advisory System (IRAS)* was launched for Northeastern Bangladesh. IRAS transmitted text advisory to farmers on optimum ways to irrigate while safeguarding crop yield. These texts were generated on the basis of weather, satellite data, estimated water consumption by crops and modeled crop water need. To quantify the impact of IRAS, a survey was carried out for a cross sectional sample of 983 farmers and pump owners who were divided into control and experimental groups. On an average, experimental farmers receiving IRAS advisory irrigated 32% less than the control group during the Boro season. Experimental pump owners with greater control of irrigation irrigated 44% less than control pump owners. Ninety-four percent of experimental farmers and 97 percent of experimental pump owners reported IRAS to be either useful or very useful. Eighty percent of experimental farmers and 87%of pump owners reported the weather forecast to be the most useful component for making decisions to avoid unnecessary irrigation. IRAS advisory triggered a change in decision for 80% and 88% of experimental farmers and experimental pump owners, respectively. Experimental group of farmers on average reported 30% higher earnings than their control counterparts.

Keywords: Bangladesh, irrigation, rice, satellite, weather, advisory, impact evaluation.

1.0 THE IRRIGATION RICE ADVISORY SYSTEM (IRAS)

Today groundwater provides about 42% of irrigational water required for growing crops (Döll et al., 2012). However, a growing population requires increased agricultural productivity. This consequently triggers a significant and often unsustainable extraction of groundwater around the world (Gao et al., 2021; Siebert et al., 2015). In countries of South Asia, such as Bangladesh, which is also a leading rice producing nation, there is a clear correlation between groundwater depletion and increased agricultural productivity where the Monsoon rains have become insufficient to replenish the groundwater extracted during the previous dry season (Bose et al., 2021; Jahan et al., 2010). Given that rice is the most water-intensive crop, a crop water demand-based Integrated Rice Advisory system (IRAS)

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to optimize on-farm water use can play an important role for sustainable rice production and improved agricultural water management (Bose et al., 2021; Hossain et al., 2017; Hossain et al., 2020).

To conserve groundwater and maintain or improve crop yield during the dry (non-Monsoon) season of South Asia, a system such as IRAS has already been in operation in Pakistan since 2016 and later in India in 2018 (Hossain et al., 2017; Hossain, 2019). This system was originally co-developed by Pakistan Government and the University of Washington (UW) in 2015 (Hossain et al., 2017). In Pakistan, IRAS began with 700 farmers in 2016, and has now scaled to more than twenty thousand farmers. These farmers currently receive (as of writing) text advisory services of IRAS in regions that are known to overuse groundwater during the dry season when food production is critical (Iqbal et al., 2017). IRAS for Bangladesh was officially launched in January 2021 for advising farmers in Northeastern Bangladesh via text messaging on how much and when to irrigate based on crop water demand, observed evapotranspiration (ET) and weather forecast. This study describes the impact evaluation of IRAS that was carried out and presents key findings and recommendations. The IRAS for Bangladesh is a modified and improved version that is described in the following section based on theoretical underpinnings that are described in greater detail by Bose et al. (2021).

In IRAS, a proxy measure of the reference evapotranspiration rate (ETo) is first computed using the common method from Allen et al. (1998) known as the “FAO56 report.” This technique is an alteration of a well-known equation reported in Monteith and Unsworth (1990) using temperature, humidity, wind speed, and solar radiation as key inputs. The modeled output is crop water need for each week for the specific crop in question (i.e., rice in this case) according to the growth stage. The inputs to the model are obtained from a Global Numerical Weather Prediction (NWP) modeling system known as the Global Forecast System (GFS) (GFS, 2021). The nowcast weather variables from GFS produce nowcast of crop water demand, precipitation, and other farming-relevant conditions such as humidity, windspeed and temperature. Similarly, the forecast weather variables from GFS help produce forecast of the same variables (Figure 1). Prior to launch of IRAS in Bangladesh, extensive validation and quality control of the basic components had been carried out in Pakistan, India and Bangladesh. Such prior validation studies are reported in Bose et al., (2021), Hossain et al. (2017), Hossain et al., (2020) and IRAS (2018) . The user interface for the IRAS decision support system for Northeastern Bangladesh can be accessed here at http://depts.washington.edu/saswe/dae.

In the operationalized version of IRAS in Bangladesh, when supply (rainfall/recent irrigation) exceeds crop water demand, the farmers get advisory to avoid irrigation (Figure 1). Similarly, when crop demand exceeds the supply, the farmers get the advisory to apply or increase irrigation (Figure 1). Prior to the official launch with Department of Agricultural Extension (DAE) of Bangladesh, IRAS was prototyped as a pilot in 2019 for 165 farmers in Bangladesh. The pilot launch revealed encouraging finding where 78% of farmers found IRAS useful, particularly during winter cyclonic events (such as cyclone Bulbul in 2019) when rainfall is unexpected and can damage moisture sensitive crops such as potato and vegetables if there is over irrigation.

1.1 IRAS MODIFICATION FOR SMALL-SCALE FARMERS OF BANGLADESH

While the basic version of IRAS described earlier and already implemented in Pakistan and India has benefits for farmers, the service has a non-negligible operational cost for phone texting. Furthermore, the spatial resolution afforded with the use of GFS-only data is too coarse (~ 10km) to provide hyper-local advisory needed for small-scale farmers of Bangladesh, many of whom own plots smaller than an acre. Although the texting cost of an irrigation advisory system can be expected to be maintained by Bangladesh Government, limited financial resources of DAE mean that the total number of texts that can be afforded in an operational setting is limited. Thus, a smaller fraction of the country’s approximately 20 million farmer population can likely be reached due to cost-constrained texting services. IRAS was therefore modified and improved using additional satellite data to allow micro-targeting of farmers based on regions already experiencing higher degree of water waste (over-irrigation)or water scarcity (Bose et al., 2021).

The idea of micro-targeting farmers who are over-irrigating is based on use of satellite data from Landsat Thermal Infrared (TIR) imagery of the Landsat mission (Senay et al., 2016). First, actual on-farm water consumption by crops is inferred from observed ET using Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a, 1998b) using Landsat Thermal Infra-Red (TIR) data at 100 m or smaller spatial resolution. The crop water demand is then computed by estimating the ET based on Penman-Monteith (FAO56) technique, as described earlier. Finally, from the comparison between actual water consumption and crop water need, IRAS can identify the extent to which plots are overirrigating or under-irrigating so that the appropriate advisory can be sent to farmers who need to reduce (or increase) groundwater irrigation. As an example, in Figure 2, we show for three irrigation districts of Northern India how one can derive the extent of over/under irrigation at 60 m resolution of the Landsat7 TIR data using SEBAL at bi-weekly frequency during a growing season (Bose et al., 2021). Previous work has already shown that SEBAL ET and the consequently derived extent of over or under-irrigation can be strongly correlated to dry season groundwater table fluctuations (Bose et al., 2021). It has been reported that an operational IRAS that integrates Landsat TIR data on average can potentially save about 85% (80 million m^3) of groundwater per dry non-Monsoon season for an average irrigation district of Northern India or Pakistan (Bose et al., 2021).

1.2 THE IRAS ADVISORY TEXT MESSAGES

From January 15, 2021 to May 21, 2021, selected farmers received a text message in Bangla (shown in parentheses) from IRAS once a week (typically every Saturday evening) as follows:

1. **Message 1 Part A (next week's rainfall):** *There is a chance of rain* OR *There is no chance of rain(বৃষ্টিপাতের সম্ভাবনা রয়েছে* OR *বৃষ্টিপাতের সম্ভাবনা নাই)*
2. **Message 1 Part B (next week's windspeed):***Windspeed is expected to be higher than normal OR Windspeed is expected to be normal OR Windspeed is expected to be lower than normal(বাতাসের বেগ স্বাভাবিকের থেকে বেশি হতে পারে* OR
3. *বাতাসের বেগ স্বাভাবিক থাকবে* OR *বাতাসের বেগ স্বাভাবিকের থেকে কম হতে পারে)*
4. **Message 1 Part C (next week's temperature):**Temperature is expected to be higher than normal OR Temperature is expected to be normal OR Temperature is expected to be lower than normal *(তাপমাত্রা স্বাভাবিকের থেকে বেশি থাকতে পারে* OR *তাপমাত্রা স্বাভাবিক থাকবে* OR *তাপমাত্রা স্বাভাবিকের থেকে কম থাকতে পারে)*
5. **Message 2 (irrigation):**

When past 7 day over-irrigation is <20% and next week'sforecast rainfall total is <5 mm: *You may need to irrigate (আপনার জমিতে সেচ লাগবে বলে ধারণা করা যাচ্ছে)*

When past 7 day over-Irrigation is >20% and next week's forecastrainfall total is >5mm: *You may not need to irrigate (আপনার জমিতে সেচের প্রয়োজন নাই বলে ধারণা করা যাচ্ছে)*

When past 7 day over-irrigation is >20% andnext week's forecastrainfall total is <5mm: *You may not need to apply additional irrigation (আপনার জমিতে অতিরিক্ত সেচ নাও লাগতে পারে)*

When past 7 day over-irrigation is <20% and next week's forecastrainfall total is >5mm: *You may not need to apply additional irrigation (আপনার জমিতে অতিরিক্ত সেচ নাও লাগতে পারে)*

For temperature and windspeed advisory, 'normal' is defined as the range of values that are within 25% of deviation from the climatologic mean. The advisories specific to irrigation were designed using language that is deliberately conservative and errs on the side of recommending irrigation or modestly prescribe avoiding irrigation. This is because farmers have a tendency to over irrigate or lack complete control on irrigation application and thus, such language was deemed to be more cognizant of the behavioral status quo. In total, about 10,000 IRAS text messages were sent to farmers from the experimental group during the Boro season of 2021.

2.0 IMPACT EVALUATION STRATEGY

The impact evaluation was carried out in twelve sub-districts (known as upazillas) selected from seven northeastern districts in the haor region of Northeastern Bangladesh (Figure 3). We first evaluated existing literature on impact evaluation in the farming sector to develop our impact evaluation strategy (such as Takayama and Nakatani, 2017; and Sharma et al. 2014). The goal of our impact evaluation was to make the survey as similar to a control trial as possible so that the impact of IRAS could be gauged accurately in context of the baseline (non-IRAS scenario).The ground operation for the impact evaluation was carried out by Environment and Population Research Center (EPRC) located in Dhaka, Bangladesh. DAE provided mobile phone numbers of farmers and pump owners. Pump owners are considered very important in any irrigation advisory impact analysis of Bangladesh because most, if not all farmers, do not own pumps. Furthermore, most farmers follow the archaic practice of fixed-price irrigation rather than pay-as-you-pump for irrigation. In fixed-price irrigation (hereafter referred to as 'pre-pay'), farmers pay a fixed amount of money during or after harvest to pump owners. This archaic practice of pre-paying for irrigation encourages farmers who do not own pumps to maximize the amount of water that can be received for irrigation for money already paid. Pump owners on the other hand who irrigate their own land or provide groundwater pumping service to their community are able to control the amount and number of irrigation applications much more effectively if they receive the appropriate advisory.

The mobile numbers provided by DAE required multiple rounds of rigorous quality control to verify that they were representative of the location and identity of the farmer or pump owner. Table 1 provides a quantitative summary of the number of farmers and pump owners in each group (experimental and control). Figure 4 provides a demographic summary, and Figure 5 provides a summary of land area owned by each group. About 20% of the sample farmers were female while there were only one female pump owner from the control group. As expected, the literacy rate was found to be very high with a near-100% for those who own pumps (Figure 4). For land type, most farmers own land that is modestly elevated

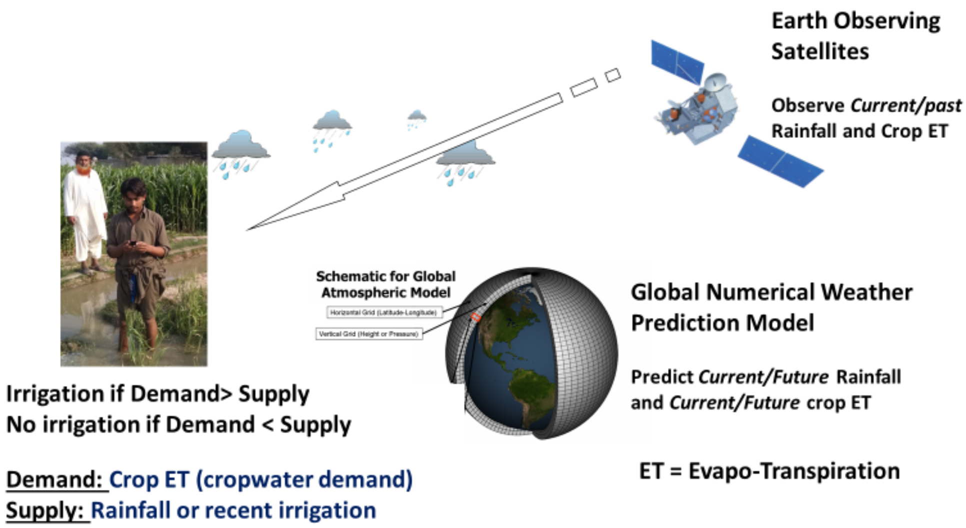

Figure 1. Schematic of the Integrated Rice Advisory System (IRAS) now in service in Northeastern region of Bangladesh during Boro season based on satellite earth observations and numerical prediction of the weather system. IRAS has been co-developed and launched with Bangladesh Department of Agricultural Extension (DAE) of the Ministry of Agriculture.

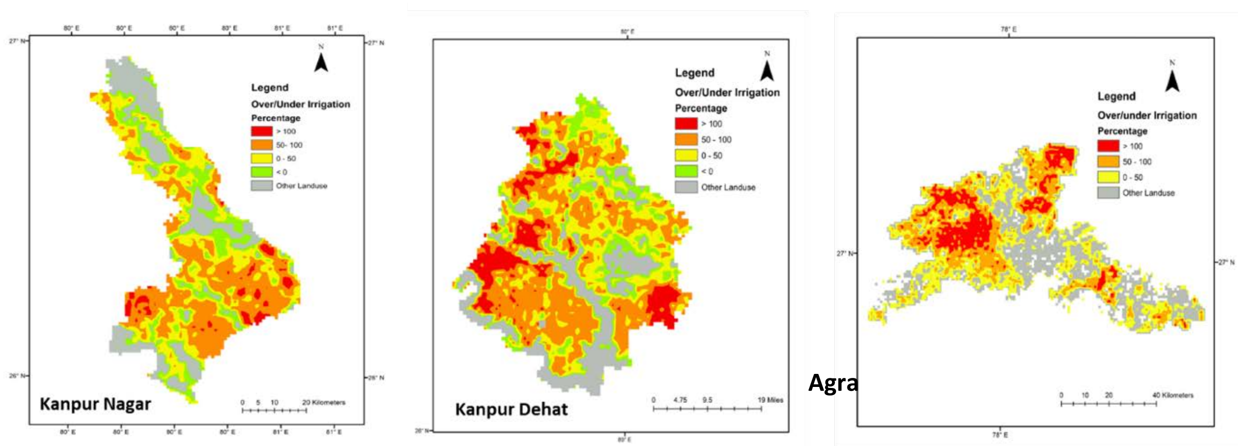

Figure 2. Map showing percentage of over/under irrigation according to actual water use (using SEBAL ET from Landsat TIR data at 100m resolution) and crop water demand for three irrigation districts of Northern India. The crop is winter wheat during the month of January in 2013.Red color indicates over-irrigation in excess of 100%.*After Bose et al., (2021).*

and not at higher elevation (requiring more irrigation due to easy draining) or lower elevation that is prone to ponding due to drainage from surrounding irrigated areas. Pump owners on the other hand owned mostly higher elevation land that are less flood prone, which could be a reflection of relatively higher affluence as higher elevation land is priced higher. Finally for land area, there is significant variability in amount of land owned by pump owners even though the average is similar to that of farmers (Figure 5).

For the survey data collection, EPRC developed semi-structured survey questionnaires separately for each group. EPRC staff were assigned and trained to conduct the survey from January 2021 to May 2021. A total of eight rounds of phone surveys were carried out by calling the mobile phone numbers. Multiple attempts made during each round to elicit a response from every single farmer and pump owner. The time interval between each survey was about 2 weeks which represents a reasonably significant growth stage change in rice requiring a change in irrigation and crop management practice.

To gauge the ground situation regarding agricultural customs and social constraints and to tailor an appropriate

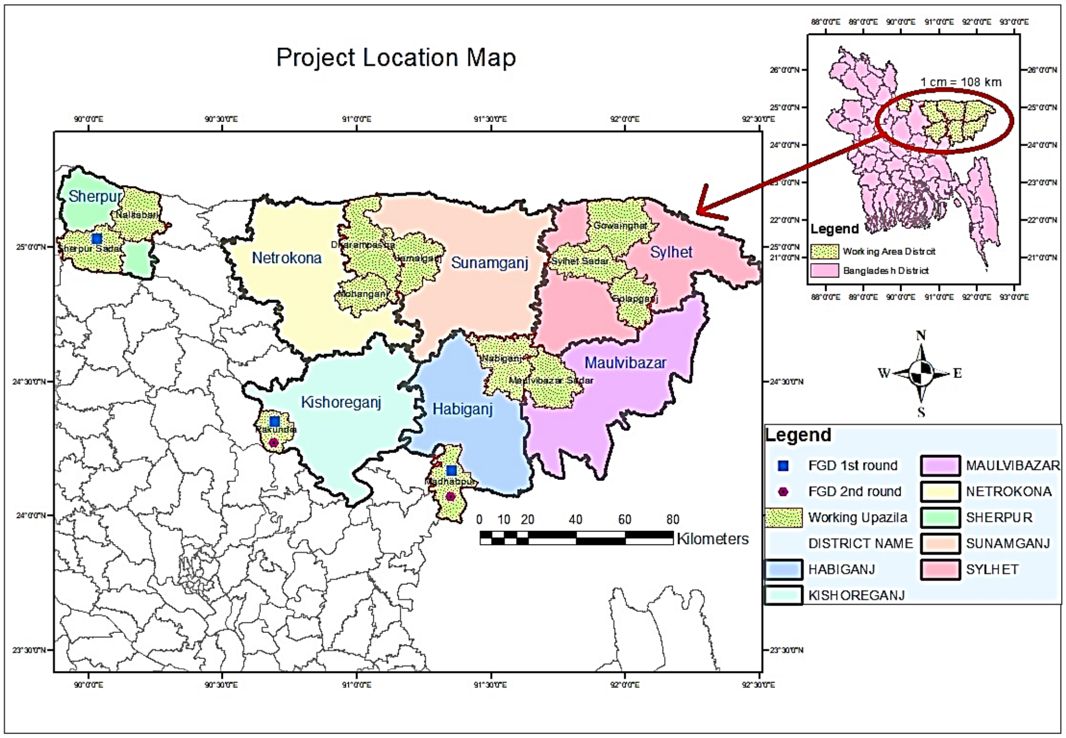

Figure 3. Selected sub-districts for impact evaluation (shown in dotted green) of IRAS from seven districts of Northeastern Bangladesh.

Table 1. Quantitative distribution of farmers and pump owners selected as control and experimental for impact evaluation of IRAS advisory during 2021 Boro season in Northeastern Bangladesh.

Category	**Male**	**Female**	**Total**
Experimental Farmers	389	85	474
Control Farmers	280	69	349
Experimental Pump Owners	68	0	68
Control Pump Owners	91	1	92
Total	**828**	**125**	**983**

and unbiased questionnaire for each group, focus group discussions (FGD) were conducted by EPRC in two rounds before and after completion of IRAS advisory operation. Findings from first round of the FGDs helped to refine the data collection and messaging tools. In total, six FGDs were conducted during the first round. Four FGDs were completed with the male farmers group and two with female farmers groups in accordance with the gender distribution (Table 1). Age of male farmers and female farmers ranged from 18 to 76 years and 25 to 55 years, respectively. During the second round, eight FGDs were conducted after the end of IRAS advisory operation. These focused on understanding perception of the IRAS advisory, yield, cost, savings and earnings. The points of discussion for first and second round of FGDs and the survey questionnaire can be seen at http://www.saswe.net/papers/IRASSurvey.pdf Figure 6 shows one such example of a FGDs carried out by EPRC staff.

Despite best efforts, about 48% experimental farmers, 55% control farmers, 60% experimental pump owners and 73% control pump owners could be reached for a response on average during a phone survey. The typical reasons for other farmers remaining unreachable during

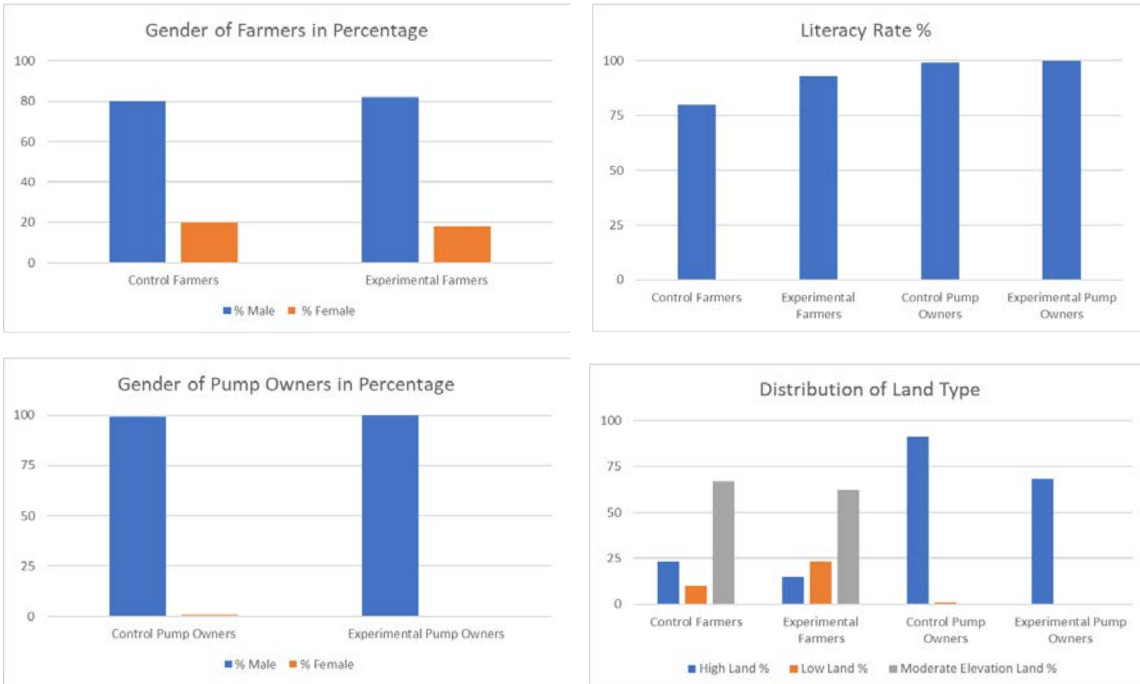

Figure 4. Demographic summary of selected farmers and pump owners for control and experimental group for impact evaluation of IRAS Advisory during Boro season of 2021.

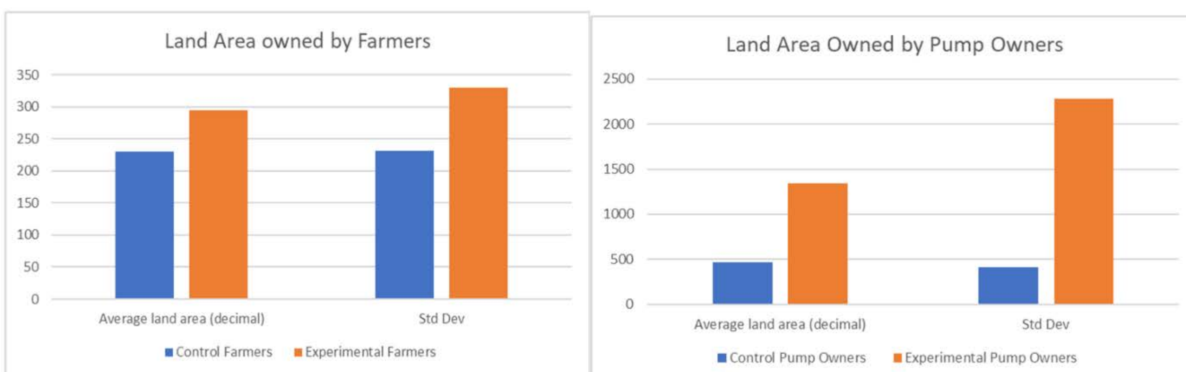

Figure 5. Distribution of land area owned by each group – farmers (left panel) and pump owners (right panel). The unit for area on the y axis is called a 'decimal' which is equivalent to 1% of an acre (or 100 decimals represent 1 acre).

a given survey ranged from phone being switched off to phone temporarily changing hands or reluctance to talk due to timing. Nevertheless, we consider a response rate of more than 45% given the total sample size of several hundred for each group as sufficient for us to draw statistically significant conclusions on impact of IRAS. In our findings of the survey, we report standard deviation and normalize responses as a percentage or by a common denominator (such as land area) where possible to allow fairer comparison.

3.0 RESULTS AND DISCUSSION

Before making comparisons between experimental and control groups, it is important to first understand how the IRAS advisory was perceived by those who received the service during the 2021 Boro season. Figure 7 provides this summary for a range of issues. In the upper panel of Figure 7, the IRAS advisory is reported to be useful for 94% and 97% of experimental farmers and experimental pump owners, respectively, with more finding it useful

Figure 6. A focused group discussion carried out by EPRC with female farmers in December, 2020. First author is in the middle facing the audience with an EPRC co-author (Tofayel Ahmed) seated on his right.

rather than most useful. This finding is not surprising in the context of the 2016 IRAS impact assessment in Pakistan (IRAS, 2018) and during 2019 pilot phase in Bangladesh. In both instances, usefulness was reported by80 %of farmers. We speculate that the higher level of usefulness for IRAS in Bangladesh (> 90%) might be attributable to three factors: i) the current IRAS is more location-specific and exclusive to the dry-season; ii) the current IRAS tracks actual on-farm irrigation and crop water need on a rolling basis to prescribe a more realistic decision for the coming week; and iii) focus group discussions held before the launch of IRAS operations helped build acceptance among users. Pump owners, with their ability to control irrigation water supply, found IRAS more useful than regular farmers who have less control over irrigation (Figure 7).

When it comes to specific actions triggered by IRAS, it is clear that IRAS advisory is able to trigger action more frequently for experimental pump owners (88%) than experimental farmers (80%). Pump owners invariably reduced irrigation far more (67%) than farmers (30%).

These actions (reduce or increase irrigation) appear to be driven by the weather forecast component of the IRAS advisory (Figure 7, lower two panels). The general picture that emerges from this perception analysis is that IRAS advisory can be more effective if it is prioritized for pump owners first before farmers who lack complete control over groundwater pumping for irrigation. The greater impact for pump owners on reducing irrigation and avoiding unnecessary irrigation is very clear. This impact can be expected to translate to higher water sustainability through minimization of on-farm water waste if pump owners are strategically targeted. Finally, there appears to be the added benefit of reducing fuel consumption and cost of irrigation for pump owners (Figure 7 bottom right panel).

Figure 8 shows the impact on reduction of irrigation application for control and experimental group of farmers and pump owners. On an average, experimental farmers receiving IRAS advisory irrigated 32% less than the control group during the Boro season while reporting very similar crop yield. Experimental pump owners who had greater control of irrigation, irrigated 44% less than control pump owners (Figure 8). This comparative analysis reinforces the emerging picture inferred from Figure 7. To reduce the water footprint of dry season rice production system while safeguarding yield, pump owners need to be prioritized with regular farmers in disseminating the IRAS advisory.

Current evidence gleaned from comparing Boro season earnings (Figure 9) seems to indicate that experimental group of farmers earned more than their control counterpart not only due to IRAS advisory but possibly due to the cultivation of non-rice cash crops. On the other hand, earnings for experimental group of pump owners are modestly lower compared to the control counterpart, which could possibly be an indication of a reduced revenue stream due to reduction of irrigation requested by the client farmer community.

Figure 7. Perception of IRAS Advisory by experimental group of farmers and experimental pump owners in Northeastern Bangladesh. Left panel: farmers; right panel: pump owners.

Overall, the impact of IRAS advisory appears to be more on sustainable use of groundwater with less ground water pumped while maintaining yield rather than on dramatic increase in profit for rice production. Although fuel consumption by irrigation pumps could not be accurately sampled in this impact evaluation study, it should be stressed that less ground water pumping translates to less consumption of fossil fuel by farmers. About 1.4 million irrigation pumps run on diesel in Bangladesh (Islam et al., 2017). It is estimated that about 22.38

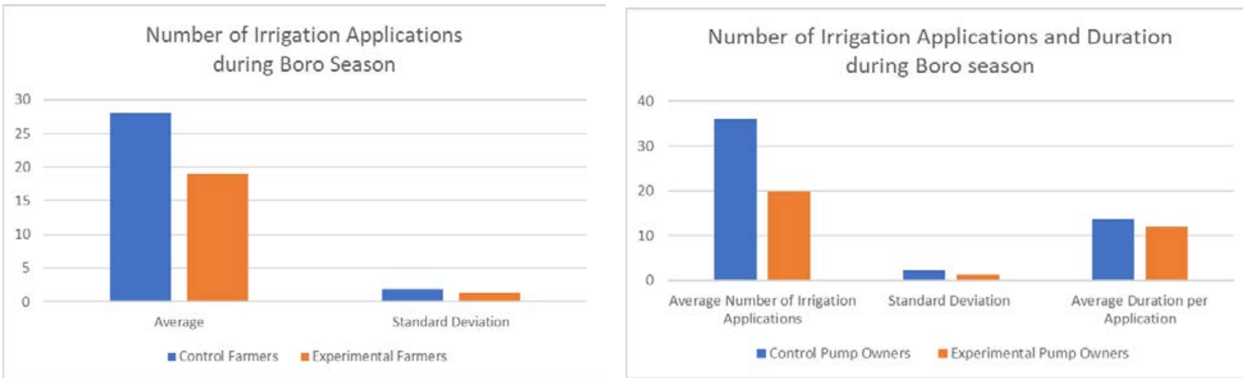

Figure 8. Impact of IRAS on irrigation application in Northeastern Bangladesh during Boro season of 2021. Left panel: farmers; right panel: pump owners.

Figure 9. Average earnings by farmers (left panel) and pump owners (right panel) during the 2021 Boro season. Earnings (y-axis) are reported here in the local currency (Taka) per unit land area, which in this case is 100 decimal or 1 acre.

pounds of CO_2 are produced by burning a gallon of diesel (El-Gafy and El-Bably, 2016). Thus, any irrigation advisory system that triggers less ground water consumption while maintaining crop yield can significantly decarbonize the food production system further (Islam et al., 2017).

4.0 CONCLUSION

The impact evaluation survey revealed very clearly that IRAS can make a significant reduction in the water and energy footprint of dry-season rice production for Bangladesh. Through a more optimal use of groundwater pumping, IRAS can also decarbonize the current farming system with less fossil-fuel consumption and make rice production more resilient against future water scarcity while also safeguarding crop yield (Islam et al., 2017). On an average, farmers receiving IRAS advisory irrigated nine times (or 32%) less than the control group during the Boro season while reporting very similar crop yield. Experimental pump owners who have greater control of irrigation, were able to irrigate sixteen times (or 44%) less than the control group. Ninety-four percent of farmers and 97% of pump owners reported IRAS to be useful or very useful. Eighty percent of farmers and 87% of pump owners reported weather forecast to be the most useful component of IRAS to avoid unnecessary irrigation. IRAS advisory triggered a change in decision for 80% and 88% of experimental farmers and pump owners, respectively. Experimental group of farmers on average reported 30% higher earnings, potentially also due to a greater amount of non-rice cash crops grown. The experimental group of pump owners however reported a 15% reduction in earnings possibly due to loss in revenue with reduced irrigation demanded by client farmers.

There are several limitations and nuances to this study that need to be recognized before findings from this study are built on for developing a national policy on the scaling of IRAS as a service for Bangladesh farmers via DAE. First, response rates during a round of survey ranged from 40% to 70% of the sample of farmers and pump owners. With more education and dissemination campaigns in the form of focus group discussions facilitated by local sub-assistant agricultural officers

(SAAO) of DAE, this response rate could be improved in future iterations of IRAS. SAAOs perform the vital role of an extension officer liaising between farmers' problems on field and solution available from science. Thus, greater involvement of SAAOs in any nation-wide IRAS service is critical. In fact, we argue that targeting SAAOs and pump owners in future iteration may be more effective than targeting every single farmer of Bangladesh.

Second, as the impact evaluation was a purely phone-based survey, findings on yield, cost and savings could not be verified from an independent source or method. DAE frequently conducts 'Field Day' during harvest time where such information could be verified and spot-checked for accuracy in future iterations. Finally, the impact evaluation strategy should be repeated over multiple Boro seasons that experience varying degrees of water scarcity to understand the limits of IRAS benefits. For example, during an extreme dry winter season where there is no rainfall in the months of March-April, zero rainfall forecast from an IRAS advisory will not be able to avoid unnecessary groundwater pumping and may even be detrimental if the forecast falsely predicts rainfall. Similarly, during an extreme wet winter season, the urgency to optimize or seek groundwater pumping services naturally diminishes for farmers.

The IRAS service, by virtue of being a collaborative project between DAE and the University of Washington, has the potential to scale sustainably to entire Bangladesh. DAE currently serves the country's farmers on crop advisory via Bangladesh Agrometeorological Information System (BAMIS; https://www.bamis.gov.bd/). BAMIS is a smart farming digital application that became operational in 2019. Co-author Dr. Md. Shah Kamal of DAE is the current BAMIS Project Director at the time of writing this manuscript). BAMIS currently sends weekly agricultural outlooks (but without the high resolution water use/irrigation need/flashflood advisory of IRAS) as a free service to all 64 district DAE offices and its13,000+ strong SAAOs. Currently, SAAOs under the payroll of DAE are located in every corner of the country. Given the very encouraging impact of IRAS on reducing the water foot print, safeguarding yield and increasing earnings, DAE should now invest in the permanent integration of IRAS within the BAMIS operations. For maximum impact on a water-sustainable rice production system for the dry season, this study has clearly revealed the need to prioritize pump owners for maximum impact along with regular farmers (Mainuddin et al., 2021).

ACKNOWLEDGEMENT

The impact evaluation component of this study was supported by Asian Development Bank TA 9057 *Building Sustainable Food and Nutrition Security in Asia and the Pacific*. The development of IRAS Advisory system and its implementation was supported by the Ivanhoe Foundation, University of Washington Department of Civil and Environmental Engineering John R. Kiely Endowment and Global Affairs.

5.0 REFERENCES

Ahmad, S, F. Hossain, T. Pavelsky, G. Parkins, S. Yelton, M. Rodgers, S. Basile, S. Ghafoor, D. Haldar, R. Khan, N. Shawn, A. Haque and R. Biswas (2020). Understanding Volumetric Water Storage in Monsoonal Wetlands of Northeastern Bangladesh, *Water Resources Research*, vol. 56, e2020WR027989. https://doi.org/10.1029/2020WR027989.

Allen, R. G., L.S. Pereira, D. Raes, and M. Smith. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements, *FAO Irrigation and drainage paper 56*. Rome, ISBN 92-5-104219-5 (available online at http://www.fao.org/3/x0490e/x0490e00.htm; last accessed July 11, 2021)

and Fluctuation Trend in Groundwater Table, *Journal Geological Society of India,* vol. 76, pp. 134-142.

Bastiaanssen, W.G., H. Pelgrum, J. Wang, Y. Ma, J.F. Moreno, G.J. Roerink, and T. Van der Wal(1998b). A remote sensing surface energy balance algorithm for land (SEBAL).: Part 2: Validation. *J. Hydrol*. vol. 212, pp. 213–229.

Bastiaanssen, W.G., M. Menenti, R.A. Feddes, A.A.M. Holtslag (1998a). A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. *J. Hydrol*. vol. 212, pp. 198–212.

Bose, I, F. Hossain, et al. (2021) Integrating Gravimetry Data with Thermal Infra-red Data from Satellites to Improve Efficiency of Operational Irrigation Advisory in South Asia, *Water Resources Research*, vol. 57(4), (DOI:10.1029/2020WR028654).

Döll, P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg andB.R. Scanlon (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, vol. 59, pp. 143-156.

ecosystem of Kishoreganj district, *The Bangladesh Journal of Agricultural Economics*, vol. 41(2), pp. 45-62.

El-Gafy, I. K. El-Din and W. F. El-Bably (2016) Assessing greenhouse gasses emitted from on-farm irrigation pumps: Case studies from Egypt,*Ain Shams Engineering Journal*, vol. 7(3), pp. 939-951,https://doi.org/10.1016/j.asej.2015.07.001.

Gao, J.X. Pengxuan, L. Zhuo, K. Shang, X. Ji, P. Wu, (2021). Water footprints of irrigated crop production and meteorological driving factors at multiple temporal scales, *Agricultural Water Management*, vol. 255, https://doi.org/10.1016/j.agwat.2021.107014.

Global Forecast System (GFS) (2021). Retrieved from: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs. Website accessed on [2021/05/10]

Hossain, F. (2019) Growing More with Less: Smart Tech Solutions to Feed the World, *University of Washington Engineering Fall Lecture series*, October 10, 2019; available at:video; presentation.

IRAS (2018). Impact Evaluation of PCRWR Pakistan Irrigation Advisory Service (available online only at http://www.saswe.net/publications/PakistanImpactEvaluation.pdf

Hossain, F., Harsha, K. S., Goyal, S., Ahmad, S., Lohani, B., Balaji, N., Tripathi, S. (2020). Towards Affordable and Sustainable Water-Smart Irrigation Services, *AWRA IMPACT*, vol. 22, pp. 28-29.

Hossain, F., N. Biswas M. Ashraf and Z. Ahmad (2017). Growing more with less using cell phones and satellite data, *Eos*, vol. 98, https://doi.org/10.1029/2017EO075143 https://doi.org/10.1016/j.rser.2017.04.052.

Iqbal, N., F. Hossain, M.G. Akhter (2017). Integrated groundwater resource management using satellite gravimetry and physical modeling tools, *Environmental Monitoring and Assessment*, vol. 189, pp.128, http://doi.org/10.1007/s10661-017-5846-1.

Islam, M. R, P. C. Sarker, S. K. Ghosh (2017) Prospect and advancement of solar irrigation in Bangladesh: A review, *Renewable and Sustainable Energy Reviews*, vol. 77, pp. 406-422,

Jahan, C.S., Q. H. Mazumder, A. T. M. M. Islam And M. I. Adham (2010). Impact of Irrigation in Barind Area, NW Bangladesh – An Evaluation Based on the Meteorological Parameters

Kamruzzaman, M. and M.T. Uddin (2020) Economic viability of Boro rice production in haor

Mainuddin M, Alam MM, Maniruzzaman M, Kabir MJ, Mojid MA, Hasan MM, et al. (2021) Yield, profitability, and prospects of irrigated Boro rice cultivation in the North-West region of Bangladesh. *PLoS ONE,*Vol. 16(4): e0250897. https://doi.org/10.1371/journal.pone.0250897

Monteith, J. L., and. Unsworth, M. H. (1990). Principles of Environmental Physics, 2nd ed., Edward Arnold, London.

Rahman, N. M.F, M.A. Aziz, M.I. Hossain and M.A. Baten (2013) *Advances in Environmental Biology*, 7(14) December, pp. 4542-4549.

Senay, G. B., M. Friedrichs, R.K. Singh, and N.M. Velpuri. (2016). Evaluating Landsat 8 evapotranspiration for water use mapping in the Colorado River Basin. *Remote Sensing of Environment,* vol. 185, pp. 171-185.

Sharma, M., G. Singh, Keshava (2014), Impact evaluation of training programmes on dairy farming in Punjab State. *Indian Research Journal of Extension Education,* vol.14(1) pp.105-108

Siebert, S., M. Kummu, M. Porkka, P. Döll, N. Ramankutty and B.R. Scanlon (2015). A global data set of the extent of irrigated land from 1900 to 2005. *Hydrology and Earth System Sciences*, vol. 19(3), pp. 1521-1545.

Takayama, T. and T. Nakatani (2017) Impact evaluation of farming by nonagricultural business organizations in special agricultural zones. *Journal of Rural Planning,* vol.36(1), pp.77-85 ref.33.